Fostering Learning Principles of Engineering Design

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Abstract

We contend that it is imperative that we recognize the internalization of the principles of engineering design as a career sustaining competency. Accordingly, we have piloted a pre-capstone course called Principles of Engineering Design. In this course we aim to empower the students to internalize the principles of engineering design, learn through doing (reading, designing, building, testing, and post-project analysis), learn to frame, postulate, and implement a plan of action for their Spring 2016 Capstone projects, and transition from being a student to a junior engineer in a company. In this course through a scaffolded set of assignments and activities, we provide an opportunity for students to internalize the principles of engineering design.

In Fall 2015 we introduced our students to a problem which involved designing, building, and testing a device capable of navigating a track filled with various sections of “difficult” terrain and pop a buried balloon. Through periodic in-class and out-of-class activities we were able to assess learning and coach the budding engineers. In keeping with Kolb’s experiential learning construct, activities include requiring students to write “learning statements” after lectures, assignments, and at the end of the semester. Learning statements are structured to enable students to articulate learning in the context of an authentic, immersive experience. These statements are evaluated for content and the depth of insight expressed therein and then returned to the students with comments.

In this paper, we cover the salient features of a course AME4163 – Principles of Engineering Design and the findings from an analysis of the learning statements. In our work we find evidence that students in project-based design courses are not being evaluated based on the actual learning taking place in the course, which we suggest is caused by a discrepancy between typical methods of instructor evaluation and the lessons learned by students over the course of a project. This conclusion is based on our finding that there is no relationship between student submitted learning statements and the grades that they achieved. Consequently, we suggest that the way students in project-based design courses are evaluated must be changed to reflect learning that takes place as a result of doing and reflection.
1. Frame of Reference

AME4163: Principles of Engineering Design is a pre-capstone course required for senior mechanical engineering students that is offered in the fall semester. Students self-organize in teams to design, refine, construct, test, and perform a post-mortem analyses of an autonomous mechanism. Our principal pedagogical goal is to have students, working in teams, learn through doing and reflecting. Through this process, we seek to enable students to internalize five principles of engineering design which broadly deal with forming a team and outlining the problem, ideating concepts while identifying advantages and disadvantages of those concepts, evaluating their concepts for functional, technical, and buildable feasibility until they have refined them into a singular feasible design, constructing and testing a prototype until it is competition ready and following that with a post-mortem analysis, and finally reflecting and articulating the lessons that they learned in the process. The learning objectives we focus on are as follows:

1. Internalize the principles of engineering design and learn how to identify and develop career sustaining competencies.
2. Learn through doing (reading, designing, building, testing, and post-project analysis), reflecting and internalizing the principles of design.
3. Learn to frame, postulate a plan of action, and implement the plan of action for the design project in the capstone course in Spring 2016.
4. Transition from being a student to a junior engineer in a company.

In this paper, we outline a particular instrument for student self-assessment, namely the learning statement, and explore its utility as a tool for understanding student outcomes and learning in a project-based design course. We outline the use of learning statements in student assignments and their utility in assessing internalization of the principles of design and, consequently, the degree to which students are meeting, or failing to meet, the learning objectives for the course. In particular, we focus on the use of learning statements to fill in gaps that arise from typical methods of student assessment, that are ensconced within assignment grading rubrics and judgements of project outcomes. These gaps represent areas of student learning that are tied to competencies useful to design engineers and it is our belief that many engineering students are not adequately being prepared for the problems facing contemporary engineers in industry and government which are complex in nature, ill-defined, and constrained by unknowable variables. In order to prepare students to meet these sorts of challenges, with the aforementioned learning objectives serving as our benchmark for success in the course, we investigate whether learning statements and what we glean from them are useful as mechanisms for improving project-based design instruction for future classes. We hypothesize that our analysis of the student learning statements will reveal a substantial flaw in the way that students in project-based design courses are being evaluated by instructors. Specifically, instructors using typical methods of evaluation ignore student learning in areas linked to team formation and organization, managing problems and decision making, and adaptability.

In keeping with Kolb’s experiential learning construct [1] and publications regarding the necessity of project-based learning courses in generating “design thinking” [2], we achieve the learning objectives through the challenge of a design, build, and test project. The student teams use a structured design process and are called on to solve a problem faced by the fictional inhabitants of a far-future, space-faring group of humans set on the planet Vayu (vignette
borrowed from [3]). In the story, a group of explorers seeking resources express the need for a device capable of navigating the rough and diverse Vayun terrain and, upon location of those resources, commencing to drill; see Figure 1. We present the problem thusly to allow our students to project simulated customer requirements onto the design, which are supplemented by added constraints (cost, weight, dimensions, etc.) in order to provide the students with the challenge of tackling a complex design problem. This backstory and the ensuing challenge to the students in our present study is dubbed “Project POP;” POP being an acronym for "prospect or perish.” In solving this problem for the Vayuns, students are able to explore new areas of learning and contextualize that learning in lived experiences to encourage long-term attainment of specific competencies. These competencies are explored by Lucas Balmer in [4] and are based on ABET accreditation criteria [5] as well as several other academic sources in which the authors explore the competencies required by engineers in a changing global environment [6-11].

![Figure 1: Map of the course used in the design experience. The course included physical barriers such as humps, sand pits, grease spots, gravel, and "swamp" terrain. At the end of the course is a box covered in Styrofoam housing a balloon.](image)

We recognize the experience needs to provide an authentic, immersive experience. It is authentic because the students are responsible for the completion of the project and the lessons they learn are applicable in other scenarios. It is immersive because we seat the technical challenges of the problem within a problem context and require students to carry out the process from the defining of the problem until a realized device is tested. Our adoption of this approach provides benefits to the learning process. For example, Todd et al. note the important role of
“realistic” constraints and problem context in reaching desired student outcomes in design engineering [12]. With the story in place, students are required not just to focus on the technical aspects of the challenge but also on the elements of design that may not be adequately emphasized in a typical project-based design course such as consideration of customer needs, team organization and planning, tabulation of student access to materials and tools, and budgetary limitations. This ensures that the experience the students go through is engaging on multiple levels that a professional design process requires, with the important exception that the consequences of failure are benign. As we gather from the literature, many seniors come to their senior capstones technically equipped, but face difficulty in making design-decisions arising from the added constraints of detailed and open-ended problems [13]. In order to prepare students to face these challenges, we expose students to a scaffolded design process.

