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Comparing Complexities of the Understanding of the Engineering Mindset between First-Year and Capstone Students

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Comparing Complexities of the Understanding of the Engineering Mindset between First-Year and Capstone Students

Abstract

The Engineering Mindset (EM) refers to the values, attitudes, and thinking skills associated with engineering. It is especially important for undergraduate engineering students to understand the Engineering Mindset as it can help those students tackle the challenges they will meet in their professional lives. To examine how well students have been able to understand the Engineering Mindset, students in a first-year engineering course and a multidisciplinary engineering capstone course were asked to make a concept map about the Engineering Mindset. The prompt asked students to complete a concept mapping exercise to benchmark their knowledge about Engineering Mindset that is required in the Engineering Design or Product Development Process. The students were asked to implement a visual representation of ideas for the Engineering Mindset using concept maps, and then the concept maps were scored on the complexity of the students' understanding of the topic using the traditional concept map scoring method. This method scores concept maps using the number of concepts, the highest hierarchy of the map, and the number of connected concepts between concept branches. The traditional scoring method was completed manually and through an automated tool to compare the scores between the two methods. The purpose of this paper is to examine the difference in understanding of the Engineering Mindset between first-year students and capstone students and understand complexity differences amongst themselves. This paper also includes an examination of how well an automatic scoring program can score concept maps and its potential uses in scoring maps from a large number of students.

Introduction

The development of undergraduate engineering students' Engineering Mindset (EM) has become a primary goal in recent engineering education because it refers to the values, attitudes, and critical thinking skills that are associated with successful and creative engineering designs [1]. Some of the focuses of EM are teamwork, considering real-world problems, coming up with multiple solutions to problems, and balancing criteria and constraints that require trade-offs [1]. It is crucial for engineering students to understand and learn about the engineering mindset throughout their education because it encourages them to innovate, take risks, and become comfortable solving open-ended problems [2]. Integrating EM into engineering programs and has been a recent focus in engineering education, such as integrating it into faculty members (e.g., [3]), engineering students (e.g., [4]), engineering courses (e.g., [5]), and classroom activities and projects (e.g., [6]).

To better understand how well students conceptualize EM, faculty in the Department of Engineering Education at The Ohio State University created an assignment to investigate how well students understand EM and what concepts they relate to it. Note, this university uses the KEEN framework to describe EM, but rather than using the word "Entrepreneurial" they have used "Engineering" in some courses to help students understand that the skills involve more than just the business aspects of engineering design [7]. This assignment was given to both a first-year engineering course and a multidisciplinary engineering capstone course. The primary goal of this study is to compare the concept map complexity scores between the two engineering courses, a first-year course and a capstone course, and to investigate the accuracy and limitations of an automatic concept map scoring program in calculating these scores.

Background

A. *Concept Maps*

Concept maps are a complex tool to visually represent how complex ideas connect. While there are other ways to visualize ideas including charts, graphs, and flowcharts, concept maps are useful for representing how a main topic connects with other ideas and concepts. Concept maps have been integrated in engineering education at various levels, such as in classrooms to describe how course topics relate or in engineering programs for faculty to describe how topics of the program are connected [8]. Additionally, concept maps are simple to introduce to students and create, requiring minimal time to teach and integrate into an activity [9].

Concepts are defined in this study as ideas that are connected by linking words and phrases. Attached to these concepts are linking words and phrases. Linking words connect the central concept to the branching concepts or branching concepts to each other. A few examples of linking words are “causes”, “includes”, and “requires.” Concept maps contain a hierarchical structure between concepts and cross-links between different branches within this hierarchical structure. Cross-links are relationships between concepts in different branches of the hierarchy structure. They can show how different branching concepts are interlinked between each other. Cross-links facilitate creative thinking and show additional complexity by understanding how different branches of topics relate [10]. The hierarchical structure is usually structured to show the thought process of the person making the concept map. Typically concept maps are considered more complex if they include more concepts, make deeper hierarchies, and add cross-links between branches. Different scoring techniques exist for evaluating how well people understand a concept through scoring or weighting parts of a concept map in different ways, which can help instructors and researchers measure understanding of a topic [11].

B. *Traditional Scoring Method*

The traditional scoring method requires individuals to quantify and score the different components of each of the concept maps. The different components include the number of concepts on the map (NC), the highest level of the hierarchy (HH), and the number of cross-links (NCL). The definitions used for scoring are provided below.

