An Experiential Learning Framework for Improving Engineering Design, Build, and Test Courses

Mr. Jackson Lyall Autrey, University of Oklahoma

Jackson Autrey is a Master of Science student in Mechanical Engineering at the University of Oklahoma from Tulsa, Oklahoma. He holds a Bachelor of Science in Mechanical Engineering from the University of Oklahoma and is currently involved with research into assessment methods and pedagogy in engineering design education. Following completion of his Master’s degree, Jackson plans to pursue a PhD. in Engineering with a focus on engineering education.

Ms. Shalaka Subhash Ghaisas, University of Oklahoma

Shalaka has pursued a B.A. in Economics and M.A. in English from Fergusson College. She has completed her MS in Teaching and Curriculum from Syracuse University.

Dr. Xun Ge, University of Oklahoma

Dr. Xun Ge (University of Oklahoma, xge@ou.edu) is Professor of Instructional Psychology and Technology in the Department of Educational Psychology, Jeannine Rainbolt College of Education, the University of Oklahoma. Her research expertise involves the design of question prompts in scaffolding students’ complex and ill-structured problem solving and self-regulated learning. Dr. Ge (2004) developed a conceptual framework using question prompts and peer interactions to facilitate discussion and problem-based learning in online learning communities, which was published in Educational Technology Research and Development, a leading journal in the field of instructional design and technology. In addition, Dr. Ge has also investigated the design of various cognitive tools and learning technologies in the context of problem-based learning. Dr. Ge’s scholarly inquiry is also an attempt to bridge cognition and metacognition with motivation. She has conducted extensive research in STEAM education in various educational settings, and she has collaborated with researchers and scholars from diverse disciplines around the world. Dr. Ge has published numerous refereed journal articles, book chapters, and two edited books published by Springer. She has been recognized for a number of academic awards by Association for Educational Communications and Technology (AECT), including 2012 Outstanding Journal Article, 2004 Outstanding Journal Article, and 2003 Young Scholar Award. Dr. Ge has been serving on the editorial board of several major refereed journals, including Educational Technology Research & Development, Interdisciplinary Journal of Problem-based Learning, and Technology, and Knowledge and Learning.

In addition, Dr. Ge serves as the Chair for the Problem-based Education Special Interest Group for the American Educational Research Association. She also serves on several editorial boards on some leading journals in the field of educational psychology and technology, including Contemporary Educational Psychology (2017 – ), Educational Technology Research and Development (2011-2013; 2016-2018), Technology, Knowledge, and Learning (2013 – present), Interdisciplinary Journal of Problem-based Learning (2010 – 2015).

Prof. Zahed Siddique, University of Oklahoma

Zahed Siddique is a Professor of Mechanical Engineering at the School of Aerospace and Mechanical Engineering of University of Oklahoma. His research interest include product family design, advanced material and engineering education. He is interested in motivation of engineering students, peer-to-peer learning, flat learning environments, technology assisted engineering education and experiential learning. He is the coordinator of the industry sponsored capstone from at his school and is the advisor of OU’s FSAE team.

Prof. Farrokh Mistree, University of Oklahoma

Farrokh’s passion is to have fun in providing an opportunity for highly motivated and talented people to learn how to define and achieve their dreams.

©American Society for Engineering Education, 2018
Farrokh Mistree holds the L. A. Comp Chair in the School of Aerospace and Mechanical Engineering at the University of Oklahoma in Norman, Oklahoma. Prior to this position, he was the Associate Chair of the Woodruff School of Mechanical Engineering at Georgia Tech – Savannah. He was also the Founding Director of the Systems Realization Laboratory at Georgia Tech.

Farrokh’s current research focus is the model-based realization of complex systems by managing uncertainty and complexity. The key question he is investigating is what are the principles underlying rapid and robust concept exploration when the analysis models are incomplete and possibly inaccurate? His quest for answers to the key question is anchored in three projects, namely,

Integrated Realization of Robust, Resilient and Flexible Networks
Integrated Realization of Engineered Materials and Products
Managing Organized and Disorganized Complexity: Exploration of the Solution Space

His current education focus is on creating and implementing, in partnership with industry, a curriculum for educating strategic engineers—those who have developed the competencies to create value through the realization of complex engineered systems.

Email <farrokh.mistree@ou.edu> URL http://www.ou.edu/content/coe/ame/people/amefaculty/mistree.html
LinkedIn http://www.linkedin.com/pub/farrokh-mistree/9/838/8ba
An Experiential Learning Framework for Improving Engineering Design, Build, and Test Courses

Abstract

We assert a need for the incorporation of educational theory into engineering design, build, and test (DBT) courses, particularly in terms of how that theory can be used to improve such courses incrementally. In our course AME4163 – *Principles of Engineering Design*, a senior-level engineering DBT course, we have incorporated David Kolb’s experiential learning construct into the fabric of course activities, assignments, and structured exercises. We now seek to additionally leverage Piaget’s cognitive constructivism and Vygotsky’s sociocultural theory into structured learning exercises. One such exercise is the ‘Learning Statement,’ (LS) a reflective exercise in which students directly translate experience into learning and articulate expected future value from that learning. In employing the LS as an instrument for a formative assessment, we attempt to identify the students’ Zones of Proximal Development (ZPD). Further, as we continually share LS ‘best practices’ in AME4163 we create opportunities for social knowledge construction through interactions to come into play. We posit that engineering design education stands to benefit from the incorporation of robust learning theories pioneered in other disciplines.

In this paper, we leverage a text-mining approach to demonstrate a framework for interpreting LS data collected from students in the course, AME4183, through the lens of educational theories. Specifically, we identify each student’s ZPD by text-mining students’ LSs over the course of a DBT project and examine the differences between the LSs students prepare. We find that, for many students, reflecting on authentic immersive activities in a DBT course and writing LSs facilitates their acquisition of new knowledge and enhances their ability to apply it unaided (per the ZPD) areas important to forming and planning with a team, developing concepts, and critically analyzing the design process, though for most, this transition occurs late in the DBT course.
1. Frame of Reference

Our goal is to ‘operationalize’ educational theory in an engineering DBT course to improve assessment of students by instructors and to enable students to engage in more critical thinking of their work; for details see [1]. In this section, we share our motivation, the genesis of the work and present our rationale for anchoring our work in Kolb’s experiential learning framework.

In Reference 2 we stated “Learning engineering design requires more than simply having design experiences. Design experiences provide a context for students to practice design skills and an opportunity for students to learn deep lessons about the nature of engineering design. Reflection on the experiences is necessary to recognize and realize these lessons.” We explored and created several mechanisms and instruments aimed at helping students to acquire concrete experiences of engineering design, observe those experiences and reflect on them through articulating their takeaways. Our explorations towards this aim led us to use Kolb’ [3,4] experiential learning as a suitable anchor for such metacognition activities.