As stated earlier, one of the key reasons the course is planned around such an intensive, semester-long project is that our goal is to get students to internalize the principles of engineering design, which are as follows:

1. **Planning**
   a. Forming a team
   b. Team contract
   c. Understanding the problem and framing the problem statement
   d. Schedule

2. **Preliminary design**
   a. Ideation – generating ideas
   b. Developing concepts: Ensure functional feasibility, ensure realizability (buildability, safety, and cost)
   c. Evaluating the concepts (functional feasibility, realizability) and identifying that concept which is most likely to succeed

3. **Embodiment design**
   a. Refining / modifying the most likely to succeed concept through technical analysis, experimentation and thought exercises.
   b. Stipulating a Bill of Materials
   c. Ensuring functional feasibility and buildability

4. **Prototyping, testing and post-mortem analysis**
   a. Bill of materials as built
   b. Ensuring that the design as built meets target performance requirements
   c. Post-mortem analysis

5. **Learning through doing, reflecting and articulating**
   a. Critically evaluating the processes of designing, building, testing
   b. Articulating, using learning statements, the Principles of Engineering Design that you have internalized.

The students are provided the opportunity to internalize the preceding five principles by executing a structured design process that is embodied in the following assignments:

1. Assignment 1: Team formation, planning and understanding customer requirements
2. Assignment 2: Concept generation, configure 8 possible systems and critical evaluation of all 8 configurations with respect to functional feasibility
3. Assignment 3: Reduction of 8 possible configurations to 2 through critical evaluation with respect to technical feasibility and realizability
4. Assignment 4: Create a CAD model of one configuration and critically evaluate to ensure that the subsystems come together in a system.
5. Assignment 5: Model critical elements using FEA and critically evaluate structural integrity of the components.
7. Assignment 7: Semester Learning Essay
8. Assignment 8: Plan of Action, for capstone projects that embody the internalized principles of engineering design.

To start the journey of internalizing the five principles of engineering design the students self-organize in groups of four students (ideally), although circumstances in Fall 2015 necessitated several teams having three members only. The instructors lecture to the assignments and student teams are required, for Assignments 1 through 5, to include team and individual learning statements. Over the course of the semester, student teams are tasked with the completion of assignments that are based on the steps of a structured design process. These assignments include:

Assignment 1
- Identifying customer wants and needs
- Developing a requirements list from the wants and needs
- Prioritizing the requirements using a ‘House of Quality’

Assignment 2
- Using those results to develop a Function Structure Diagram to explore and explicitly outline the functions that must be embodied in a successful device
- Turning functions into a Morphological Chart to generate possible solutions for each function
- Using that chart to generate several potential concepts

Assignment 3
- Analyzing those concepts for beneficial and detrimental qualities
- Synthesizing the critiqued concepts into a single concept
- Performing a reality check on that concept to identify possible points of failure and make adjustments

Assignment 4
- Modelling the device using computer drafting software
- Analyzing components using techniques learned in prior courses

Assignment 5
- Analyzing the computer model of the device using finite element analysis software
- Developing a bill of materials and construction plan for the device

End of Semester Deliverables
- Prototyping, testing, and finally putting the completed device to the test

Each assignment is designed to encompass a portion of this process and the steps are performed in the identified sequence, leading to a device that is built and tested. Furthermore, the steps of a structured design process which we build into each assignment are based on prior research with pre-capstone design students [14].
Ultimately, while the process itself is structured, the potential space of realizable solutions is deliberately open. Some restrictions are necessary, such as those involving safety. For example, in the Fall 2015 course, we disallowed the use of fire to pierce the Styrofoam, a method which several teams considered. Other stipulations are included to simulate realistic design constraints. Examples of these rules include cost, weight, and size limitations for the completed device. Despite certain achievable functions (navigate the course, pop the balloon, etc.), the open nature of the problem requires students to prioritize their own metrics for success. Though this is beneficial for the students, in that exposure to a complex design problem nurtures critical thinking and the development of the targeted competencies [9], it poses a challenge for the instructors: how can student progress be evaluated? The gap between typical student evaluation techniques (assignment grades, project performance) and a more general understanding of student learning is a topic well-explored by others [15-17] and currently there is no consensus that typical evaluation methods such as grading project outcomes are superior to other methods. However, what is clear is that we are not identifying many areas of student learning project-based design courses, despite evidence that students are progressing toward attainment of specific competencies.

2. Literature Review

To contextualize this course and our decision to pursue alternative means of student assessment, we offer the following review of the relevant literature. In the context of our argument, the literature falls into five categories: foundational literature, course context, existing pedagogy, limiting factors, and evidentiary support. In foundational literature we describe the pedagogical roots of our work. Essentially, we use this category for sources if they describe the academic basis on which the current iteration of AME4163 rests. In the course context section we describe the authors who have endeavored to understand the problems in engineering education raised in Section 1. In addition, we outline the limits of their conclusions and what insight they offer. In the existing pedagogy section, we evaluate the literature discussing researchers who are trying to solve similar problems and where existing solutions fall short. In limiting factors, we highlight the literature covering aspects of the problem which our investigation does not focus on: additional factors which may be at work in our problem. Finally, in evidentiary support, we evaluate the state of literature on this topic and briefly explain how they support (to varying degrees) the conclusions reached in this paper. The major findings for each section are summarized in Table 1.
Table 1: Summary of Key Findings from Literature