> Number of Concepts (NC): The number of concepts (other than the central concept) that are connected to the central concept directly or indirectly through other concepts.
>
> Branch: Each concept directly connecting to the central concept is considered its own branch, where any concepts connected to the central concept through this concept are considered in the same branch. In cases where branches overlap, the researchers must decide which branch a concept better fits under.
>
> Highest Hierarchy (HH): The number of concepts deep the longest branch has. For cases where multiple paths from one concept in a branch to the first concept in that branch that connects to the central topic, the shortest path to connecting each concept to the central concept was used.

Number of Cross-Links (NCL): The number of connections between two different branches.

The formula below is used to determine the total complexity score of the concept map [10]:

$$Complexity\ Score\ =\ (NC * 1) + (HH * 5) + (NCL * 10) \qquad (1)$$

This equation shows that the complexity it not just based on the size of the concept map (by the number of concepts) but also how deep the maps are and how many different concepts are connected across branches. While the weights for each of these components can differ, these weights are commonly used in scoring concept maps using the traditional scoring method [10]. This equation puts additional emphasis on having a greater highest hierarchy than the number of concepts and even more emphasis on the number of cross-links included in the map. These weights show that the complexity does not evenly consider these three components but more heavily weights how deep a concept map is (through the highest hierarchy) and how well-connected different branches of the concept map are (through the number of cross-links).

Figure 1 shows two examples of simple concept maps to illustrate how this scoring method is used, where the linking words have been removed for the purpose of simplicity. In the left example, the concept map includes three concepts other than the central concept, so the NC is 3. Its longest branch (the left branch) has a length of two, so the HH is 2, and there is one connection between different branches, so the NCL is 1. Thus, the complexity score of this map can be calculated to be 23. Considering the example on the right, the number of concepts is 5, the longest branch (now the right branch) has a length of 3, and there are now two connections between branches, so the NCL is 2. In this example, the complexity score is calculated to be 40.

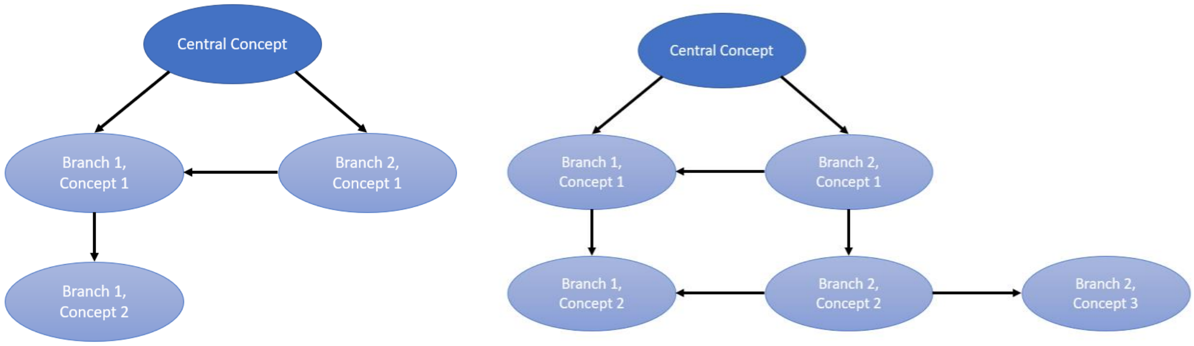

Figure 1: Two example concept maps used to illustrate how to use the traditional scoring method

C. *First-Year Engineering Context*

The first-year engineering (FYE) program at The Ohio State University is a two-semester sequence where all students, regardless of engineering major, enroll in the course. The version of this course that this assignment was given in was an honors section of the first-semester course with 35 students. This honors section included both engineering and business students (who are pursuing an engineering minor). The first-semester course focuses on problem solving and programming, and the second-semester course focuses on engineering design.

Students were given the concept-map assignment at the end of the first-semester course in Autumn 2021. This assignment was given before the students were exposed to completing a user-centered design process in the first-year engineering course. The assignment was introduced in class as part of an introduction to design and students could complete the map in-class or for homework. The Engineering Mindset 3 C's (curiosity, creating value and making connections) were not explicitly discussed with these students prior to making the concept maps.

D. Multidisciplinary Capstone Context

The capstone course that was used in this study was a multidisciplinary capstone program. The program is a two-semester sequence that is offered every academic year to senior engineering students meeting the prerequisites for the capstone course. Capstone is a required course for all engineering majors to meet their major program requirements. The multidisciplinary capstone (MDC) is an option for engineering students to take as substitution credit for their respective program's capstone course. MDC is offered to all 14 engineering majors across the College of Engineering. In addition to engineering majors, MDC is offered to the College of Engineering's Engineering Science Minor students to fulfill the minor's capstone collaboration requirement. These students are non-engineering students who have completed the College's first-year engineering course sequence and other introductory engineering courses to cap off the minor with the capstone collaboration course sequence. MDC has an annual enrollment of 60–80 students for the 2-semester course sequence.