Following Kolb’s experiential learning framework, we created and made it available to students as an electronic scaffold in a design, build and test course at Georgia Tech called the Reflective Learner [2]. The scaffold for students to write their Learning Essays included prompts to get students think about issues such as limitations of a given design approach and applications of design principles to situations beyond classrooms. As students acknowledged the value of such scaffolds, we were encouraged to investigate this line of research further. Retrospectively, we note that this was the beginning of our journey towards creating increasingly immersive learning environments for students and complementing those with instruments for reflection on learning.

Through the millennial decade, as we witnessed the world and the engineering communities across the world become wired and interconnected, we recognized a need to extend the concept of experiential learning to a wider set of stakeholders, the most obvious and natural to us being the engineering faculty. We conducted workshops in two locations- Ahmedabad, India and Montreal, Canada to introduce the concept of experiential learning, facilitate knowledge sharing (to gain) and form a learning community, and to deliberate on strategies to promote mindful, metacognitive learning that would lead to enhancing student learning via reflecting on doing. In this context, we included Bloom’s taxonomy as reflected in the Intentionally Reflective Kolb +Bloom (IRK+B) model developed by one of the workshop coordinators, Amy Bradshaw [5]. A concrete takeaway from these efforts were two clearly differentiated set of competencies, namely, task specific competencies that make a learner competitive today and meta-competencies that enables a learner to adapt to future needs. IRK+B provides an instructor with a conceptual framework to understand and evaluate (using Bloom’s taxonomy) where a learner is today and where he/she needs to be in future and thereby determine the scaffolds (using Kolb’s experiential learning) a learner would need in attaining the goal.

These experiences were foundational to the design a curriculum that embodies the need for a systemic development of career-sustaining competencies at higher-order cognition, and most importantly, meta-competencies that will help students prepare to lead innovation by developing essential self-directed learning, career development, and lifelong learning competencies [6] that include various aspects of learning management skills, e.g., information, learning, attitude, thinking, and collaboration.
The curriculum aiming at career sustaining competencies called for enhancing the experiential learning by bringing in requirements from the world of engineering practice, namely, team organization, concept generation, and critical analysis of the design process. As we enriched our courses with more and more authentic experiences around these requirements, we also felt the need (1) to equip the students with instruments for articulating their reflections on the courses more deeply and comprehensively and (2) equip the instructors with means to capture students’ learning experiences and use them for formative assessment of the course itself, as much as of the learning outcomes for individual students. It is this endeavor that led us to the construct of Learning Statement (LS) – a triplet, consisting of Experience x, Learning y and Value.Utility z) [1], which helps students express succinctly where they were at the time of starting their learning at multiple granularities (e.g., an assignment, a learning essay, or a course on the whole), how they engaged with the immersive learning experience and what the takeaway (or lack thereof) was for them as they moved towards conclusion of the experience (such as completion of a given lecture, assignment, or the course itself). Consistent with the IRK+B model, the LS construct efficiently helps students articulate their experiences in a series of triplets. This inherent triple structure of the LS and its adherence to the Bloom’s taxonomy makes it easier for both students and instructor to establish a shared understanding of the “learning zone” that they are residing in for a given experience. Additionally, it also makes the experiences amenable for processing automatically using Natural Language Processing (NLP) techniques followed by text mining to discover to what extent students have learned by reflecting on doing.

In this paper, we explore and deconstruct this learning zone using two additional constructs for a deeper understanding of the experiential learning. We now complement our curriculum design and evaluation by viewing the Design Build and Test (DBT) courses through the lens of Vygotsky’s Social Constructivism [7] and Piaget’s Cognitive constructivism [8].

1.1 AME4163 and Course Pedagogy

In this section, we outline the course structure and establish links between the course goals and the educational theory underpinning the course. While education is a term broadly used to describe all experiences that lead to learning, engineering education because of its applied nature has an inherent and specific focus on problem solving. Engineers need to be/are educated to transfer learned principles into practice by way of designing solutions for various practical problems. It is the centrality of problem-solving that inspired us to design our DBT course AME4163 – Principles of Engineering Design with an explicit anchoring in multiple theoretical constructs that provide an immersive and authentic learning experience to our students while enriching their learned outcomes. Accordingly, the course is designed to embody the following essential components:

1. Internalizing the principles of engineering design and learning how to identify and develop career sustaining competencies.
2. Learning through doing (reading, designing, building, testing, and post-project analysis), reflecting and internalizing the principles of engineering design.
3. Learning to frame, postulate a plan of action, and then implement that plan of action for the capstone project in the following semester.
4. Transitioning from being a student in the School of Aerospace and Mechanical Engineering at the University of Oklahoma, Norman to a junior engineer in a company.
The Principles of Engineering Design (POEDs) woven into our assignments and based on the ‘Learning by Reflecting on Doing’ theme reported in earlier work [1] map to relevant theoretical constructs and Bloom’s taxonomy as shown in Table 1. Our work is anchored in Bloom’s taxonomy, although we do not report on it in this paper, so that the course design offers the intended experiential learning by covering learning domains adequately.