<table>
<thead>
<tr>
<th>Section</th>
<th>Key Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foundational Literature</td>
<td>Establish target competencies. Kolb’s learning process. Value of project-based design courses in design education.</td>
</tr>
<tr>
<td>Course Context</td>
<td>Use of design-based courses enable students to attain competencies not possible in other engineering courses. Others demonstrate value of self-assessment in design courses.</td>
</tr>
<tr>
<td>Existing Pedagogy</td>
<td>Textual analysis of student work largely limited to technical analysis of text. Further, existing methods do not track learning progression. Students who self-assess predisposed to view themselves as technically proficient. “Connectivity” in student writing is linked to desired student outcomes.</td>
</tr>
<tr>
<td>Limiting Factors</td>
<td>Team formation (methods, basis for selection, etc.) is important to design course project outcomes. Managing decisions as a team is one of the largest obstacles for students in design courses.</td>
</tr>
<tr>
<td>Evidentiary Support</td>
<td>Students need to be able to identify the reasons for their successes and failures. Self-assessment instruments can be useful tools for that process. Self-assessment is most valuable when paired with instructor evaluation. Team organization and problem management are two areas that design students improve upon.</td>
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**Foundational Literature**

Principally, we build on the work of investigators such as Lucas Balmer [4] who explores the development of a framework for AME4163, a project-based senior-level design course for mechanical engineers. We anchor our course framework around a central project and largely in the work of Kolb [1], who postulates a cycle by which individuals use experiences to iteratively improve their learning. This cycle is also the foundation on which learning statements are based, which we explore in Section 3. Additionally, Balmer builds on the work of Mistree et al. [3] whose work on project-based design education includes open design projects that are composed of a technical problem and problem context, which together are used to create an authentic, real-world experience. In agreement with the work of Dym et al. [2], we assert that preparing engineers for existing challenges faced by professional working engineers necessarily requires exposure to open problems that force students to confront unknown variables, non-prioritized requirements, and situational context. Furthermore, we leverage the work of ABET [5], Eggert [6], Lahidji [7], and others [8-11] in establishing the set of competencies required of modern engineering graduates in modern industry. In AME4163, we use the competencies identified to produce the learning objectives outlined in Section 2 and seek to determine whether or not those objectives are met. We further seek to iterate the course to better meet these learning objectives. In the following section, we explore our efforts to achieve these objectives by building on the research of others.

**Course Context**

In the context of the course foundation thus established, we build on the questions posed by others facing similar challenges. Todd et al. [12] and Etlinger [13] explore the challenges in
attaining the outlined competencies faced by students in project-based design courses and how that particular course model is best suited for development of these competencies in students due to the fact that it forces students to make difficult design choices and compromises in the face of practical concerns. We leverage that knowledge into preparing students to deal with complex problems in the belief that such challenges enable the development of student course-targeted competencies. In addition, Smith et al. [14] demonstrate that students in project-based design courses report increased confidence in their own competencies when they are provided opportunities for self-assessment. Further, the authors highlight a general trend between the overall confidence expressed by students and grade received when using their self-assessment instrument (surveys). While they do not conclude an explicit model for predicting grades with student self-assessment, their results demonstrate the utility of self-assessment instruments as a possible predictor of student success. Furthermore, using surveys can allow instructors to highlight particular areas of learning for the students. In this paper, we take this a step further in Sections 3 and 4 by analyzing learning statements, an alternate form of self-assessment which follows a more open construct than surveys.

Existing Pedagogy

Various forms of textual analysis exist in many disciplines; in this paper, we analyze text of discrete sentences with a pre-determined structure (learning statements). As we discuss in Section 3 and 4, our assessment of the student submissions is based on a desire to categorize subject matter and determine the insight expressed with the purpose of understanding self-reported learning. While textual analysis to assess learning is used both outside of engineering pedagogy [18, 19] and within [20], the creators of these analytical frameworks largely deal in writing samples: essays or paragraphs at the least. In addition, while the authors reveal certain insights about patterns among student writings which can be useful for efforts to teach successful ‘patterns’ of writing to other students, they also focus their analysis on the more mechanical, quantifiable aspects of student writing: word choice, sentence length, and number of references to certain key phrases and words. In contrast, we assess insight expressed and subject matter explored. In addition to limitations in the literature available on textual analysis, authors such as Kaslow [21] reveal another short-coming of self-assessment instruments: that they are prone to bias and misuse when students do not properly understand their purpose. Kaslow recommends that self-assessment tools to assess student learning should be paired with secondary tools to corroborate results. As we explore in Section 6, this limitation in our approach in this paper will be addressed in future investigations. However, corroborating our approach to analyzing the learning statements is the work of Reidsema and Mort [26], who tentatively suggest that certain “linguistic features” such as connectivity and appraisal are linked to higher levels of learning insight in design students.

Limiting Factors

One aspect of project-based courses and the learning of students in them which we do not focus on in this paper is the relative importance of team formation. Specifically, we do not choose student teams nor force them to form their teams based on personality criteria or methods outside their own best judgement. As a result, we do not control our results for interpersonal issues within teams nor do we control for individual student abilities within their teams. From the work of Reilly et al. [22], we see that models can be used by organizers to form teams tasked with the development of new products and systems which attempt to manage interpersonal issues
to increase team effectiveness. From Barrick’s work [23], we gain insight into the particular qualities of individuals in workplace teams which tend to be most effective at handling tasks. In addition, from Pournaghshband [24], we learn that the most common problems faced by students in design teams, many of whom have not, until the projects outlined in the paper, been members of a design team before, is managing team decisions. Pournaghshband also outlines strategies to manage these issues and notes their effectiveness in a classroom setting. Some issues, such as students having difficulty in managing the scope of a problem early on, are common to AME4163 and we leverage the advice to have students identify the key requirements of the system early on, modifying the document as their understanding of the problem grows. We explore the consequences of this further in Section 5 and in Evidentiary Support, we outline the evidence supporting the conclusions reached in that section and Section 6.