The engineering mindset was introduced to MDC students in the autumn course in Autumn 2021 as a lecture presentation and as in-class activities related to the students' team sponsored capstone projects. The Engineering Mindset 3 C's (curiosity, creating value and making connections) were discussed in terms of how these concepts could be implemented into their project design and implementation. The section included both engineering majors and non-engineering majors that were pursuing an engineering minor and had completed the first-year engineering sequence. During week 2 of the Spring 2022 semester, students were assigned to complete a concept map for points for the course. Concept maps were introduced along with the research study in class. The instructors gave the students four days to complete the assignment and submit their concept map.

Methods

A total of 81 concept maps were collected from both of the courses, 28 from the first-year honors engineering course and 53 from the capstone engineering course. Only concept maps from students who opted to allow their concept maps to be used in this research were collected. These concept maps were anonymized so that we would not be able to connect any concept map to a given student, only which course they were collected from.

We used the traditional scoring method the score these concept maps. The manual scoring method was conducted to all concept maps by two researchers. When conducting manual scoring, we met and discussed any differences in scores to decide whose interpretation best matched the intent of the scoring in order to ensure consistency in scoring. Each different score was discussed until the researchers came to an agreement, so both researchers ultimately agreed to the scores of all concept maps. Once all scores matched, the manual scoring was considered completed.

Additionally, each concept map's score was calculated automatically using a concept map scoring software [12]. This program calculated each of the components (NC, HH, and NCL), as well as the final score for each concept map. While scoring was similar between the manual and automatic scoring methods, because it is not entirely objective whether some concepts belong in one branch or another when a concept is connected to both, there were some differences between the manual and automatic scoring in what branch some concepts belonged in, therefore the two scoring methods resulted in different scores. The purpose of using the automatic scoring program is to decrease the time taken to score each map while hopefully having small or no differences in the actual score calculated. Ultimately, the data collected in this study was the number of components and final scores for both the manual and automatic scoring of each concept map.

Of the 81 concept maps collected, 1 of the files was corrupted, so only 80 concept maps were manually scored. Additionally, the automatic scoring program did not calculate a complexity score for 7 of the concept maps due to an error where the program did not score maps that had a single concept branching off of the main concept not connected to any other concepts. To analyze the data collected, we performed a two-sided t-test to determine if there was a significant difference between the final scores of the first-year and the multidisciplinary capstone students in their concept maps. Additionally, a paired t-test was performed to compare the manual and the automatic scoring and determine if the difference in scores between the manual and automatic scoring was significant.

Results and Discussion

A. *Comparing Complexity Scores Across Courses*

Table 1 includes details on the complexity score mean, standard deviation, and each of the average components across students for both courses. A two-sample t-test was conducted to analyze the complexity scores of the two courses with a p-value of 0.1647. These results show that while the first-year course had a higher average complexity score, the difference was not statistically significant. Considering the data for the different components of the score, the capstone students included approximately 1 more concept on average but had about 1/3 shorter HH and about 1 NCL fewer on average. Because the HH and NCL were more heavily weighted, the capstone students had a lower complexity score on average.

Table 1: Statistics for the complexity scores for both courses

Course	N	Mean	Std Dev	Average NC	Average HH	Average NCL
FYE	27	63.778	44.369	14.70	3.96	2.93
MDC	53	50.547	27.389	15.64	3.58	1.70

To better visualize the scores across both courses, Figure 2 includes a box and whisker plot and Table 2 contains the quartile data for this plot. As seen in the figure, while the first-year students have a higher average score, there is a large outlier that would increase the average of the scores greatly. This figure also shows that the middle 50% of each course was approximately the same. As seen in Table 2, the median scores between the two courses only differed by 5 points, smaller than the difference in average scores.