**Table 1: Knowledge Construction Processes in Assignments**

<table>
<thead>
<tr>
<th>Theoretical Constructs in Assignments</th>
<th>Cognitive Constructivism</th>
<th>Social Constructivism</th>
<th>Bloom’s taxonomy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a. Forming a team</td>
<td>Accommodation in Piaget’s Constructivism</td>
<td>Exchange of ideas to establish terms of contract acceptable to all team members</td>
<td>Knowledge domain (recognize, list), Application (execute)</td>
</tr>
<tr>
<td>1b. Accepting and executing a team contract</td>
<td>Foundation/Environment for social-constructivism.</td>
<td>Learning by Reflecting on Doing</td>
<td></td>
</tr>
<tr>
<td>1c. Understanding the problem</td>
<td>Same as 1b</td>
<td>Comprehension (internalize, explain, infer)</td>
<td></td>
</tr>
<tr>
<td>1d. Proposing a plan of action</td>
<td>Team contract is formed by making proposals within the team, challenging each other’s suggestions, and defending the suggestions or accepting changes.</td>
<td>Analysis (of problem), Synthesis (of solution)</td>
<td></td>
</tr>
<tr>
<td>2a. Ideation: generating concepts</td>
<td>Piaget’s assimilation and accommodation at play as ideas modify existing schema and promote new schema</td>
<td>Vygotsky’s social constructivism as ideas are exchanged and new knowledge is constructed</td>
<td>Evaluation and application</td>
</tr>
<tr>
<td>2b. Developing concepts (ensure feasibility and realizability)</td>
<td>Developing concepts involves assimilation using the ‘now existing’ schema. Feasibility, Realizability involves reflective observation in Kolb’s Learning Cycle</td>
<td></td>
<td>Application, Synthesis</td>
</tr>
<tr>
<td>2c. Evaluating concepts; identifying most likely to succeed</td>
<td>Social Constructivism as concepts are challenged, critiqued, and finalized also reflective observation in Kolb’s Learning Cycle.</td>
<td>Evaluation, Analysis</td>
<td></td>
</tr>
<tr>
<td>3a. Refining/modifying most likely to succeed concept</td>
<td>Piaget’s Accommodation as we modify concepts.</td>
<td>Analysis, Application</td>
<td></td>
</tr>
<tr>
<td>3b. Stipulating a Bill of Materials</td>
<td>Piaget’s accommodation as we extend the concepts to plan to make concrete devices</td>
<td>Implicitly – a result of discussions and concurrence in a team</td>
<td>Synthesis (generating BoM), Knowledge (recognizing what is needed to create the device)</td>
</tr>
<tr>
<td><strong>Theoretical Constructs</strong>&lt;br&gt;<strong>POEDs in Assignments</strong></td>
<td><strong>Cognitive Constructivism</strong></td>
<td><strong>Social Constructivism</strong></td>
<td><strong>Bloom’s taxonomy</strong></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>3c. Ensuring functional and technical feasibility, safety, etc.</td>
<td>Accommodation and Assimilation as these properties are ensured by extending schema and creating new schema for their evaluation</td>
<td>Team activity involving verification of these properties and exchange of ideas thereby. Also challenging and defense of ideas would be implicit.</td>
<td>Application (Applying knowledge to realize the concepts)</td>
</tr>
<tr>
<td>4a. Bill of Materials as built; understand all components</td>
<td>Assimilation as the BoM for conceptualized device is extended to the built concrete one</td>
<td>Synthesis, Evaluation, Comprehension</td>
<td></td>
</tr>
<tr>
<td>4b. Ensuring built device meets performance requirements</td>
<td>Disequilibration from device not meeting one’s expectations</td>
<td>Team activity involving verification of performance which would involve knowledge construction because of exchange of ideas</td>
<td>Application, Analysis, Synthesis (as materials and knowledge are employed to create a device performing to expectations)</td>
</tr>
<tr>
<td>4c. Critical analysis of device; causes of success and failure</td>
<td>Disequilibration from device not meeting one’s expectations. Assimilation of new knowledge in schema Accommodation- schema would be modified based on success or failure</td>
<td>Implicitly- ownership of success and failure would be assigned and thereby ideas that succeeded would be affirmed. Ideas that failed would be discarded.</td>
<td>Analysis, Evaluation, Comprehension and Knowledge (of refined concepts)</td>
</tr>
<tr>
<td>5a. Critically evaluating the design, build, and test process</td>
<td>ZS: Disequilibration from device not meeting one’s expectations. Assimilation of new knowledge in schema SG: Accommodation- schema would be modified based on success or failure of steps in a process</td>
<td>Implicitly- ownership of success and failure would be assigned and thereby process steps that succeeded would be affirmed. Ideas that failed would be discarded.</td>
<td>Analysis, Evaluation, Comprehension and Knowledge (of refined process steps)</td>
</tr>
<tr>
<td>5b. Articulating internalized POED via learning statements</td>
<td>POEDs internalized = new schema formation for engineering design process</td>
<td>Comprehension, Knowledge, Synthesis (of concepts and process elements)</td>
<td></td>
</tr>
<tr>
<td>5c. Carrying lessons to future: capstone and other ventures</td>
<td>Schema for at least a set of new stimuli exist. (POEDs applicable to capstone and other ventures). The process of new schema formation may be now efficient because the junior engineer is already</td>
<td>Sharing of knowledge in new situations wherein the knowledge may again be challenged and modified suitably base on new experiences</td>
<td>Knowledge, Application, Evaluation</td>
</tr>
</tbody>
</table>
We show in Table 1 that the knowledge construction processes invoked while learning the POEDs are in accordance with Piaget’s Cognitive Constructivism [8] and Vygotsky’s Social Constructivism [7]. Piaget proposes that the mind creates and maintains structures called ‘schema.’ As stimuli are taken in, they are classified into schema that already contain similar information, content, or characteristics. This is called ‘assimilation.’ At times, however, existing schema do not allow incoming information to be processed. The new stimuli do not fit any existing schema. Consequently, accommodation occurs, allowing for a modification of existing schema to better fit incoming stimuli. The accommodation process represents a change in a person’s thinking. S/he adjusts to new experiences or objects by revising an earlier method of information processing. In other words, when there is a discrepancy between what a person expects and what happens (a discrepancy between expectations and experiences), there is a temporary disequilibration, followed by the process of accommodation. Engineers as problem solvers must expect to be disrupted or disequilibrated on a regular basis. They must be able to continually absorb the new stimuli posed by the problems to be solved by recreating and adjusting their existing schema. We believe that engineering education therefore must include training that incorporates exposure to ill-structured, unusual situations that accustom engineers to get disequilibrated and work towards equilibration by creating and recreating schema for knowledge absorption and its application. Our assignments are designed keeping in mind this need.

Social constructivism [7] suggests that learners first construct knowledge in a social context. The process of discussing/ (arguing for) one’s understanding of an experience with peers and/or more knowledgeable others (teachers, parents) is in effect, the process of knowledge construction (“first between people”) which is followed by the individual process of internalizing the knowledge (“and then inside the child”). Social interaction may thus act as a trigger and/or a catalyst to the process. However, for a meaningful social construction of knowledge to happen, the participants must be adept at creation and recreation of knowledge. While it is true that engineers may almost always work in teams, knowledge useful for problem solving will get created only when each engineer can make sense of his/her experience by accommodating new stimuli by adjusting or even discarding old schema and creating new ones. A constant exposure to practical problems must therefore be interwoven into their education. The lab demonstration of prototypes and class discussions incorporated into the assignments are opportunities for social knowledge construction which is to be individually internalized later.

1.2 Vygotsky’s Zones of Proximal Development
In this section, we introduce the concept of Vygotsky’s Zone of Proximal Development (ZPD). Before embarking on this, we briefly discuss how cognitive constructivism and social constructivism in fact complement each other. Disequilibration happens when one’s expectations are not confirmed by environmental stimulus. Existing schema cannot be used to make sense of new experiences. Disequilibration thus motivates one to accommodate information and grow cognitively. Vygotsky proposes a concept called Zone of Proximal Development. In a ZPD, a learner must do tasks that s/he cannot do alone, but can, with help. When there is a mismatch
between skills and tasks, the learner is disequilibrated. The learner then constructs new schema with the help of a “knowledgeable other.” The new schema helps them to assimilate and accommodate information. The learner also goes through an Anxiety zone when disequilibrated. In the Learning zone, matching of skills and tasks happens, permitting the learner to reach equilibration and the Comfort zone. When confronted with a new task for which there is a skill mismatch, s/he may land in the Anxiety zone again.