Evidentiary Support

Current literature on the need for better metrics of self-assessment in engineering design education is plentiful and varied amongst disciplines and course types. For project-based design in particular, both Besterfield-Sacre et al. [15] and Segers and Dochy [16] explore the need for better instruments to understand and explore student attitudes about their learning. Segers and Dochy in particular point out that, in the context of a rapidly changing and globalizing world with increased competition between nations, we need to prepare engineers who are not only capable technically but who also respond well to change. To assess the degree to which peer-evaluations, a non-typical form of student evaluation are useful as a metric of student progress in desired learning outcomes, the authors compared the results of peer evaluations given by students in a project-based course with those of a written examination. Similar to our findings in this paper, the researchers found that peer evaluations were not good predictors of student achievement of learning objectives. In their case, the peer evaluations were substantially more positive than their evaluated outcomes. Furthermore, in the work of Old et al. in [17], the authors discuss the challenges facing engineering educators today and explore the utility of a variety of atypical assessment techniques. In addition to the work above, we find that our conclusion that engineering design educators are not properly analyzing the learning that students are experiencing in project-based courses substantiates a claim in an editorial by Mistree [25]. In addition, we see in our results that team formation and problem management are two of the largest areas of student learning and corroborate the work of Reilly et al. [22], Barrick et al. [23], and Pournaghshband [24].

From the available literature, we establish the theory at work in AME4163 and further create a basis for our assertion that improvements in assessing learning in project-based design courses is vital to student outcomes. Further, we find in the literature support for our hypothesis that the methods instructors use to evaluate students in project-based design courses are not adequate for understanding student learning. Specifically, instructors typically assess student success based on project outcomes and technical analysis while they ignore student progress in team formation and decision-making, two areas of learning which appear frequently in design projects. Based on our review of this material, we reassert the need to more fully understand gaps in student evaluation in project-based design courses. In addition, we leverage this academic background to develop a plan for crafting and maintaining future improvements to the course.
3. A Framework for Course Improvement

We recognize the need for a systematic way to improve a course based on evidence. We adopt the approach embodied in Figure 2 (see Reference 4) and in this paper we discuss Steps 5 and 6. Based on prior iterations of the course and the earlier findings [4], we have at our disposal three main student assessment tools:

1. **Evaluation of the assignments and the performance of the autonomous vehicle:**
   Instructors graded the team performances on the group assignments and in the project competition based on how well the students followed the steps of the design process and demonstrated deep thinking about the process itself. This metric of success is fine as far as students are concerned; one of their primary selling points in their near-future job hunt will depend on the grade point average earned during their undergraduate careers. However, it leaves open room for error in terms of an instructor’s ability to gauge the degree to which the principles of design were internalized. As a result of this obstacle, two additional tools have been developed.

2. **Periodic surveys of the students over the course of the semester:** Using the course site D2L, we ask the students to rate a variety of statements pertaining to their confidence in their abilities within certain learning domains (the Principles of Design) on a seven point Likert scale following specific course milestones. The results of those surveys are not the focus of the current study but we note the utility of self-reported surveys in other areas of pedagogical research [15].

3. **An analysis of the learning statements:** A learning statement is a sentence written by a student in which he/she identifies something learned as a direct consequence of a particular experience. The formulation of the learning statement is anchored in the work of Kolb [1] and embodies the ‘experience,’ ‘reflection,’ and ‘conceptualize’ stages of the learning cycle (the learning statement itself does not cover the ‘test’ stage). The students are required to write learning statements using the construction embodied in Figure 3. The sentence begins with a statement regarding a particular activity immediately followed by an acknowledgement of a specific insight provided by that activity.
Figure 2: AME4163 iterative improvement process diagram, which illustrates the steps taken to gradually improve the learning experience of the students.

Figure 3: Chart detailing the proper formatting of a learning statement. This information was provided to the students both through reading materials made available through the course website as well as through in-class lectures.

The structure of the learning statement we show in Figure 3 is important because it underscores the need for students to abstract through reflection what they learned as a result of
doing an activity. Examples of properly structured and particularly insightful learning statements include the following:

“Through the formulation of a team contract in Assignment 1, I discovered that development and growth is maximized when roles are assigned based on competencies that are desired to be developed.” – AME4163 student, Fall 2015

“By constructing a PMI list during this phase of the project, I learned that this was an extremely useful tool for realizing the probable failure modes for each of the concepts and from this list, we were able to see the strengths and weaknesses of each individual component of our best designs, which allowed us to further improve upon it by fixing the probably failure modes.” – AME4163 student, Fall 2015

For each assignment, student teams are required to provide several team and multiple individual learning statements. As the distinction in names implies, individual learning statements (hereafter abbreviated to LS or LS’s) are written by individuals about learning through doing that are particular to them whereas team LS’s revolve around experiences and lessons common to all members of the team. The number of learning statements to be included at the end of Assignments 1 through 5 is not specified; teams are free to put as many or as few as they desire in each category as long as all team members are represented. In addition to the team assignments, we require students to write one learning statements at the end of most lectures. These are returned to them with comments to foster ongoing improvement. For Assignment 7, the semester learning essay, each student is required in two pages to provide 30 LS’s anchored in at least 10 experiences over the semester and relate these to one or more of the principles of engineering design.

In Section 4, we discuss the methods and strategies used to quantify and organize the LS’s offered by the students. This includes explanations for the data gathering process as well as what numerical techniques were used to analyze the data. In Section 5 we focus on the data and analysis of the data. In Section 6 we summarize our findings and offer some remarks.

