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Introduction

In recent years, opportunities to learn and do engineering prior to matriculating in a university engineering program have greatly increased. The incorporation of engineering content and practices in the Next Generation Science Standards represents the first time engineering has been formally incorporated into the national science education standards that guide the content and development of state and local science education standards and practices[1]. Studies of the incorporation of engineering in statewide educational standards have also shown the widespread inclusion of engineering in science, mathematics, and technology standards and the development of standalone engineering standards[2,3].

Further evidence of increased opportunities for K-12 students to explore engineering comes from the growth of national pre-college engineering programs and curricula. Project Lead The Way (PLTW), the largest provider of K-12 technology and engineering curricula, has been adopted in all 50 states and measures student participation in the millions[4]. FIRST Robotics, which sponsors robotics competitions for elementary, middle, and high school students, has grown from a small local competition established in 1989 to involving over 460,000 students in the 2016-2017 academic year[5]. PLTW and FIRST represent two of the largest pre-college engineering initiatives among the numerous curricula, afterschool programs, university outreach activities and other programs that provide increasing opportunities and exposure to engineering for young people.

Research on the effects of participation in pre-college engineering activities has focused primarily on assessing the effects of individual programs. Studies of PLTW suggest that students who have participated in the program may score better on state mathematics and science assessments, are more likely to pursue undergraduate degrees in STEM fields, and have slightly higher undergraduate grade point averages[6], while evaluations of FIRST Robotics programs have shown similar outcomes[7,8]. One of the few studies exploring the effects of a wide range of pre-college engineering activities measured significantly higher engineering self-efficacy among students who had participated in pre-college engineering classes or had engineering-related hobbies[9]. Overall, relatively little work has been done to broadly understand the effects of pre-college engineering participation on the experiences and success of university engineering students, resulting in limited theory to guide the understanding of this experience.

To address these limitations, we developed a qualitative quantitative sequential mixed methods study[10] to explore how pre-college engineering activities influence students' transitions to first-year engineering programs. Utilizing phenomenographic research methods, we conducted and analyzed interviews with first-year engineering students to develop an outcome space comprised of five categories of description of the limited number of qualitatively different ways that students experienced the transition from pre-college to first-year engineering. Using this theoretical framework, we then developed a quantitative instrument to understand the ways of experiencing this transition among a larger sample of students. In this paper, we briefly present the theoretical framework developed in an earlier part of this study, and provide a detailed description of the instrument development and validation component of the study.

Theoretical Framework

We developed this instrument based on a theoretical framework developed during an earlier part of this study. We conducted phenomenographic interviews with 33 first-year engineering students, and analyzed these interviews to develop an outcome space[11] consisting of five categories of description[12] of ways that these students experienced the transition from pre-college engineering programs and activities to their first-year introduction to engineering courses. In order of increasing integration in their first-year engineering course, as shown in Figure 1, these ways of experiencing the transition were Foreclosure, Frustration, Tedium, Connection, and Engaging Others. We have described the development of this outcome space in earlier publications[13,14], but in the following present a brief description of each of these ways of experiencing the transition from pre-college to first-year engineering.