1.3 Mapping of Assignments to the ZPD

As can be seen from Table 1, the POEDs incorporated in the assignments provide ample opportunities for disequilibrium-led accommodation (Piaget) as well as social construction of knowledge (Vygotsky).

In this section, we elaborate on the mapping of assignments to Vygotsky’s ZPD. In Figure 1, we illustrate this mapping and the mechanisms at play in the different sections of the ZPD as they relate to our specific course assignments, which are structured around a central engineering design challenge spanning most of the semester.

In Assignment 1 (POEDs 1a through 1d), we set up an environment for social construction of knowledge by forming teams. We require the teams to come up with a team contract that embodies code of conduct, leadership, and protocol for escalation if necessary. Further, the teams need to acquire an understanding of and come up with a plan of action to address the design problem central to the DBT course. The process of contract formulation and understanding the problem require an exchange of proposals, challenging suggestions and concurring on a commonly agreed upon terms for the contract. We believe that the internalization of this mode of working as professional (junior engineers) at an early stage of career creates schema conducive to meeting future expectations from these individuals who would work in teams to solve problems in industry. Here, the junior engineers, for perhaps the first time in their career are required to act as professionals by doing the activities that would be required of them in their future professional lives. As such, they are initiated into the Anxiety Zone, which is the initial stage of the ZPD. Here, we draw upon Clapper’s [9] method of employing ZPD in conjunction with cooperative-based learning to simulate a real-life challenge. Though discussed in the context of healthcare, it is extendible to our work because we too, are aiming to prepare future professionals to address real-
life (engineering) challenges. Clapper argues that when learning new information or solving problems, our natural tendencies of looking at what others are doing or listening to their interpretation of the problem, and our propensity as humans to assist others with solving problems is complemented by both co-operative based learning and ZPD. The requirement for entering into a formal contract rests on the premise that encouraging such co-operation would offer our students an opportunity to complement each other as they would indeed be required to, for any large-scale engineering project in future. We thus also consider a caution raised recently by Smagorinsky [10] about understanding the more accurate translation of the ZPD as the zone of next development for a mediated holistic human development and not just scaffolding to achieve task objectives. To mitigate the risk that students may not buy into the process and thus not really enter the Anxiety zone, we have introduced demonstrations of the prototype and assessments at multiple points during the course. The mandatory demonstrations of working (or not working!) devices and open reflections on reasons for success and/or failures ensure that our soon to be junior engineers enter the Anxiety zone.

In Assignment 2 (POEDs 2a through 2c) the junior engineers are tasked with ideation and concept development. Piaget’s assimilation and accommodation are at play because ideas create stimuli that modify existing schema and promote new schema for making sense of the new knowledge being generated. As students develop concepts from the angle of realizability and feasibility, they need to assimilate these criteria into the created schema for evaluating the ideas and finalizing them by reflective observation. When this is done in a team, concepts will be challenged and defended thereby promoting social construction of knowledge.

In Assignment 3 (POEDs 3a through 3c) the emphasis is on refining the “likely to succeed concepts” and producing a preliminary Bill of Materials (BoM). Functional and technical feasibility together with preliminary realizability are delved into deeper at this stage. This assignment takes the project a step from the conceptualization stage to concrete realization by requiring detailed construction plans via the BoM. During the deliberations for the BoM, teams would have to modify existing schema and create new schema for understanding the functional-techno-realizability aspects. Needless to add, challenging one another’s design proposals while ensuring functional-techno-realizability soundness allows for social construction of knowledge.

In Assignment 4 (POEDs 4a through 4c) the full BoM for the as-built device is produced along with detailed engineering drawings for construction of the device. The schema formed while conceptualizing the device are therefore modified through the process of assimilation since invariably, there would be modifications to the original BoM. The built device is verified for its expected performance. Critical analysis of the device is performed as causes for success and failure are analyzed. Success of a design would affirm the formed schema. However, the important activity here is disequilibration when the device does not perform to expectations. Invariably, in this case, the process accommodation would come into play as new knowledge is generated when the junior engineers analyze failures. We suggest that, in addition to accommodation, a process of organization of schema, particularly, classification, may come into play based on the successful and unsuccessful strategies employed using the schema. The ones that were successfully employed are likely to be marked for future use and those that were not, are likely to be “parked” because of the lack of return on investment. This process is likely to introduce some bias while responding to new stimuli in the future because if a junior engineer encounters an apparently similar practical problem, s/he is likely to employ knowledge (as existing schema) that s/he has experienced to be successful.
Considering the novelty of the tasks, Assignments 1 through 4 are scaffolded to offer the help and provide “hand-holding” by the “knowledgeable other” as the junior engineers proceed through the Learning zone which is the intermediate stage of the ZPD. In Assignment 5 POED 5a, the process of DBT for creating the device is analyzed. We posit that the knowledge processes are likely to be like those described for Assignment 4 above since here too, success and failure of process steps would be viewed critically. In POED 5b, the junior engineers produce Learning Statements (LSs) to articulate the internalized POEDs so far. This construct, published in earlier work [1], is detailed in Section 2. It facilitates both reflection by the junior engineer and insight for the instructor into students’ learning outcomes. The POED 5c requires articulation of lessons to be carried forward for the Capstone project and more importantly, other real-world ventures. Given the self–reflective nature of tasks involved in this assignment, Assignment 5 is the least scaffolded. As the junior engineers proceed through the Learning Zone through previous assignments, we expect that they would now be in the Comfort Zone because they have by now, accommodated the new knowledge facilitated by the stimuli posed in the POEDs. In other words, they are in the Comfort Zone, which is the final stage of the ZPD.

2. The Learning Statement and Formative Assessment

Having established our theoretical framework for assessing the process of student learning in AME4163, we now explain the Learning Statement (LS) construct that is used to scaffold student thinking and in its written form serves as an instrument for gauging what the student has learned because of reflecting on doing; for details see [1]. The LS takes the form of a scaffolded statement in three distinct portions. In a single sentence, a student is required to identify an experience (e.g.: “By researching components for...”), articulate a lesson arising from that experience (e.g.: “I realized that I could...”), and then identify some future expected utility of that lesson (e.g.: “...which will allow me later, during my career, to do...”). LSs are submitted by students following each lecture and assignment. These LSs are then evaluated by instructors for the degree of critical thinking and/or insight achieved and returned to students as feedback to help them learn how to think deeper while reflecting on doing. This process also enables us to capture and evaluate the LSs for research purposes in addition to providing insights for formative assessment of students and our course design itself.

The LS serves multifold roles; for the students, it is a tool that enables self-reflection on the learning experience and provides an opportunity to formally articulate that reflection as a lesson learned. For the instructors, it serves as a means for formative assignments because its structure helps in highlighting what the student knew or did not know prior to the learning experience, what s/he learned, and, importantly, what value s/he perceives the learning to have created.