4. Method for Analyzing Learning Statements

We utilize a two-pronged approach to categorization which involves sorting the statements into domains and then rating them based on their relative insightfulness. Due to the fact that in this course our assignments and objectives all revolve around instilling in the students the Principles of Design, we choose these categories for the domains into which the statements are sorted. These domains are “planning,” “preliminary design,” “embodiment design,” “prototyping, testing and post-mortem analysis,” and “learning through doing, reflecting and articulating.” In cases where a statement pertains to more than one domain, we make a judgement as to which domain the statement most closely belongs. In terms of the rating of statements, a four point scale is proposed in which statements are assigned a numerical value on a scale of zero to four based on the following criteria:

1. Zero points: Statements earn a rating of zero if the requisite LS structure is not present and are thus not technically learning statements.
   a. Example: “Through rechecking the project requirements, I will make sure that our material, energy, and information selections are covering the whole points of this project.” – AME4163 student, Fall 2015
   b. The above statement is not properly formatted because it neither expresses the insight in terms of a prior experience nor does it specifically imply learning. Instead it focuses on a future goal.
2. One point: Statements receive a rating of one point if the structure is present but the insight is trivial or obvious.
   a. Example: “From listening during today’s lecture, I now understand the prioritization matrix and its importance in engineering design.” – AME4163 student, Fall 2015
   b. The above statement both states something obviously true and neglects to explore any deeper relevance that the learning might have.

3. Two points: Statements are rated at two points if they demonstrate connection between their learning and something not explicit to the experience such as a novel circumstance in which the lesson might be applied.
   a. Example: “Through this lecture, I learned that additional tools, such as sketching our POP design, can lead to new perspectives that can potentially improve our design.” – AME4163 student, Fall 2015
   b. The above statement expresses learning in terms of an experience and then connects that to a future scenario involving a later stage of the design process.

4. Three points: Statements merit a rating of three points if they exhibit a deeper understanding of the lesson learned and explore its utility in a wider context.
   Additionally, statements which embody any of the Principles of Design merit this rating.
   a. Example: “After recognizing the SWOT analysis that we used in my internship during the lecture, I realized that the point of that analysis is not to record pros and cons, it is to categorize your thoughts and bring attention to the gaps in the design’s strengths and weaknesses.” – AME4163 student, Fall 2015
   b. The preceding statement simultaneously draws connections between multiple experiences while demonstrating a more generalizable lesson learned. It takes the learning beyond the obvious and directly relates to the second Principle of Design, which involves evaluating concepts.

Though the above two-pronged approach toward categorizing and rating of the LS’s involves a certain level of subjectivity on the part of the instructor performing the evaluation, through its use we are able to establish a suitable foundation for the analysis of the LS’s in the context of the overall learning of the students in the course. Furthermore, to ensure consistency of feedback one instructor comments on and grades all LS’s and is not involved in the analysis of the data nor in the development of findings. Given the qualitative and quantitative aspects of our rating systems, our approach to textual analysis is novel. Though we find textual analysis to ascertain student learning explored in some contexts [18-20], we find that most methods tend to focus on various ‘mechanical’ aspects of writing samples (not discrete statements) such as: word count, word order, passage length, frequency of keywords, and density of course-relevant phrases. However, others have noted the connection between insightful student reflections on learning and connectivity to other concepts [26].

To address our primary hypothesis posited in Section 1 that student learning is not being evaluated adequately by instructors we must analyze our data in two ways. First, we must identify areas in which students report their learning. Second, we must attempt to find a relationship between student performance (course grades) and their self-reported learning. Failing to do so provides evidence that our hypothesis is correct: that despite evidence of student learning, this learning is not being used to evaluate the students. This analysis consists of the following steps. First, we separately analyze team and individual learning statements provided by the students in the first five team assignments according to which Principles of Design were
explored in each assignment. To accomplish this, we tabulate team and individual learning statements, for each assignment, and the percentage of LS’s embodying each Principle of Design (hereafter abbreviated as POD) are plotted for each assignment. From this we provide insight into which POD’s were more thoroughly explored by the students, which will allow for future development in areas which are lacking. In addition, because students are not required to submit a particular number of statements per assignment, each team’s total number of provided LS’s in a given assignment are plotted against the grade received for that assignment, in order to identify whether there exists a relationship between the number of LS’s produced by the students and their performance from a grade standpoint. Finally, we produce a total POD breakdown of all LS’s provided by the teams in Assignments 1 through 5 in order to determine the overall focus in learning experienced by the students.

In addition to an analysis of the LS’s provided in Assignments 1 through 5 (which are team assignments consisting of graded components other than the LS’s), the student Semester Learning Essays (hereafter abbreviated as SLE) are analyzed against the final semester grade given to each student. Because the grade of the SLE for an individual is tied to the number of statements provided in the essay as well as the score of each statement (zero to four), comparing the relationship between the SLE and the final grade for the students serves as a more direct answer to the question of whether or not LS’s are an effective tool for measuring student learning. In Section 5 we provide the results obtained by following the method outlined above for students who took AME4163 in Fall 2015.

5. Data and Analysis

As explained in Section 4, in the first stage of the analysis we tabulate the proportions of team and individual LS’s pertaining to particular POD’s. As an example, if, on Assignment 1, a team provides twenty statements, five for the team as a whole and fifteen from the individual team members, and of the individual LS’s five fall into the domain of the first POD (labelled POD 1 on the following charts), then 25% (5/20) of the total team statements on Assignment 1 are individual learning statements falling into the domain of POD 1. We perform the same analysis using the complete pool of all team LS’s provided on Assignments 1 through 5. Our plot of the results of the individual and team LS percentages are shown below in Figures 4 and 5.

As a reminder, the five POD’s correspond to the five principles of design as follows:

1. POD 1: Planning
2. POD 2: Preliminary design
3. POD 3: Embodiment design
4. POD 4: Prototyping, testing, and post-mortem analysis
5. POD 5: Learning through doing, reflecting, and articulating
Figure 4: Domain of learning breakdown for individual learning statements provided by teams in Assignments 1 through 5.

