

First-Year Engineering Students' Experiences and Perceptions Viewed Through the Lens of Transdisciplinary Knowledge and Threshold Concepts

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Abstract

This complete research paper involved an in-depth qualitative analysis on how learning interventions in two consecutive first-year Introduction to Engineering courses supported first-year engineering students' development of three transdisciplinary knowledge domains which we call as metacognition, systems thinking, and emphatic thinking. Our overarching question examined the extent to which learning activities in a course supported and influenced student development of transdisciplinarity viewed through the lens of transdisciplinary knowledge and threshold concepts. Analyses were based from pre- and post-course interviews and focus group discussions. Students' manifestations of systems thinking, metacognitive development, and emphatic thinking as perceived by the students themselves, teaching assistants and instructors were summarized and presented into levels of liminality of the threshold concepts. These manifestations in the forms of key experiences and perspectives were highlighted to inform how learning interventions in the two courses promoted the development of students' transdisciplinary knowledge.

1. Background

The COVID-19 pandemic has exacerbated the urgent need among universities to connect engineering programs and curricula with the changing demands of local, national, and international stakeholders. Societal challenges, even before the current global pandemic, require scaffolded and interconnected engineering approaches and solutions. These challenges demanded the integration of different disciplines, practices, or competencies in redesigned undergraduate engineering curricula which were particularly directed to enrich first-year engineering students' learning experience [1-3]. Engineering education saw the birth of the many faces of integration like multidisciplinary, interdisciplinarity, and transdisciplinarity. Most studies agree that if arranged according to the increasing level of complexity of integration, multidisciplinary should come first as having the lowest level and transdisciplinarity on the top with the highest level of integration [4]. In this study, we employed the lens of transdisciplinarity by combining metacognition, systems thinking, and empathy in an introductory engineering course. The education literature on transdisciplinarity [5-7] acknowledges that generally, current higher education practice does not yet effectively train students as empathic and systems thinkers, nor to practice metacognition. To align with the primary aim of First-Year Programs Division (FPD) to advance first-year engineering education through research and innovation in curriculum and pedagogy, this research explored how learning interventions in engineering programs support students to acquire transdisciplinarity. Our overarching question examined: To what extent did learning activities in an Introduction to Engineering course support and influence student development of transdisciplinarity viewed through the lens of transdisciplinary knowledge and threshold concepts?

The examination employs the lens of transdisciplinary knowledge, a combination of our synthesis of transdisciplinary and sustainability literature and model of empathy in engineering

[8], and threshold concepts [9]. We look at transdisciplinary knowledge lens as an integration of personal characteristics and abilities of students and examine these characteristics and abilities as threshold concepts by assigning them a state of liminality (students' journey of learning transformation composed of varying levels of pre-conceived, partial, and emergent understanding, ideas, and experiences).

Threshold concepts are viewed as portals or gates from which "new perspectives open up, allowing things formerly not perceived to come into view" [10]. Crossing, and being in, a threshold is a difficult journey - simultaneously disconcerting and enlightening. Meyer et al. [9] view this journey in stages, from preliminal, to liminal, and then to postliminal states. In a preliminal state, the learner encounters a threshold concept which is troublesome and difficult. Partial understanding of a concept leads to a liminal state. This is a state where the learner reconfigures prior conceptual schema and reconstitutes an ontological or epistemic shift of a given concept. In a postliminal state, both the learner and the learning process are transformed. The transformations are described as distinct characteristics of threshold concepts which include transformative, integrative, irreversible, and troublesome [9, 11]. As transformative, understanding threshold concept offers significant shift in the perception of a subject. As integrative, it opens to the previously hidden inter-relatedness of topics. As irreversible, learner is unlikely to forget the concepts. As troublesome, learner might undergo variety of interpretations.

Since the inception of threshold concepts in 2003 [11] to enhance teaching and learning in undergraduate courses, starting off with economics, the application of the concepts in higher education has expanded to different subject disciplines. For example, 'Legal Narrative' in Law; 'Depreciation' in Accounting; 'Deconstruction' in Literature; 'Gravity' in Physics; 'Geologic Time' in Geology or 'Limit' in Mathematics [9].