In the context of this paper, we treat LSs as vehicles for data collection to inform us of (1) the location of a student in the ZPD and (2) the movement of individual junior engineers through the ZPD. Consistent with our effort to provide an immersive and authentic experiential learning experience to all students, we believe this knowledge to be critical to further improve and enhance their learning experience as well as outcome. From this angle, it is important for us to know if our course design has imparted the opportunities for knowledge construction by providing the right stimuli.

2.1 Mapping the LSs to the ZPD
The LS construct incorporates linguistic patterns that could bring to the fore the location and movement through the ZPD and can point to knowledge construction processes occurring as students participate in class activities. The absence of knowledge with respect to a POED may be explicit or implicit. The process of learning and the presence of a scaffolding mechanism is indicated by a mention of class activities or reference to a specific artifact such as a research paper or a handbook. The movement of the student through the ZPD, that is, from the Anxiety zone to the Comfort Zone is indicated by a specific achieved target or perceived value for future use. In Figures 2 and 3, we show an illustration to map the linguistic patterns with the ZPD and knowledge processes.

In Figure 2, Junior Engineer 1 explicitly indicates a lack of knowledge of subtleties with respect to intercultural communication. The junior engineer further specifies what s/he learned about difference in social acceptability in different cultures and articulates what is achieved, thus demarcating the three different zones in ZPD. S/He does not however indicate the mechanism (e.g., scaffolds, discussions, class activities) involved in the knowledge creation.

In Figure 3, we see that Junior Engineer 2 does not explicitly state that s/he is not aware of the House of Quality procedure for generating technical data from non-technical data. However, it is apparent that s/he has learned this from “active participation in today’s lecture.” S/He also indicates that s/he would use this knowledge while meeting “future clients’ needs and wants,” which implicitly shows that a high value is created in the process of active participation (social construction of knowledge).

In Figures 2 and 3, we highlight examples in which students are transitioning between different ZPD, but we also identify LS which do not cut across all three zones. For example, in some LS, although the student states that learning has occurred, s/he does not adequately demonstrate having left the anxiety zone.
In the preceding statement, the student states that s/he has learned and that value has been created, but simply stating these things does not make it so. The learning and its associated value which are identified do not demonstrate reflection nor do they demonstrate the creation of knowledge; they are simply a paraphrase of the learning objectives mentioned by the instructor for the lecture. In assessing the LS for evidence of the ZPD of the student, we are therefore looking for evidence that the student has created knowledge not explicit to the specified experience. Meanwhile, we find other LS demonstrate transition to the learning zone exclusively.

“While putting together our team’s House of Quality, I realized that the needs of differing customers are often in conflict, and an engineer must be able to balance these needs appropriately for given scenarios.” – Fall 2017 Student

In the preceding LS, the student thoughtfully connects a specific realization to the prompting stimulus. This is indicative of how the scaffolded exercise has prompted a change in a student’s mental model of a design activity. However, the student does not identify how this model may apply in novel circumstances. From this, we gather that the student has not yet reached the comfort zone.

2.2 Mapping LS Data with the ZPD and Assignment POEDs

In Table 1, we mapped the principles of engineering design (POEDs) to the different possible knowledge construction processes they are likely to invoke. We need to examine if indeed these knowledge processes are seen to have been invoked. In Table 1 we present a map of intended knowledge construction whereas in Table 2 we aim to present evidence of knowledge construction. Specifically, we outline connections between some sample learning statements from Assignments
1-5, the associated POED for each LS, connections to the ZPD for the authoring junior engineer, and some comment on connections between the statement and our identified learning processes. We have selected fifteen LSs from students in our DBT course. These LSs provide insights into the movement of the students through the ZPD as they proceed from Assignment 1, in which students form teams and diagram plans to complete the design project, to Assignment 5 towards the end of the course, in which the students reflect on the performance of their device as built and attempt to identify how mistakes could have been avoided or corrected. In this table, we show that, over the course of the design project, students are beginning to classify successful and unsuccessful strategies for solving novel problems.

Table 2: Map of Assignment 1-5 LSs to Learning Theories

<table>
<thead>
<tr>
<th>Assignment</th>
<th>LS</th>
<th>Cognitive Constructivism</th>
<th>Social Constructivism</th>
<th>POED</th>
<th>ZPD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>After performing the House of Quality and Requirements portion of assignment A1, I realized how many different variables that need to be considered when tackling a complex and thorough project like project POP, this revelation ties directly into the engineering principle 1d. “Proposing a Plan of Action” because now I am better suited to create an effective action plan since I have learned to consider all of the requirements of a certain task, this will be useful during real-world projects assigned by my employers since many of them will involve numerous aspects to consider (1d).</td>
<td>✓ Internalization of new knowledge through disequilibration and accommodation</td>
<td>–</td>
<td>1d Anxiety Zone as indicated by absence of knowledge about variables. Learning Zone as indicated by consideration of requirements for the task. Comfort Zone as indicated by articulation of value</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>From the Assignment 2 exercise, I realized that a morphological chart can be very useful when determining possible design ideas as it allows an engineer to quickly identify possible solution steps however, I also became aware that it is a dangerous assumption to think that the only options available are listed within the chart because assuming the chart is complete allows the engineer to miss possible solution ideas.</td>
<td>✓ Internalization of a new tool</td>
<td>–</td>
<td>2b and 2c Learning zone as indicated through realization</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Through the construction of learning statements throughout Assignment 2, I have realized that our critiques of our own concepts as well as our team members via the PMI’s and Go/No-Go analyses will lead to an internalized ongoing investigation on functions, even if not identified for our concepts yet, so that in the future, we may locate what needs more attention and be led to what questions we must ask before deciding entirely on an action.</td>
<td>✓ Internalization through reflective observation</td>
<td>✓ Critiquing of each other’s concepts leading to knowledge construction</td>
<td>2a and 2c Learning Zone moving towards Comfort Zone as indicated by meta-cognitive analysis of LSs themselves</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Through completing assignment 2, I have learned the importance of being able to clearly articulate, whether through the drawings or verbal explanation, the components and functions of a design concept, this will add value to my professional career by helping me remain concise and direct with my designs and explanations.</td>
<td>✓ Internalization through reflective observation</td>
<td>–</td>
<td>2b and 2c Comfort zone with respect to articulation and communication</td>
<td></td>
</tr>
</tbody>
</table>
## Assignment 3

Completion of Assignment 3 further reinforced to me the importance of a good team that is capable of operating and adapting to a morphing team-dynamic, enabling them to make progress and complete line items when the whole team is not available to work on the project.