Figure 5: Domain of learning breakdown for team learning statements provided by teams in Assignments 1 through 5.

One important aspect to consider in interpreting the analysis is that, though LS’s are required for Assignments 1 through 5, we do not require explicitly that the statements provided pertain directly to the assignment in which they are submitted. Students are free to explore learning regarding class lectures as well as design-related activities not expressly related to a particular assignment. However, for early assignments, we find that student LS’s largely track with the assignment subject matter.

As expected, for both team and individual learning statements in Assignment 1, POD 1 is the exclusive focus of learning on both the team and individual level. In Assignment 1, teams are tasked with organizing their team and planning their design approach as well as developing an understanding of the design problem and formulating a requirements list. Similarly, in Assignment 2, in which the teams’ focus is on developing early concepts and exploring ideas for
potential solutions to the problem, we see POD 2 as the major focus of the learning on both the team and individual level, accounting for 12 and 59 percent of total statements, respectively. In addition, POD 1 is still well represented in Assignment 2. This makes sense as Assignment 2 is early enough in both the semester and the design process that teams are still working through issues related to planning, team communication, and refining their requirements.

In Assignment 3, in which students focus on critically evaluating the concepts generated in Assignment 2 and narrowing the design to a primary and secondary concept, we note that the focus of LS’s turn towards POD 3, which involves refining and modifying through analysis concepts which are “the most likely to succeed.” However, unlike in Assignments 1 and 2, it is in Assignment 3 that we find that the LS breakdown begins to broaden out and form a distribution between the five POD’s. Additionally, it is here that the trend of spikes in successive POD’s on each assignment ends.

Between Assignments 3, 4 and 5, POD 3 remains the most common area in which both individuals and teams express learning. This is surprising and we offer a possible explanation. In completing Assignments 4 and 5, the students further refine their concept first through developing a rigorous CAD model (Assignment 4) and then by performing finite element analysis on critical design components (Assignment 5). We structure both Assignments 4 and 5 to pertain to refinement of the primary team concept and thus we expect learning to stay primarily within the domain of POD 3. However, what makes the breakdown interesting is that many (if not most) teams have begun the prototyping phase by Assignment 4. Even as they refine the detailed CAD models and perform analyses of their critical components the teams have begun testing physical models and experimenting with prototyping. Though we see the relative proportions of LS’s pertaining to POD 4 (which deals with prototype testing) rise around Assignments 4 and 5, one might expect that process to have been more impactful on the students as they prepared their Assignment 4 and 5 reports and thus should have represented a greater proportion of student learning during that time period.

One possible explanation is that fewer teams than we expected have actually started constructing and testing the device in a meaningful way by this point in the project. This explains why fewer individuals and teams would report learning statements categorized in the domain of POD 4, which deals with prototyping and testing of the device, in Assignments 4 and 5. From an instructor standpoint, this is worrisome. The device demonstration date is only one week after the Assignment 5 due date. If the teams are not reporting learning in POD 4 in Assignment 5, we infer that they have not begun serious prototyping and testing the device as recently as one week before the device must be completed. If the above explanation is correct, then teams were waiting until the final week to begin constructing and testing their prototypes, putting them in a difficult position with regards to the device demonstration.

An alternate explanation is anchored in the particular focus of the teams while formulating their assignment reports. Specifically, though they are free to explore individual and team learning as it pertains to the course and design process in general, we see in the results that students tend to submit learning statements which are more directly related to the immediate assignment being worked on, rather than what they might be working on in general. For example, though a team may be constructing and testing a prototype as early as Assignment 4, in their LS’s they provide on Assignments 4 and 5 they might tend to focus on the work required by
those assignments, which to us suggests that the students at times compartmentalize aspects of the project (such as assignments and device construction) separately.

Figures 6-10: (From left to right, top to bottom) Regression model between number of learning statements submitted by each team and the grade received for that assignment for Assignments 1 through 5

In the next stage of the analysis, we explore the relationship (if any) between the number of learning statements provided by a team (individual and team LS’s) and the grade received. One might think that a team providing a greater number of learning statements on a given assignment might tend to have performed better on that assignment, indicating that learning objectives are being achieved. However, as we see in Figures 6 through 10, there is no statistically significant correlation between the number of LS’s provided by a team on a
particular assignment and their grade on the assignment. Using simple linear regression, a line of best fit for each assignment is generated and we see that none possess a linear model with a multiple $R^2$ value greater than 20%, which we interpret as a low probability of a correlation between the number of statements provided and the assignment grade received by each team.

From the results of the linear regression we surmise that, in general, the number of LS’s provided by a team does not correlate statistically with the assignment grades received. However, despite an absence of a relationship between the LS’s and the student grades, we find evidence that a significant amount of learning is reported by the students. In fact, we find this to be strong evidence of our assertion that current grading techniques in project-based design courses is insufficient to assess student learning. What we see in Figures 4 and 5 is evidence of student learning in specific areas and what we see in Figures 6 through 10 is that that same learning is not appearing in the course grading. We therefore see that learning is taking place independent of the grade received. Students are thereby learning through doing, precisely as outlined by Kolb in his model for experiential learning. We therefore categorize that learning further in Figures 11 and 12.

In addition to Figure 4 and Figure 5, we highlight in Figures 11 and 12 trends between the first assignment and the last assignment before the device demonstration. On an individual level, we see that learning within the domain of POD 3 is best represented among the tabulated assignments, with learning in the domains of POD 1 and POD 2 coming in virtually identically (though quite far from POD 3). We suggest that when focusing on individual learning, the students are most influenced by assignments which require them to critically evaluate their concepts and bridge the gap between concept generation and prototyping. This is an important point: we suggest that learning within POD 3 implies improvement in the ability to take the steps necessary to actualize more abstract, hypothetical concepts. Similarly, at the group level, we see that the students improve their knowledge most significantly in the embodiment design phase. Whether the group focus on this domain is simply the aggregate result of virtually all students experiencing this learning on an individual level or whether thinking about POD 3 domain
learning in a group context forces them to reflect on the group nature of concept refinement may be the subject of future investigation.