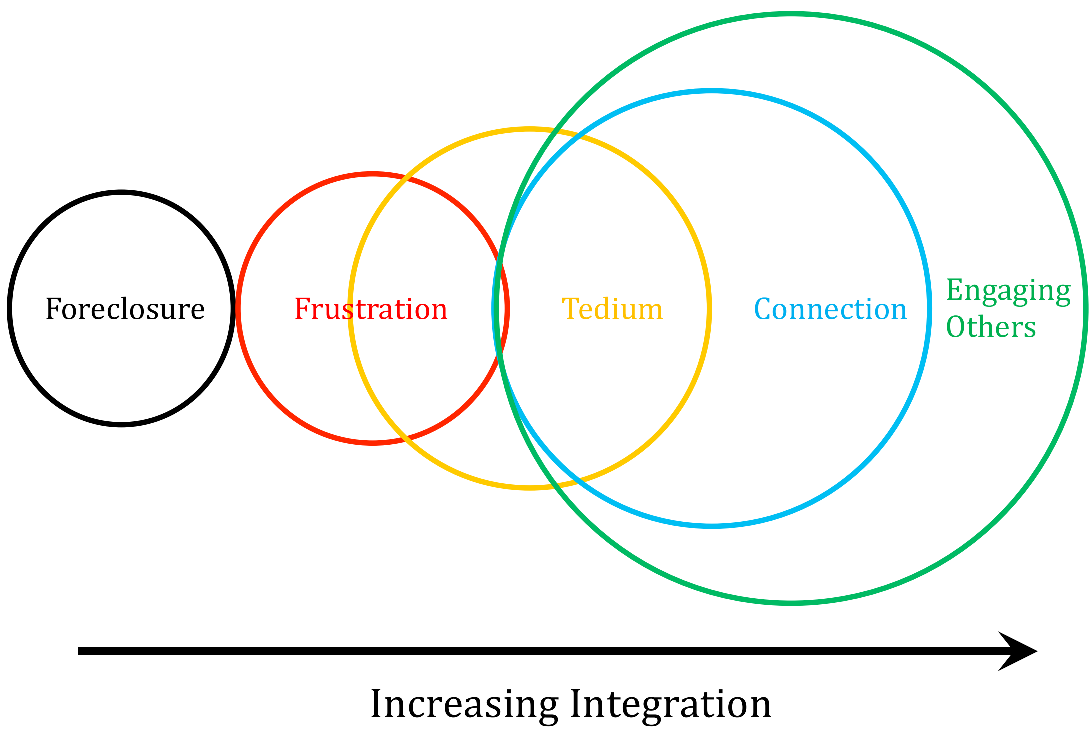

Figure 1: Outcome space representing ways of experiencing the transition from pre-college to first-year engineering.

Foreclosure describes the experiences of students who are in first-year engineering but do not feel like they belong there. This can be the result of external pressures from family or others to pursue a degree in engineering or students not knowing what else to do besides engineering. These students recognize that an engineering degree has value and can be a pathway to a stable career but lack passion or inspiration related to engineering.

Frustration includes the many ways that students may struggle when transitioning from pre-college to first-year engineering. This includes being unprepared for the level of mathematics and science integration and requirements present in undergraduate engineering programs, fewer hands-on activities, and issues with the relevance and authenticity of what is being learned in the first-year engineering classroom. Frustration has affective elements as well, including feeling a weaker sense of belonging or less connected to teammates in first-year engineering when compared to their pre-college experiences. Despite these frustrations, these students tend to have a strong identity as an engineer and commitment to studying engineering, primarily due to their pre-college experiences.

Tedium also captures an aspect of frustration in the transition from pre-college to first-year engineering, however these students' frustration stems for boredom due to perceiving first-year engineering as less challenging and engaging than their pre-college experiences. These students see themselves as better prepared and more capable than their peers, and feel like they are relearning material that they already mastered in pre-college engineering.

Connection captures the experiences of students who feel better prepared for first-year engineering as a result of their pre-college experiences. Whereas students experiencing the transition as tedium are bored or frustrated when relearning material they learned in pre-college engineering, these students feel more confident and better prepared when placed in the same situation. These students possess strong identities as engineers and confidence in their decision to study engineering and ability to be successful, and attribute these qualities to having participated in pre-college engineering programs.

Engaging Others includes all of the aspects of Connection, but with an additional commitment to working with other students and helping others to be successful in first-year engineering. They recognize the value in others' ideas and contributions, and embrace engineering design as a collaborative endeavor.

Together, these five categories of description form a hierarchical outcome space capturing the variation in students' experiences of the transition from pre-college to first-year engineering, with the hierarchy representing increasing integration in their first-year engineering course.

Instrument Development and Validation

To capture the experiences of a larger sample of students, we developed a quantitative instrument based on the theoretical framework. The instrument consists of three parts: experiences with pre-college engineering, ways of experiencing the transition to first-year engineering, and demographic information.

We designed the first part of the instrument to collect students' experiences with engineering prior to attending the university. Based on a review of relevant literature, we identified seven primary types of pre-college engineering experiences. These included incorporation of engineering in elementary school and in middle school and high school math and science classes; standalone courses in engineering in middle school or high school; afterschool or extracurricular activities; university-sponsored pre-college engineering programs; summer camps; jobs or internships; and military experience. Respondents then provided more detailed information for each type of pre-college engineering activity they participated in. This included the specific programs that they participated in, and the number of semesters, projects, or experiences they had with each activity. Where appropriate, respondents also indicated their participation in specific nationally distributed pre-college engineering curricula and programs such as Project Lead The Way or FIRST Robotics. Finally, the respondents rated their level of participation in activities that may have been incorporated in their pre-college engineering experiences. Examples of these activities include working on a team, doing engineering design, using math or science to solve engineering problems, presenting or documenting engineering projects, and technical skills like CAD or fabrication.