In engineering education, Kabo and Baillie [12], explored how social justice is seen in engineering through the learning experiences of engineering and social science students. Using a semi-structured interview, they found nine conceptions of increasing complexity of students' collective experiences positioned along the stages of liminality. They reasoned out that identifying students' learning liminalities and finding out how to facilitate students' transition through the threshold could contribute in looking at engineering education through the lens of social justice. Parkinson [13] investigated 435-engineering students' experiences of threshold concepts and Male and Bennett [14] focused on two of these threshold concepts, namely, "roles of engineers" and "value of learning" to find out how engineering students can overcome them through a workshop format method.

For first year engineering students, navigating the meaning, application, and relevance of the three transdisciplinary skills (systems thinking, metacognition, and empathy) in engineering is a common struggle since they bring with them different pre-conceived ideas and experiences. Moreover, developing these transdisciplinary skills is not well supported in traditional engineering programs. Hence, it is logical to situate and frame these three transdisciplinary skills and how students are learning of these skills in a way to inform teaching practices and curriculum design. Since we viewed first year engineering students confronting with their learning around transdisciplinarity like entering new portals where new perspectives might open

up, we framed how they grappled around their learning of transdisciplinarity through the lens of threshold concepts.

2. Design/Method:

APSC 100 and 101 are first year Introduction to Engineering courses spanning two semesters. They are design-focused and flipped-classroom core courses offered annually to approximately 1000 students. The coverage of this study is the academic year 2018-2019.

A weekly course structure starts with screencasts viewing by the students done online and outside class hours. Then, students engage on a team quiz with peer group discussions and culminates with a brief lecture from the instructor. Next, students gather as a team in a studio design class and apply the concepts from the lectures in project designs. Finally, students join in another studio design class for more learning activities to reinforce the lectures and project designs through role-playing, case study, debates, etc. with subsequent de-briefing sessions. The contents of these activities consisted of regional energy sources, environmental sustainability, transportation and safety, health care, community and stakeholders' perspectives, etc.

Screencasts [15] are series of interactive online screencasts aimed at developing students' metacognition. Examples of screencasts series included "Mindset and grit", "How learning works", and "Understanding and managing stress." Eight screencasts were introduced in 2018, and nine in 2019. The recent findings on students engagements with the screencasts are described in [15]. Learning activities like role-playing, case study, debate, etc. in classes including studio design class were geared towards the development of students' metacognition, systems thinking, and empathy.

The data used for this study were based from pre- and post-course interviews and focus group discussions. A week after pre- and post-course surveys were completed, separate semi-structured interviews [16] were conducted among groups of students, using probing and open-ended questions on transdisciplinary knowledge. Separate focus group discussions for studio instructors and TAs' with different probing and open-ended questions on transdisciplinary knowledge allowed the instructional team to discuss their communal experiences, their perspectives, and beliefs [17] on students in their studio classes. Seventy students joined in both pre- and post-course semi-structured interviews. Eleven instructors and TAs participated in the pre-course focus group discussion, while only five joined in the post-course discussion. The composition of the participants differed in the pre- and post-course interviews and focus group discussions.

Student interviews, and focus group discussion with the instructors and TAs, were conducted by a graduate student not involved in teaching first-year engineering students. All pre-post course transcripts were transcribed and member-checked prior to analysis. Four coders of varying specializations (STEM education, engineering, education, and economics) performed inductive coding derived from a priori theory [18]. Using threshold concepts, the coders developed five levels of liminality to describe both students' transdisciplinary knowledge, and instructors' and TAs' observations of students learning of transdisciplinary knowledge concepts. Each code has corresponding distinct indicators. For example, students' statements were coded as preliminal if they signified no prior knowledge or first encounter, while liminal indicates confusion or conflict

in understanding, etc. The indicators were used by four coders to identify levels of: (a) students' self-assessed views of transdisciplinary knowledge as applied in engineering during pre and post-course semi-structured interviews; and (b) instructors and TAs' assessments of students' transdisciplinary knowledge as manifested and observed during the class, pre- and post-course, respectively. Since the first three coders were aware of the differences between pre-survey and post-survey statements as they have coded each at separate time, a fourth coder was invited to reduce unexpected bias in the result.