Proportions of total learning for POD 2, POD 4, and POD 5 are comparable between both individuals and groups. For POD 4 and POD 5, we recall issues detailed earlier regarding an overall lack of emphasis on learning in domains POD 4 and POD 5 by both groups and individuals. However, the proportion of total LS’s in the POD 2 domain is 19.5 percent for individual and 12.1 percent for group LS’s, which is a much larger disparity, relatively. We infer that the design aspects of the domain POD 2 largely resonate with individuals, despite the team-orientation of the assignment itself. We reach one possible explanation by consulting Figure 4 and Figure 5. During Assignment 2, we note that individuals largely write about learning in the POD 2 domain, whereas groups are split close to evenly between both POD 1 and POD 2. As an early assignment, teams are still working on building up their team dynamic and developing detailed future plans. This group emphasis on learning in POD 1 may draw attention away from group focus on learning in the POD 2 domain.

Moving into the final stage of the analysis, we seek to identify whether a link exists between performance on the SLE and overall course performance. As mentioned earlier, the grading for the SLE involves counting the number of statements provided and adding the point values of the individual learning statements (based on the rating criteria we specified). However, since we request 30 statements in at least 10 domains without specifying the penalty for too few or the possible benefit of additional statements, there is little variation in the number of statements submitted. Consequently, the primary factor in the grading is the insight rating of the individual learning statements. Further, this means that the relative proportion of highly rated statements (ratings of three) correspond directly to the SLE grade. Therefore, by comparing the grades on the SLE with the final course grades of the individuals who submit them, a positive correlation between the two implies that the average rating of statements provided by individuals correlates with student performance (as measured through grading). However, when plotting the two series, as is done in Figure 13, and fitting a linear regression to the data we see that once again there is something else significant at play. Though from the data and trend line we do observe a slight positive correlation between learning statement ratings and overall course performance, the trend is not rigorous enough to account for all the variation in the course grading. From the multiple R² value of .0531, we conclude that only 5.3% of the variability in overall course performance is explained by the ratings of the student LS’s. This is likely due to the fact that the majority of the grading that goes into the calculation of a student’s overall course grade is based on evaluations of that student’s teams as a whole, thus somewhat reducing an individual’s ability to independently impact his or her grade. However, to us this further demonstrates that though many students are demonstrating both learning and a substantial degree of insight with that learning, that learning is not substantially impacting the way the students are assessed in the course.
In addition to the above analysis, we break down the domains of learning explored by students in the SLE, in a fashion similar to the analysis done for Assignments 1 through 5 (Figures 11 and 12). By comparing the results of the assignment learning statements to those of the SLE, we hoped to gain a better picture of the overall learning that took place. During Assignments 1 through 5, student LS’s are developing as they move through the design process. In the SLE however, students write LS’s after the entire experience takes place. By comparing the final LS’s of the SLE to those of the assignment LS’s, what we see emerge is a complete picture of the learning process, allowing us to identify gaps in the learning. In Figure 14 we present the proportionate breakdown of the roughly 2700 SLE LS’s into their respective domains.

![Figure 13: Regression analysis for the plot of the students' individual SLE grades versus their overall course grades.](image)

![Figure 14: Learning statement domain breakdown for the Semester Learning Essay, expressed as a proportion of the total number of statements.](image)
As we see in Figure 14, some of the gaps seen in the LS’s of Assignments 4 and 5 are covered by the end of the semester in the SLE. From the data gathered, we note that students primarily focus on the lessons learned from working with teams and, more specifically, how important an effective team dynamic is in design success. This result corroborates existing literature regarding the role that teams play for students in the design process and in engineering design education [22-24]. What we infer is that students in project-based design courses begin to see engineering as a collaborative enterprise more so than a solo endeavor, requiring adequate planning, established communication protocols, and robust methods for working through group conflict. Furthermore, we observe in the SLE domain breakdown that students view the critiquing and refining of design concepts (POD 3) as more impactful to their learning than prototyping, testing, and post-mortem analysis (POD 4), despite the fact that, by the end of the experience, students retain substantially more lessons from POD 4 than they do during the experience itself.

In addition, we note several gaps in the student learning that took place. Though we see in Figure 14 that, by the end of the semester, all domains of learning are represented, some gaps still exist when compared to key domains highlighted in Figures 11 and 12. For example, while planning, group formation, and developing the requirements list (POD 1) are well represented in the SLE, we see that POD 5 is still the least represented domain. Given that the SLE is intended to give the students the opportunity to express their overall learning in the course, it would be logical to infer that analyzing the design process as a whole and reflecting on the degree of internalization of the POD’s (POD 5) should be better represented at this stage. In addition, we note while the lack of learning expressed regarding POD 4 in Assignments 1 through 5 is corrected in the SLE, learning in POD 2 is still only weakly represented in both the assignments and the SLE. From this, we conclude that overall, students do not feel that they learned much about concept generation and ideation.