We developed the second part of the instrument, ways of experiencing the transition, by creating items grounded in the language and experiences of the students' descriptions of their transition from pre-college to first-year engineering acquired from the data collected in the qualitative part of this mixed methods study. This resulted in an initial pool of 65 Likert-type items; 6 representing Foreclosure, 22 representing Frustration, 12 representing Tedium, 14 representing Connection, and 11 representing Engaging Others. Each statement is assessed using a five point scale ranging from strongly disagree to strongly agree.

The third part of the instrument collects demographic information. In addition to the typical demographics of sex, race and ethnicity, and number of semesters at the university, respondents also indicated if they had family or other people they were close to who were engineers, intended engineering major, likelihood of graduating with a degree in engineering, and most likely destination if they intend to leave their College of Engineering. We also identified international students, and although we collected response data from these students, these data have not been included in analyses to date of this project as our primary focus has been on the pre-college engineering experiences of domestic students.

Validation of the instrument involved expert review followed by administration of the instrument to a sample of first-year engineering students at two universities. A total of six experts with experience in pre-college engineering, first-year engineering, and engineering education research reviewed the instrument and provided feedback on both the content and language which we incorporated to create an initial version of the instrument.

A total of 279 domestic students (152 from University A and 127 from University B) completed the initial instrument using Qualtrics online survey software. Reliability analysis of the instrument focused on the items related to ways of experiencing the transition from pre-college to first-year engineering, and we assessed the reliability of individual items, reliability of the five constructs which the items measured, and the overall reliability of the instrument. To analyze individual items we first looked at the variation for each item and eliminated those items with a standard deviation of less than 0.5 on a five point scale. Next, we looked at Cronbach's Alpha for each of the five constructs and for the whole instrument, and identified items where Cronbach's Alpha increased when the item was removed. Using these measures of reliability, we identified and removed a total of 15 items, reducing the total number of items from 65 to 50. The revised instrument contains 5 items related to Foreclosure, 16 for Frustration, 11 for Tedium, 10 for Connection, and 8 for Engaging Others. The revised instrument has a Cronbach's Alpha of 0.91, which is greater than the value of 0.7 widely considered as necessary for an instrument's reliability to be considered acceptable[15].

Data Collection and Analysis Using the Revised Instrument

With the reliability of the instrument established, we administered the instrument to students at six universities to generate a larger dataset. However, low response rates due to issues with survey distribution and a lack of incentives for respondents resulted in usable data from two of the six universities. Removing incomplete responses, international students, and students not from University A or University B, resulted in a sample size of n=413.

Table 1 provides basic demographics of the respondents. The most commonly reported majors were Mechanical Engineering, Computer and Electrical Engineering, and Civil Engineering, which is consistent with the institutional characteristics of University A and University B. Thirty percent of respondents were female, which exceeds the percentage of female engineering students at both University A and University B, and suggests that women are overrepresented in this sample. Eighty percent of students are in their first year of study at the university, and 63% of respondents indicated that they had a friend or family member who was an engineer.

Table 1: Respondent demographics (n=413)

	Number	**%**
Institutions		
University A	164	40%
University B	249	60%
Majors		
Mechanical	141	34%
Computer & Electrical	56	14%
Aeronautics & Astronautics	41	10%
Civil	47	11%
Respondent is Female	125	30%
Respondent is Male	288	70%
Respondent identifies as non-white	104	25%
Student progress in program		
First semester	89	22%
Second semester	243	59%
Third semester	30	7%
Four or more semesters	51	12%
Respondent has friend/family member who was an engineer	261	63%

Table 2 summarizes the pre-college engineering activities of the respondents. High Schools were the most commonly reported type of pre-college engineering activity, followed by afterschool experiences and middle school classes. The most commonly reported pre-college engineering programs were Project Lead The Way and FIRST Robotics, which is consistent both with the widespread national adoption of these programs[16,17] and results from earlier surveys conducted as part of this project[18–20]. Table 2 also presents the most commonly encountered pre-college engineering content or tasks, which includes working on a team, presenting a project, tinkering, and troubleshooting.