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Learning Zone as indicated by progress and completion of work</td>
</tr>
<tr>
<td>Through the fulfillment of the Assignment 3 I did not consider initially the importance of stipulating a bill of materials and now I’ve realized how helpful is to have this bill in mind to be more conscious what materials do we need and why do we need them, this bill is not only important for estimating the final price of the pop but thinking conscientiously about the function of each part of the car by abstracting.</td>
<td>✓</td>
<td>Reference to “we” – team-based learning and usefulness of the new tool</td>
<td>3b and 3c</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Anxiety zone as indicated by absence of knowledge</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Learning zone as indicated by the realized importance</td>
</tr>
<tr>
<td>Through modifying our selected concept that we decided on in assignment 3. I realized that even if you believe your concept is acceptable the way it is, a design change may make it an even better design, I can utilize this in the future by allowing myself to change a design even if it is later in the design process.</td>
<td>✓</td>
<td>Reference to “we” – team-based learning</td>
<td>3a-3c</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Learning Zone as indicated by a new realization</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Comfort zone as indicated by value articulation</td>
</tr>
<tr>
<td>After brainstorming our Bill of Materials as team, my team realized we were more equipped to build a different design concept that what we concluded at the end of assignment 3 which helped me to internalize how the proposed plan of action can change several times of the course of a project when applying new discoveries.</td>
<td>✓</td>
<td>Reference to brainstorming showing explicit social knowledge construction</td>
<td>3a-3c</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Learning Zone as indicated by a new realization</td>
</tr>
</tbody>
</table>

## Assignment 4

I did not initially consider creating a CAD model however during the completion of assignment 4 I quickly realized the importance of creating a CAD model to ensure all the components fit and will function properly, in the future I will continue to create CAD models before assembly to analyze structure and space limitations.

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Learning Zone as indicated by new realization of usefulness of a tool.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Comfort zone as indicated by value articulation</td>
</tr>
<tr>
<td>Through completing the bill of materials in Assignment 4, I discovered that articulating a plan and understanding the limitations that I am faced with are important to being efficient and operating within the given parameters and that this will help me as a junior engineer to analyze and identify the limitations, either financially or in terms of skills, of my team and of my company.</td>
<td>✓</td>
<td>Internalization of use of a new tool</td>
<td>4a, 4c</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Learning Zone as indicated by new realization of usefulness of a tool.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Comfort zone as indicated by value articulation</td>
</tr>
</tbody>
</table>
Assignment 5

While completing Assignment 5, I realized the importance of ensuring that the design as built meets the requirements by testing the design early as well as keeping an updated manufacturing Gantt chart, because starting testing early will allow for a thorough analysis of the design’s projected performance, this will benefit me in my career as an engineer by helping me plan ahead using a manufacturing Gantt chart and, therefore, begin testing as soon as possible and ensuring that the prototype will meet expectations.

Internalization of use of a new tool

Learning Zone as indicated by new realization of usefulness of a tool.
Comfort zone as indicated by value articulation

During the completion of the project demonstration and Assignment 5, I realized that the learning statements I have written throughout the semester all helped me to truly internalize POD 3c, due to our robot meeting that POD, which will have a positive impact on all of my future designs (POD 5b).

Internalization of use of a new tool – LS construct for articulation

Learning Zone as indicated by new realization of usefulness of a tool.
Comfort zone as indicated by value articulation

Before Assignment 5, I did not realize the importance of determining the causes of the successes as I was solely focused on the failures of the design, but I now realize that by performing this evaluation, it will add value by allowing me to correlate successful aspects of the design to certain components or methods that can be used in future design ventures.

Internalization of a DBT process
Also, classification of successful and unsuccessful aspects as we have ventured to suggest in Section 1.3- but at a later stage than A4!

Learning Zone as indicated by new realization of usefulness of a tool.
Comfort zone as indicated by value articulation

As a result of completing Assignment 5 - the Post-Mortem Analysis, I became conscious of the importance related to creating a bill of materials for the design as built and how this design can help me determine the effectiveness of the design and component properties for their desired task, by internalizing this knowledge I will know to keep a list of used components and materials so that I can effectively complete a Post-Mortem analysis of the design.

Internalization of a DBT process

Learning Zone as indicated by new realization of usefulness of a tool.
Comfort zone as indicated by value articulation

2.3 Paper Research Method

We have thus far laid out our motivation to ‘operationalize’ robust educational theory within the context of an engineering DBT course centered around a team-based DBT project. We have established how we wish to contextualize our understanding of an assessment instrument, the LSs, in terms of several schools of constructivist thought as well as Vygotsky’s ZPD construct. Having therefore established our motivation and resultant theoretical framework, we now seek to outline our plan to put this into practice.
In Fall 2017, we collected approximately 9,000 LSs from 164 students across the five assignments which map to the course design project, two assignments which were individually focused and followed the course design project (engineering ethics and a semester learning essay), and an assignment in which students were formed into new teams which would be their groups for their Capstone project the following semester. In that final assignment (Assignment 8), students essentially had to complete the same challenge as in Assignment 1: form a team, develop a strategy for cooperative work, form an understanding of their assigned problem, and formulate a plan of action. In terms of using the ZPD to understand student self-reported learning (via the LS), we thus have an opportunity to compare the new schema students report developing in Assignment 1 to a similar, though novel, design problem in Assignment 8. Assignment 8 is like Assignment 1 in that students must complete similar targets but it is dissimilar in that students are not provided the same scaffold to accomplish these targets that they are given in Assignment 1. This is because the AME4163 course design project has a separate set of ‘customers’ (the instructors) than the students’ new Capstone projects (faculty advisors, company/private sponsors). Students therefore cannot simply ‘redo’ Assignment 1 mindlessly, they must think critically about the lessons they have learned and how to employ them.

For this paper, we therefore draw from our overall data set a subset of LSs containing individual student LS from Assignments 1 and 8, as well as from Assignment 5, the post-mortem exercise. In total, this set includes 2,235 LSs. Due to the size of our data set, and in conjunction with our prior work, we opt to employ a text mining method to analyze the word choice and frequency within our LS. We have developed a customized database tool using SQLite to store LSs and their associated characteristics (POED, date, assignment, student ID), which allows us to generate subsets based on queries. For example, we can look at all LSs from an assignment, or all from an assignment that contained material pertinent to specific POED. Once the desired subset has been queried from the database tool, it is output as a text file which is then read in by our text mining program, built using R and Visual Basic. The tool allows us to see histograms and word clouds for the entered subset and we are even able to manually remove words or select the minimum frequency cutoff for words to be displayed. In this paper, this is our primary means of comparing our aggregate LS data. Specifically, we look at relative word frequencies for LSs taken from Assignments 1, 5, and 8. We then further break those down by POED, to compare statements written about a POED in one assignment to similar statements in another assignment. In some respect, this approach is less empirical and more exploratory. It is our hope to use the approach employed in this paper as a springboard for more sophisticated approaches in future reporting on our work.

Following this section, we briefly survey the relevant literature on which our prior claims and theoretical framework lie. This is covered in Section 3 and includes an overview of the literature pertinent to our course pedagogy, Vygotsky’s ZPD, and our prior work in engineering design assessment. In Section 4, we outline our results from the text mining the aforementioned LS subsets and discuss our findings. Finally, in Section 5, we critically analyze our results and method, discuss our contributions, and identify our way forward.