6. Closure

LS’s and the SLE are tied to “Abstract Conceptualization” and “Reflective Observation” from Kolb’s Experiential Learning Construct [1]. From our analysis of the LS’s submitted by the students over the course of the Fall 2015 AME4163 we observe several facets about the learning of the students in the class. First, in our attempts to compare the learning statements of both individuals and teams to the assignment grades we find no significant correlation (a conclusion that maps well with recognized inconsistencies in the literature [15] between other forms of student self-assessment and instructor evaluation), implying that our hypothesis (Section 1) is true. Second, our categorization of the learning statements into groups based on the domain of learning which encompassed each statement that we see in Figure 4 and Figure 5 tracks nicely with the intended domains designed into the assignments in which the statements were submitted. Specifically, Assignment 1, in which we scaffold the assignment to focus on team organization, planning the design, and understanding the design problem, is the assignment in which we see both group and individual learning statements pertaining exclusively to the first Principle of Design, which addresses those same principles. Similarly, in Assignment 3, in which we emphasize ideation and concept generation, we note that the vast majority of both individual and group learning statements fall into the “Preliminary Design” domain of POD 2. Third, we note that learning statements in the “Embodiment Design” domain (POD 3) constitute the majority of submitted LS’s for Assignments 3 through 5.

Over the course of the five team assignments, students largely focus their LS’s in the area of POD 3 (“embodiment design”). From this we gather that students, during the course of the
project itself, are most challenged by the portions of the project which deal with translating general ideas into feasible concepts. This is an understandable difficulty they face; at this stage, we are essentially asking the students to abstract from the hypothetical to the concrete and then refine that effort into something practical. We feel that this reflects an important moment of growth for the students into junior engineers.

Furthermore, from what we see in Figure 4 and Figure 5, we conclude that student and team learning in the “Prototyping, testing and post-mortem analysis” domain of POD 4 is weaker during what should be a period where that domain is explored thoroughly (the weeks leading up to the device demonstration). Despite the fact that in the SLE domain breakdown we see that, over the course of the entire semester, learning in POD 4 is being well represented, we assert that the learning should take place during Assignments 4 through 5 and to rectify this discrepancy we intend to explore at least one of the following avenues:

1. Alter the course structure to encourage the students to begin prototyping earlier in the semester, so that they have more time to fully explore that domain.
2. Alternatively (or conjointly), make clear earlier in the semester that learning statements submitted by both teams and individuals on a particular assignment can relate to any aspect of the process they have experienced to that point.

Both of these suggestions hinge on our assumption that more information for the students is better for their learning. As Kaslow et al. notes, for self-assessment to accurately reflect learning, students must be well aware of both the purpose and intention of the assessment as well as the competencies being looked for by instructors [21]. A lengthened prototyping phase may be especially necessary due to the fact that there is currently no assignment which specifically focuses on the prototyping and testing phase of the design process.

We find in our data no strong, positive correlation between the quality of learning statements and course performance (via grading), despite the fact that notable aspects of the learning which students achieved are clearly identified and understandable. From this we infer that the methods by which design students are currently evaluated (ability to follow design steps, device performance, and quality of written work) are not a complete picture of the learning actually taking place, a position consistent with other investigations [15]. From this, we posit the following: either design students are not learning what the instructors seek to teach and thus the way the material is taught must change, or, students are not being assessed on criteria relevant to what they need to learn in a design experience and thus the way students are assessed must be revisited. We find some additional evidence for the latter conclusion over the former. In an editorial submitted to the Journal of Mechanical Design [25], Mistree suggests that as the global engineering landscape changes and people begin to focus on more collaborative, interdisciplinary projects attempting to solve complex problems with unclear customer needs and wants, the competency most needed by students deals with an ability to adapt and learn rather than any particular technical skill or analytical technique. With that in mind, we suggest that what we should be looking for in engineering design students is evidence that they are learning from mistakes and progressing in a relative sense, rather than simply meeting some fixed technical standard.

Further, we note several things about the development of the targeted competencies in the students from these results. First, we see in Figure 14, students overwhelmingly demonstrate learning in the POD 1 domain, which concerns team formation and planning. We note several statements provided by the students which are representative of this phenomenon:
“Through implementing a system in which each person is in charge of a particular project task and also assists as a secondary supporter of at least one other task, I learned that a two-person system ensures that each task is completed and checked with efficiency and equality in the team workload, and quality of design deliverables.” – AME4163 student, SLE, Fall 2015

“Through the formulation of a team contract in Assignment 1, I discovered that development and growth is maximized when roles are assigned based on competencies that are desired to be developed. Challenging an individual to learn makes them a better individual contributor which improves the overall team.” – AME4163 student, SLE, Fall 2015

We interpret this to mean that students who took AME4163 in Fall 2015 significantly improve in their ability to manage collaboration and information, two of the target course competencies. Further, from the strong showing we observe of student statements in the POD 3 domain, which involves refining concepts and ensuring functional feasibility, we infer that the students developed an enhanced ability to manage thinking, another of the target competencies. Still, where we see relative lapses in student learning is in the domain of POD 5, which involves critically evaluating their own work and focusing on the learning that they experience. To that result we posit that, relative to other competencies, students did not develop in their ability to manage learning as much as might be expected.

Given these conclusions, we raise additional issues as topics of further inquiry. Assuming that student learning is not being used to adequately evaluate students, how can our understanding of the areas in which learning is taking place be leveraged to correct this error? We have suggested that relative student progress in project-based design courses is a more relevant criteria for assessment than technical proficiency but how this may be implemented in a practical sense is a matter for additional investigation. Further, we must develop metrics to gauge this progression for both teams and individuals, a matter complicated by the complex nature of team formation and organization, which we do not control for in this work. This necessity is underscored by our finding that students devoted a substantial portion of their LS’s to learning in the POD 1 domain. In addition to these new metrics, we must continue to refine the LS evaluation methods outlined in Section 3 to provide a more rigorous, objective picture of student learning. From our survey of the literature, we know that some forms of student self-assessment such as surveys have issues with subjectivity [21]. Consequently, in the future we plan to investigate any correlative link between the students’ learning embodied by the learning statements with the self-reported progress of the students in the course surveys mentioned in Section 3. However, to ensure that such a comparison is robust, a greater emphasis in lectures on the desired course competencies and the relevance of the LS’s and surveys to their own learning processes is required.

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8. References