Table 2: Respondents' pre-college engineering participation

	Number	**%**
PCE Type		
High School Class	265	64%
Afterschool experience	110	27%
Middle School Class	71	17%
Other	81	20%
PCE Programs		
PLTW in High School	92	22%
FIRST Robotics	32	8%
PCE Content		
Working on a team	240	58%
Presenting a Project	218	53%
Tinkering	160	39%
Troubleshooting	159	38%
Design Process	132	32%
Engineering with Math	130	31%
Research on an Engr Topic	105	25%

To examine responses to the items related to transition from pre-college to first-year engineering, Exploratory Factor Analysis (EFA) was used. This analysis was performed using SPSS v24 in multiple different ways to assess the robustness of the results and to explore alternative underlying conceptual models. Principal Axis Factoring was utilized to determine the factors, along with oblique rotation (‘Oblimin with Kaiser Normalization’). Oblique rotation was chosen to allow for correlations between the factors, which would be expected based on the theoretical framework underlying the instrument. Initial analyses involved identifying items that were either highly correlated (>0.5) or loaded strongly on multiple factors. After removing these items, the results presented here are based on running the EFA with 34 items, all respondents included, and using an oblique (‘Oblimin with Kaiser Normalization’) rotation. The KMO statistic for this analysis was 0.868, which is well above established cut-offs.

Exploratory Factor Analysis identified eight coherent components of students’ experiences of the transition from pre-college to university engineering programs, and suggest that some aspects of the transition that are included in a single category of description in the outcome space that emerged from the qualitative data are more independent than that model would suggest. Table 3 summarizes the factors, their connection to a category of description identified in the theoretical framework, and the amount of variance explained by the factor. The structure matrix, consisting of a full list of the items along with the factor loadings, is shown in Appendix A.

Table 3: Summary of factors identified using EFA

Factor	Primary Alignment	Eigenvalue	% of Variance	Cumulative % of Variance
1. Connection	Connection	6.40	18.83	18.83
2. Engaging Others	Engaging Others	4.24	12.48	31.31
3. Frustration	Frustration	2.96	8.72	40.03
4. More competent than peers	Tedium	1.80	5.29	45.31
5. Foreclosure	Foreclosure	1.60	4.71	50.02
6. Less Challenging	Tedium	1.27	3.74	53.76
7. Seeking Other Engineering	Tedium	1.01	2.96	56.72
8. Less Hands-on	Frustration	1.00	2.94	59.67

The first factor, which explains 18.8% of the variance in the responses, draws from instrument items that emphasize positive connections between pre-college and first-year engineering experiences. The most heavily weighted items for this factor were derived from the *connection* category of description from the theoretical framework, including feeling better prepared for first-year engineering, better able to overcomes challenges, and more confident at being successful in first-year engineering due to having positive pre-college engineering experiences. The second factor, which explains 12.5% of the variance, aligns directly with the category of description *engaging others* from the qualitative data analysis. This factor included weightings on all factors derived from that category of description, and placed the heaviest weights on listening to teammates and recognizing value and incorporating their ideas when doing engineering design. The third factor, which explains 8.7% of the variance, aligns with experiencing *frustration* in the transition from pre-college to university engineering identified in the qualitative portion of this study. Aspects of frustration weighted most heavily by the factor analysis focused on respondents believing that their pre-college engineering activities were more like real engineering and feeling stronger sense of connection to their pre-college engineering teammates. The fourth factor of the EFA, which explains 5.2% of the variance, aligns with an aspect of *tedium* from the theoretical frameworks and captures respondents feeling more competent than their peers in performing engineering tasks. Items included in this factor are respondents feeling like they were more capable of solving open-ended design problems, did more of the work in their group, and that group designs were primarily based on their ideas. The fifth factor, with 4.7% of the variance, aligns directly with the category of description *foreclosure* from the qualitative data analysis. Heavily weighted items for this factor included feeling trapped in engineering, majoring in engineering because of others' expectations, and feeling a lack of belonging in engineering. The sixth factor, explaining 3.7% of the variance, aligns with another aspect of experiencing the transition as *tedium* from the theoretical framework and is composed of items focused on first-year engineering being less challenging and having lower expectations than their pre-college engineering activities.

Although factors seven and eight each explain approximately 3 percent of the variance in the data and have eigenvalues greater than one, they are each theoretically problematic. Factor seven primarily draws from a single item: "I have sought out other opportunities to do engineering at the university or in the community outside of my engineering courses." Factor 8 draws from items related to frustration at the lack of hands-on activities in first-year engineering, however these items are also included in the third factor that captures these as well as other items related to experiencing frustration in the transition from pre-college to first-year engineering.

These results suggest that ways of experiencing the transition that informed the development of the *tedium* category of description are more independent of each other than the qualitative results suggested. Factors 4,5, and 7 each capture aspects of experiencing tedium in the transition from pre-college to first-year engineering, but their identification as independent factors suggest that they are not necessarily as grouped as our interpretation of the qualitative results suggested.

Conclusions

Recognizing the different ways that students experience the transition from pre-college engineering to university engineering programs has important ramifications for the developers, teachers, and facilitators of pre-college engineering programs, first-year engineering course designers and instructors, and educational policymakers.