3. Results and Discussion:

The manifestations of systems thinking, metacognitive development, and emphatic thinking as perceived by the students from the semi-interviews conducted among them and as perceived by course instructors and teaching assistants (TAs) during the focus group discussions, pre and post, are described below. The levels of liminality were introduced in three levels, preliminal, liminal, and postliminal only. The statements presented for each liminality (maximum of two statements), attributed to students by both, the students themselves and by course instructors and TAs, were selected because a combination of three out of four and/or all four coders perfectly agreed on the coding of such statements. Naturally, either pre-course or post-course interviews and focus group discussions resulted with three levels of liminality. However, since statements were selected based on the agreement of the majority of coders, there was an unequal number of pre-course and post-course statements for each liminalities. As shown below, most of the statements that described students levels at preliminal and liminal were found during pre-course while postliminal level converged most during post-course. Entries written in bold emphasized key transitions, ideas, and indicators of students' experiences in and perspectives on systems thinking from preliminal, liminal, and postliminal.

Systems thinking (students)

For both pre and post interview, students were asked:

How do you define “systems thinking” as you understand it in your APSC 100 course? Were you familiar with the concept before your APSC 100 course? Are you comfortable applying systems thinking during APSC 100 activities and/or outside of your APSC 100 course? What do you think is the value of systems thinking in your future career?

Table 1 shows that while the environment outside the classroom or prior learning experience might provide opportunities for the students to understand systems thinking, course instructors should consider and maximize first-year engineering course as an appropriate and relevant venue for first-year students to unpack the meaning and importance of systems thinking and provide engaging learning activities to enhance the application of the concept inside and outside the classroom. As one student's response under preliminal state indicated that “honestly, outside of class, I almost never think about systems thinking” and in postliminal state points that “I feel like I did this before APSC 100 but did not know what it was called...”

Table 1. Systems thinking as perceived by the students

Threshold State	Systems Thinking	Pre or Post
Preliminal	I'm not too sure what it is. I was not familiar with the concept before the course.	Pre
	No, I was not familiar before the course. No, I'm not comfortable applying this concept. I'm not sure of its value	Pre
Liminal	To apply comprehensive structure and pattern in problem solving. Yes. In high school. Yes. Help me organize thoughts	Pre
	To me, it is not very different from what I was thought about critical thinking in high school except with the added emphasis on sustainability. In terms of application, I'm never sure the extent to which I should apply in depth analysis on or stimulus or solution. In other words, how much is too much and how little is too little.	Post
Postliminal	Systems thinking is the way of looking at a system and all of its components and reactions with its surroundings/environment. I feel like I did this before APSC 100 but did not know what it was called and so I think I am comfortable applying it during our modules in APSC. I think this is valuable and useful in the future as one always needs to consider how everything will interact.	Post
	It is the ability to understand the synergy of the different components constituting a system (how well they work together). The aspects of a system are viewed at multitudes of point of views and also at different scales for a more profound knowledge system. It broadens ones perspective and I consider it important to improve ability to think out of the box.	Post

Metacognition (students)

For both pre and post interview, students were asked:

Can you describe any changes (positive or negative) in your learning strategies when you compare how you learned before taking APSC 100 with how you learn now? How do you explain such changes?

While it is imperative that first-year engineering course should provide for opportunities for students to developing their metacognitive skills, the growth process takes time. Consistent curricular and pedagogical interventions from instructors and teaching assistants like providing students with “opportunities for reflection to connect thinking and doing” [19] in lecture, labs, and design studio classes help in the growth of students’ metacognition. Specifically, as shown in Table 2, students might appreciate the value of honing their metacognitive skills every step along the way if the course (a) offers learning resources (like screencasts) to enrich their understanding of metacognition and (b) students with the help of instructors, teaching assistants, and team members find ways on how to apply such skills in coping up with the demands of higher education which are more challenging than what they have had in their high schools. As one student recalled (under postliminal state) that “I saw positive changes in my learning strategies because I applied some of the screencast lessons and it helped me.”