3. Survey of Relevant Literature
In this section, we briefly highlight the relevant literature to our present work, including work by authors which we cite as foundational to our course structure and pedagogy as well as work which has influenced our approach taken in this paper.
3.1 Course Pedagogy

As already mentioned in Section 1, our course, AME 4163 is largely grounded in the work of educational researcher David Kolb. We have leveraged his long discussed and gradually-modified experiential learning cycle into the framework of our course. Specifically, the presence of the cycle within the course structure is most evident in the LSs, which, as a student exercise, encompasses three of the four stages of the experiential learning cycle [2,3]. Furthermore, on a larger scale, following the four assignments which make up the design, build and test phases of the course project, students complete Assignment 5 which, as we have already noted, is a post-mortem exercise in which student teams identify the sources throughout the process of their successes and failures as well as how they might have changed their decisions had they known what they know now. In this way, students are completing the first three stages of the experiential learning cycle before moving onto Assignment 8, in which they are required to apply those extracted lessons and apply them moving forward to a novel situation.

3.2 Applying Vygotsky’s ZPD

Purzer employs correlation between self-efficacy, achievement and discourse types and suggests that use of different theoretical frameworks to understand student learning can lead to the development of more effective instructional tools and methods [11, 12]. This suggestion aligns with our belief to anchor the course in constructivist learning theories, particularly Vygotsky’s sociocultural theory. Fila et al. [13] have explored the significance of situating engineering innovation projects within the ZPD. Their commentary indicates the importance of scaffolding while the students engage with innovation. This research ties perceptions of students about the innovation element in their projects with respect to their contributions to the project. While they focus on only the innovation aspect of projects, in our course design and assessment we attempt to explore comprehensively, the principles of engineering design as learned through immersive and collaborative experiences.

Cheville [14] reports a ‘transformative’ design course by merging the design process found in most engineering design textbooks with the Vygotsky cycle. The research evaluation although most of the direct and indirect course goals were met, there are aspects of design that students fail to master. While the attempt of this work is to adapt the textbook design processes to the Vygotsky cycle, in our work we focus on creating a design process based on the knowledge construction processes described in learning theories and situate the learning experience in the ZPD for maximizing the learning outcomes. Hasan [15] cautions that while applying ZPD in assessments, (as in the assignments in our course design), the students “should be given the opportunity to express his/her views about the learning situation.” The teacher should find out the effects of assessment task on their learning. The assessment and evaluation results will guide the teacher at a later stage in the right direction towards their ZPD in relation to the whole learning situation. We note that our LS construct-incorporates this feedback loop as discussed in the Section 2. Furthermore, the linguistic patterns employed in the LS directly map to the three zones as explained in Figures 2 and 3, in Section 2.2, within a ZPD. Consequently, in our course, the LS construct serves a dual-role as both a scaffolding and an assessment instrument.

3.3 Need for Improved Assessment

Autrey et al. [1] highlight a gap which exists between what students are learning in engineering DBT courses (often soft skills such as working on teams and managing complexity, among others)
and in what areas they are often evaluated by instructors (often overtly technical skills judged via design artifact performance). The authors assert that this is indicative of a need for improved methods of assessment, of which they also opt to explore the utility of the LS. This highlighted need for new assessment instruments in engineering design courses is not new. For example, Besterfield-Sacre et al. [16] indicate that there is a need in engineering education for forms of assessment built specifically to assess students in non-technical domains. They also recognize the potential for self-assessment to fill that niche. Similarly, Segers and Dochy [17] suggest that self-assessment might fill the gap in engineering design courses but only if instructors are careful to train their students in the methods of critical self-reflection and analysis.

4. Results and Discussion
As discussed in Section 2.3, in this paper we analyze just over 2,200 LSs collected from Assignments 1, 5, and 8. Using our text mining tool, we produce word clouds of the most frequently utilized words for subsets. Where necessary, we also note the frequency cutoff used (minimum number of uses of a word to appear in the figure). For a given LS subset, the chosen frequency cutoffs depend both on the sample size as well as on the breadth of different words used. We first present the overall results for all three assignments, and then move on to comparisons between A1 and A5 in Section 4.2 and A1 and A8 in Section 4.3.

4.1 Overall Breakdown of A1, A5, and A8 LSs
In Figure 4, we illustrate a word cloud for the most frequently occurring words amongst student submitted LSs in Assignments 1, 5, and 8. The text mining program automatically removes from consideration so-called ‘stop words;’ that is, common English words which are of no interest to us. We further remove an additional three words from our analysis: learned, learning, and design. For virtually all assignments and all LS subsets queried on various criteria, these three words were by far the most frequently occurring words. We suggest that learned/learning show up frequently because the structure of the LS requires students to explicitly state their learning and most use that word to do so. Design similarly appears so frequently due to that concept being central to the course purpose.

In Figure 4, we see that the word which appears most frequently is ‘team.’ Now, we usually associate team with POEDs 1a-1d, which deal with forming the group and planning the project as a team. According to our LS-ZPD framework (Figures 2 and 3), this implies that the ‘team’ concept appears in the Learning and Comfort zones of our framework. However, for many students, we also see that the word is often used in the portion of the LS in which they identify the prompting experience, which we have associated with the Anxiety zone.

The next most frequently used word was ‘project,’ which is used by students discussing learning across many POEDs. In this sense, ‘project’ likely does not provide us many clues about the progress of student learning in the course. However, we note that ‘problem’ is also among the top five words. Unlike ‘project,’ which occurs throughout the semester, the word ‘problem’ was predominately used early in the semester, before the students’ solutions to the design challenge had begun to take shape. If we assume that ‘problem’ is appearing frequently in the LSs due to its relative importance to student learning, then we might deduce that Assignment 1 was a particularly challenging/impactful period of the project.

We now elect to look at direct comparisons between LSs across multiple assignments.
4.2 Comparing A1 and A5 LSs
In Figure 5, we separately present word clouds for all LSs from Assignments 1 and 5, to get an overall sense of the differences in focused on subject matter. Recalling Table 2 and our discussion thereof (Section 2.2), students in Assignment 1 are formulating an understanding of the problem and how they will go about completing it. During Assignment 5, students have already built and tested their devices in front of their peers and now must reflect on their successes and failures as well as speculate on the causes of both, respectively. In Assignment 1, we target POEDs 1 and 5, whereas, in Assignment 5, we target POEDs 4 and 5 (see Table 1).

Unsurprisingly, we see that, in Assignment 1, POED 1 (words such as ‘problem,’ ‘team,’ ‘contract’) appears to be the dominant subject matter. In addition, we note that, in our readings of the LSs, relatively few students can successfully identify value from the learning identified. This implies that, early in the course, students are less able to make the transition from the Anxiety zones to the Learning Zones, and fewer still to the Comfort Zone. Further, if we compare LSs discussing the same POED between Assignments 1 and Assignment 5, we see some evidence in the text mining that more students are making that transition later in the course.