Foremost for first-year engineering instructors and course designers is recognizing that they should not consider their students *tabulae rasae* with regards to their knowledge of engineering. Students are arriving in first-year engineering programs with a wide variety of pre-college engineering experiences, and these experiences can significantly affect their success and sense of belonging in first-year engineering programs. This suggests a need for first-year engineering instructors to consider differentiation strategies to accommodate the diverse backgrounds and preparation of their students. These strategies could include considering pre-college engineering experience when forming student teams or developing and utilizing pre-assessments to measure students' baseline engineering knowledge as a tool for tailoring instruction.

Tailoring instruction based on pre-college engineering experience is complicated by the preliminary findings of this study that suggest that students experience the effects of similar pre-college experiences very differently in their first-year engineering courses. For example, while some students may find that being familiar with an engineering design process or technical skills such as programming increases their confidence and ability to learn this material in a first-year engineering course, other students may be disengaged and less motivated when learning material that they feel like they have already been exposed to or mastered. Ultimately, first-year engineering instructors and curriculum developers need to know their students and their experiences, and work with their students to create educational activities that are meaningful for the students and promote their continuing development as engineers.

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Appendix A: Items and Factor Weights

Item	Factor 1	2	3	4	5	6	7	8
My pre-college engineering experiences helped me learn how to overcome the challenges I have faced in university engineering.	0.738							
I am better prepared for university engineering because I participated in engineering program and activities prior to university.	0.736		0.305				0.323	
Participation in pre-college engineering programs has helped me to overcome frustration that I have experienced in my university engineering program.	0.72							
Learning similar content in my pre-college engineering classes and activities has helped me to be more successful in my university engineering courses.	0.703						0.342	
My experiences with engineering prior to university taught me what to expect in a university engineering curriculum.	0.699						0.34	
Working on an engineering team before coming to the university has helped me to work on a team as part of my university engineering classes.	0.644		0.368					
I can solve open-ended problems with more than one right answer because I solved these kinds of problems in my pre-college engineering activities.	0.609							
Engineering design in my university courses is similar to the engineering design that I did in my pre-college engineering classes and activities.	0.553					0.355	0.313	
My experiences with engineering prior to university prepared me to understand the role and importance of mathematics to engineering.	0.548							
If I didn't participate in pre-college engineering programs, I probably wouldn't be in engineering right now.	0.445							0.328
It's important to listen to your teammates when doing engineering design.		0.737						
It's useful to have multiple perspectives/lots of peoples' ideas when doing engineering design		0.691						
I like helping other people on my team to be successful.		0.673						
I am patient with other peoples' ideas, even if they're different than how I would approach a problem.		0.667						
I incorporate ideas and feedback from my teammates when we are working on an engineering design problem		0.657						
Compromise is an important part of the engineering design process.		0.632						
I am comfortable working with people who are different than me.		0.598						

Note: Factor weights <0.3 not shown for clarity

Appendix A: Items and Factor Weights (cont)

Item	Factor 1	2	3	4	5	6	7	8
I am less motivated to do my university engineering projects than I was when I was working on my pre-college engineering projects.			0.727		0.302	0.341		
The pre-college engineering activities I participated in were more like real engineering than what I am doing now in university engineering.	0.339		0.649					
I felt a stronger sense of connection to my teammates or classmates in my pre-college engineering experiences than in my college engineering classes.			0.564					
University engineering courses are less welcoming than my pre-college engineering experiences.			0.563					0.356
I am frustrated by the lack of hands-on projects and activities in my engineering courses.			0.536					0.662
Based on my pre-college engineering experiences, I thought engineering in college would be more hands-on.			0.512					0.682
I tend to do most of the work on my team's engineering design projects.				-0.764				
Most of my team's designs are based mostly on my ideas.				-0.683				
I am more comfortable than my peers solving open-ended problems that can have more than one right answer.				-0.45				
I majored in engineering because I was expected to.					0.688			
I am mostly studying engineering because of the influence of other people.					0.681			
I chose engineering as a major because I didn't know what else to do.					0.625		-0.421	
I'd rather be studying something besides engineering.					0.581			
My university engineering courses are less academically challenging than my pre-college engineering classes and activities	0.345		0.348			0.745		
I don't have to work as hard in university engineering classes as I did in my pre-college engineering programs and classes	0.311		0.313			0.699		
I have sought out other opportunities to do engineering at the university or in the community outside of my engineering courses.	0.322						0.595	
I would rather be doing things with my hands than learning theory.								0.56

Note: Factor weights <0.3 not shown for clarity