Table 2. Metacognition as manifested by the students

Threshold State	Metacognition	Pre or Post
Preliminal	No changes in learning strategies	Pre
	Nothing really changed. I just had no change the way of learning in university	Pre
	No changes, less time to study, more cramming.	Post
Liminal	Since I started studying APSC 100 I have learned to take better notes, screencasts are very helpful and teach you what's important. Although I haven't really changed my way of learning	Pre
	Positive: My notetaking involves more drawing than actually writing down information. Negative: Due to many modules I rarely get to learn about any particular concept in any great depth and detailed notes are not as useful.	Pre
	No notable change. I suppose my outlook on engineering is different, however	Pre
Postliminal	The most valuable learning strategy that I learned in APSC 100 was to study in numerous short sessions instead of one long one.	Post
	Positive changes in my learning strategies because I applied some of the screencast lessons and it helped me. For example, practice was of the strategies mentioned to move information into long term memory as well as the diagrams that were shown	Post

Emphatic thinking (students)

For both pre and post interview, students were asked:

*What makes it difficult for another student to see things from another person's point of view?
How does APSC 100 help students appreciate the value of perspectives other than their own (e.g. another person's, or other team's, perspectives)?*

While there are different ways on how to develop first-year students emphatic thinking skills, a student mentioned (under postliminal state) that integrating metacognition and systems thinking in a role play of community and stakeholders' needs and realities allowed them to crucially "understand the diversity of people and culture at work." A student also pointed out that doing project designs in teams with immediate feedback received from TAs and instructors helped them see others point of view and as a result expanded their understanding of individual and group dynamics.

Table 3. Emphatic thinking as perceived by the students

Threshold State	Empathic thinking	Pre or Post
Preliminal	It's new and different	Pre
	No	Pre
Liminal	APSC 100 really makes you more open-minded person. You learn how to work in technical projects in groups. Seeing everybody POV (point of view) expands your understanding and knowledge	Pre
	It is difficult to understand about others values so it is difficult to consider their perspective. APSC 100 considers stakeholders which is important	Pre
Postliminal	Differing personal values and believing their own values are the only one that's "right" can make it difficult to see things from another perspective. APSC helps students appreciate other perspective by having us more in teams.	Post
	We are not sure of people's thinking process or students' background. But surely, learning metacognition, empathy and systems thinking crucially helps to understand the diversity of people and culture at work.	Post

Systems thinking (Instructors and TAs)

For both pre and post interview, instructors and TAs were asked:

Have you seen any changes in first year engineering students' ways of thinking in the first two months of the term as manifestations of dealing with big picture and systems thinking embedded in the course activities (e.g. screencasts)? What were these changes?

TAs and instructors pointed out that flexible structure in facilitating activities like prototyping, sketches, and cardboard design allowed students to think different aspects of the needs of stakeholders. As observed by a TA, “before students think of stakeholders as “barriers” in engineering but now they integrated or internalized the needs of stakeholders in their designs, the importance of the product and thus beginning to see stakeholders not as a barrier but a medium to inform their plans and that describes more about empathy and digging deeper on the why questions.”

Table 4. Students' perception of systems thinking as perceived by the instructors and TAs

Threshold State	Systems Thinking	Pre or Post
Preliminal	I don't really think that I answer this accurately based on the interactions I've had with students. Some students have demonstrated an interest in fitting what they learn into a larger picture understanding of society, and some are interested mostly on the technical outcomes of their projects.	Pre
Liminal	I think they know how to think like the way wanted them. So they know how to incorporate different layers into the whole picture	Pre
Postliminal	I find that they have learned to take broader issues into account while doing projects. Specifically, they make efforts to understand and evaluate the impact a recommendation might have on the environment, communities, etc. Also, they have started to plan for the next steps ahead of time. This means that while doing a certain studio, they anticipate possible changes/modification they may have to apply in future studios. So, they leave room to have the flexibility to make changes accordingly.	Post

Metacognition (Instructors and TAs)

For both pre and post interview, instructors and TAs were asked:

Have you seen any changes in first year engineering students' ways of learning (learning strategies) in the first two months of the term as manifestations of an increased level of self-awareness and understanding of one's self relating to the lessons of the course? What were these changes?

For instructors and TAs, screencasts provided a bridge on how to concretize ideas and practices which are in some nature, technical. They also highlighted that the growth of students' self-awareness, maturity, and motivation to learn takes time. Constant and immediate feedback from TAs and instructors as well as explicit scaffolding and mentoring in team projects promoted students' self-confidence, attained sense of ownership for their own learning, and placed more importance on teamwork.