In Figure 6, we make that comparison between the target POED common to both Assignment 1 and 5. As POED 5b deals with the metacognitive exercise of reflecting on their reflection during the semester (specifically via the LS), it is unsurprising that for both ‘statements’ is the top word. However, we see that, in Assignment 5, there is much greater relative representation of words such as ‘engineering’ and ‘future.’ In both cases, these words are more likely to appear in the portion of the LS which we have modeled as indicating the students Comfort zone. This suggests, by Assignment 5, students are more comfortable performing critical self-reflection and articulating those lessons and their expected future utility.

We bear this in mind as we move into the final portion of our analysis, in which we compare two assignments with identical target POED but completed under much different circumstances.

4.3 Comparing A1 and A8 LSs
In Kolb’s experiential learning cycle, the final stage of the cycle (before it repeats) is active experimentation, in which the learner attempts to employ what s/he has learned. Viewed through the cognitive constructivist lens, this is when learners attempt to employ their new ‘schema.’ In AME4163, our students have such a learning opportunity between Assignments 1 and 8. In both, students form new teams, attempt to understand and frame a problem, and develop a plan for
addressing that design problem. However, Assignment 1 is heavily scaffolded whereas Assignment 8 is not. Comparing the two, as we do in Figure 7, we can see how students move from the lower ZPD to the higher over the course of the semester.

Figure 5: Word Clouds for LSs from A1 (left) and A5 (right)

Assignment 1

Assignment 5

Figure 6: Word Clouds for LSs from A1 (left) and A5 (right) from POED 5

We see, from the top row, in which we compare LSs from Assignments 1 and 8 dealing with POED 1, that the words ‘team,’ ‘project,’ and ‘problem’ are our top three words for both assignments, though by A8, description of the design challenge as a ‘project’ edges out ‘problem.’ We see substantial overlap between the words in each assignment, though, outside of the top three, the relative differences in frequency are extremely slight. It appears that, at least for target POED 1, our approach does not reveal marked differences between Assignments 1 and 8 which would enable us to characterize student ZPD. However, we observe some differences in LSs dealing with POED5 between the two assignments. In A1, students heavily emphasize the ‘statement’ itself. Reading the LSs directly, many simply acknowledge their utility without being more specific. In contrast, in A8, we see greater diversity of focus in the topics discussed. To highlight a few, student LSs in A8 heavily focus on ‘future,’ ‘capstone,’ ‘principles,’ and ‘new.’ Many of these words most likely appear in the portion of the LS in which students identify future utility, the portion which we have linked to the ZPD comfort zone. Viewed this way, in terms of their comfort
with critical self-reflection and identifying new design principles (POED 5), many more students are transitioning from the Anxiety to the Comfort zones by the end of the semester than at the beginning.

5. Closing Remarks
We have used the LS construct in AME4163 in 2016 and 2017. In this paper, we put our findings in the context of ZPD for the first time. With this as background, in this section, we highlight some of our key findings and discuss how engineering design education stands to benefit from the incorporation of robust learning theories pioneered in other disciplines.

5.1 Critical Analysis of Work
In this paper, we present a framework to operationalize educational theory in the context of an engineering DBT course. We have taken a course, already grounded in Kolb’s experiential learning construct, and attempted to understand what is learned by our students through the lens of constructivist theory, particularly Vygotsky’s Zones of Proximal Development. This follows from a need, highlighted by researchers (see Section 3.3) for improved methods and instruments of assessment in engineering design courses. Students in the DBT course periodically reflect on their doing by completing learning statements, self-contained exercises in which lessons are
abstracted from experiences. We then map the elements of the LSs to the ZPD and see how students transition from Anxiety to Comfort Zones skill areas.

In this paper, we employ text mining to characterize different zones using aggregated LS data. One of the limitations of this approach is that currently it provides us some macro-level understanding of the learning taking place in our course, and does not permit us to examine students and map the individual’s progress. As an example (see Section 4), we can discern semester-level trends in subject areas and concepts challenging for students. Specifically, we find that elements of Assignment 1 dealing with POED 1 are relatively impactful, compared to events taking place later in the course. Whether this is because it is simply their first Assignment or POED 1 is particularly challenging to students remains to be seen. Though we do note that the lack of difference between the word frequencies for POED 1 between Assignments 1 and 8 may imply it is the latter.

Furthermore, we see that (Section 4.3) by the end of the semester, students are moving into the Comfort Zone for tasks related to POED 5 much more readily than earlier in the semester. This is significant because the components of POED 5 are meta-cognitive in nature = students attaining proficiency in these areas demonstrate improved aptitude for critical self-analysis and knowledge creation vital for their future careers.

5.2 Contributions and Way Forward
In this paper we introduce a practical method for bringing widely-discussed educational theory to bear in an engineering DBT course. Operationalizing this theory by instructors could potentially provide a useful means of improving student outcomes in DBT courses. Improving assessment instruments and methods for non-technical skill areas in engineering design will help improve the degree to which our students are able to compete in industry in the future.

We plan to refine the model presented in this paper to identify subtle shifts in student capability skill areas. At present, we only highlight strong trends. We are developing the means to use text mining to understand learning at the individual student level throughout the semester. From a course management/iterative improvement standpoint aggregate data analysis are useful but instructors need tools which can enable them to provide feedback to individual learners rapidly. We recognize this as an opportunity to use machine learning / artificial intelligence to enhance the computational framework. Accordingly, we will expand capabilities of our data mining tool to identify themes or perform semantic analysis on student writing samples.

In addition, from an initial examination of learning statements for assignments and in-class submissions, we see that some students frequently derive large value from our course and others do not seem to gain as much. As such, we are interested in tracking individual student submissions over the course of a semester to identify the characteristics of students who frequently express strong insight, what is the progression of the “average” student through the ZPD in such a course, and how other students can be motivated to emulate the top students.

Acknowledgements
Jackson Autrey acknowledges the Graduate Teaching Assistantship from the School of Aerospace and Mechanical Engineering at the University of Oklahoma, Norman and the financial support granted through the Dolese Teaching Fellowship program. Shalaka Ghaisas acknowledges the Graduate Research Assistantship from the Systems Realization Laboratory at the University of Oklahoma. Farrokh Mistree acknowledges the financial support that he received from the LA Comp Chair. Zahed Siddique acknowledges the financial support that he received from the Dick
and Shirley O’Shields Professorship in Mechanical Engineering. This material is based in part upon work supported by the National Science Foundation under Grant Numbers DUE 1712103. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

References


10. Smagorinsky, P., (2018). Deconflating the ZPD and Instructional Scaffolding: Retranslating and Reconceiving the Zone of Proximal Development as the Zone of Next Development. Learning, Culture, and Social Interaction, 16, pp. 70-75.