Table 5. Students' manifestation of metacognition as perceived by the instructors and TAs

Threshold State	Metacognition	Pre or Post
Preliminal	I think this would be a no. Self-awareness in first year is quite hard to come by. It needs to be facilitated with a 3rd person/TA	Pre
Liminal	Yes, they were encouraged to work independently and extend their knowledge, then share the information with group members	Pre
Postliminal	I believe that students have gained a great knowledge about their talents, and have gained new sets of skills through practice. I am seeing that they are more cooperative through the studios sessions and ask very interesting questions about the course materials, which means that they are gaining a good sense of engineering concepts.	Post

Emphatic thinking (Instructors and TAs)

For both pre and post interview, instructors and TAs were asked:

Have you seen any changes in first year engineering students' way of learning/thinking in the first two months of the term as manifestations of an increased level of empathy relating to the activities and lessons of the course? What were these changes?

For TAs and instructors, role playing served as a very promising approach in developing students' empathy. As one instructor described, "for the first minute students might not really understand and navigate their roles as stakeholders but after few minutes they're completely immersed." Role playing in engineering class is seen to develop clear empathy on the situations of stakeholders like understanding indigenous and local community's plight with the proposed oil pipeline construction. As narrated under postliminal in Table 6, students struggled to balance priorities between people's lives and financial loss in thinking about car designs. One TA also described that students' growth in empathy depends in a group effort and it is a "case to case basis. A team that takes efforts on social investments among group mates, is the same team that performs well."

Table 6. Students’ perception of emphatic thinking as perceived by the instructors and TAs

Threshold State	Emphatic thinking	Pre or Post
Preliminal	Empathy manifests itself in certain groups, and not in others. I think the time they spend together bonding and learning together provides them the opportunity to gain a social investment in their group mates. Teams that struggled with working with each other haven’t improved much.	Pre
Liminal	Yes, they were encouraged to work independently and extend their knowledge, then share the information with group members	Pre
Postliminal	I recall the session that we were discussing and focusing mainly on the topic of empathy, were the students had to think of design that has the minimum damages in a car accident. Also the students had to come up with a way of defining the term "minimum" and prioritize the people's lives or the financial loss, I believe they showed a great attitude toward the engineering design in this exercise.	Post

4. Conclusion

Course contents of APSC 100 and 101 like regional energy sources, environmental sustainability, transportation and safety, health care, community and stakeholders’ perspectives were delivered through design-focused and flipped-classroom approached. The approach introduced learning activities like role playing, case-study debates, viewing of screencasts, prototyping, etc. In this study, these learning activities as interventions were investigated as to how they promoted first-year engineering students’ transdisciplinary knowledge related to metacognition, systems thinking, and empathy.

Qualitative analysis revealed that students gradually manifested the three transdisciplinary knowledge domains as narrated by the students themselves, and observed and perceived by instructors and TAs, pre and post, respectively. The key experiences and perspectives of students, TAs, and instructors, pre and post, implied that the learning interventions supported the development of students’ transdisciplinary knowledge. The highlight of these key experiences and perspectives as shown from Tables 1-6, pre and post, described students as if they enter a different level of unstable “liminal space” where they may oscillate between pre-conceived and emergent ideas and experiences [20], as they encounter unfamiliar discourse that might forge new understanding (transformative) [21]. This process establishes new connections, applications, thinking, and practices (integrative) [22] as students navigate their first-year engineering courses. Consistent and explicit integration and bridging of course design, projects, and contents with appropriate learning activities might further enhance students’ transdisciplinary knowledge which eventually will allow them to connect the “doing and thinking” in engineering disciplines and practices to self, school, and society.

Our wider study is on-going and it encompasses a mixed methods analysis (qualitative and quantitative design) on how learning activities in an introductory engineering course impact the growth of students’ transdisciplinary knowledge: metacognition, systems thinking, and sympathy. This initial study was conducted to get baseline data on first-year students’ levels of knowledge in the three knowledge domains. The instructors saw that the learning activities have a positive effect and now there is a need to hone these activities to further improve. The instructors felt more confident with integrating these three knowledge domains into first-year

programs. The collection of qualitative data has brought tremendous insight into the student experience and is something we plan to expand. And while this current qualitative study did not measure and compare which learning activities helped the most with the development of transdisciplinarity among students, our findings showed that first-year engineering students' conceptual schema and perspectives diverged and transformed through their engagement with the courses' learning activities [23].

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