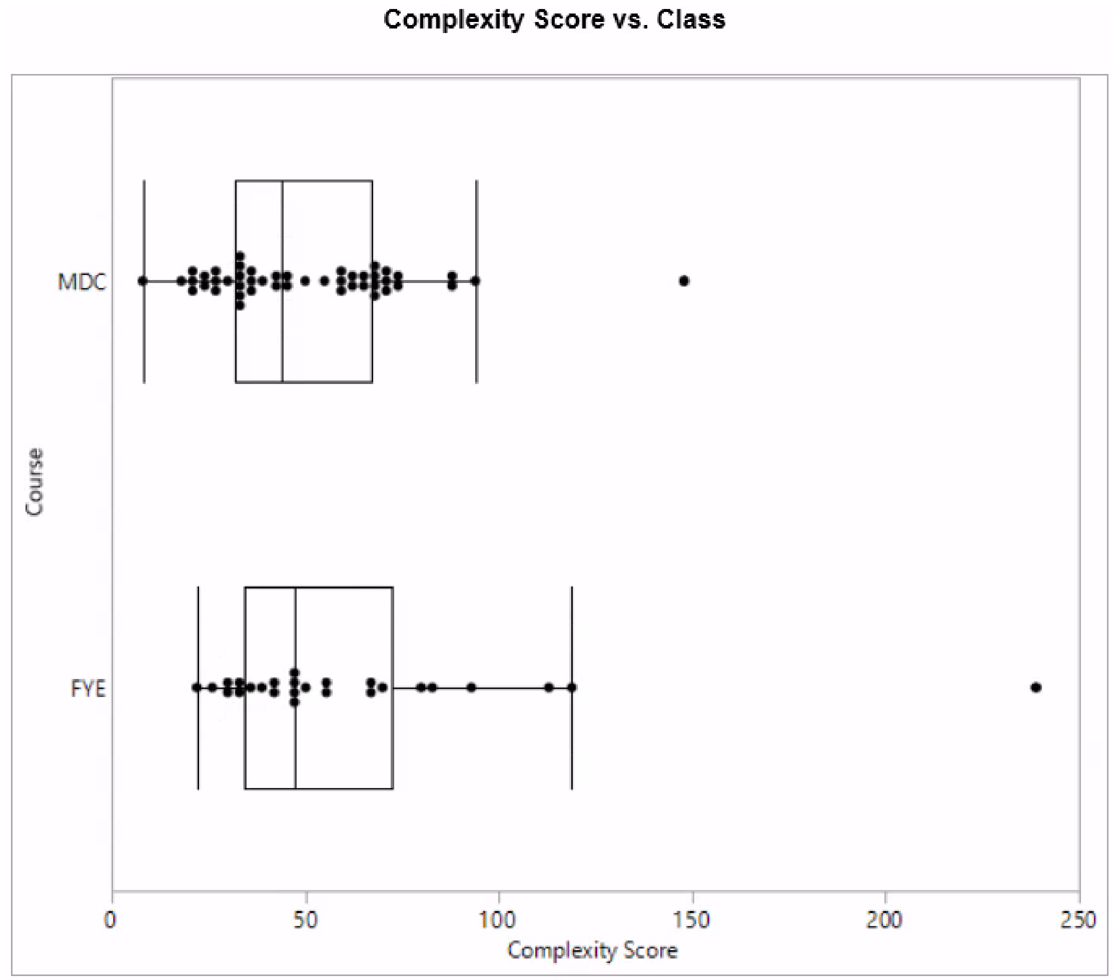

Figure 2: Box and Whisker Plot of Complexity Scores of the Different Courses

Table 2: Quartile data for each course complexity scores

Course	N	Min	25%	Median	75%	Max
FYE	27	22	35	48	80	239
MDC	53	8	31	43	68	148

The differences between these two courses may be related to how and how often EM is discussed to these students. At this university, EM has been heavily integrated and discussed in various aspects of the first-year program and the capstone courses, however not many middle year courses have integrated it into their coursework or explicitly discussed it. These results may show evidence that what students learn and understand about EM is consistent or decreases slightly before their capstone year. Additionally, the differences observed may relate to the effort students put into the assignment. Because the scores depended on the number of concepts, the longest branch length, and the number of connections, the more time and effort a student put into the assignment, the higher their score may be. While we cannot conclude why these differences existed, the FYE students on average had fewer concepts than MDC students but deeper and more connected maps. The data appears to suggest that FYE created more complex maps that focused on the relationships between fewer concepts while MDC students had less complex maps and focused more on the number of concepts and less on their relationships. If these differences exist because capstone students have not interacted with EM during their second and third year courses, additional focus on this material could help to strengthen and support students' understanding of EM throughout their entire undergraduate engineering program.

B. Comparing Automatic and Manual Scoring

Figure 3 shows a histogram of the percent differences between the automatic and manual scores. The average percent difference was 8.0% and the standard deviation was 16.3%. While the difference in percent differences between the two scores was significant with a p-value less than 0.0001, this result does not mean that the automatic scoring does not have utility in calculating complexity scores of concept maps, as being able to estimate a score may still have value to instructors measuring scores for their students. This histogram shows that the majority of scores, about 56%, had no difference between the manual and automatic scores. Additionally, 75.3% of scores fell within one standard deviation of 0 between -16.3% and 16.3%).

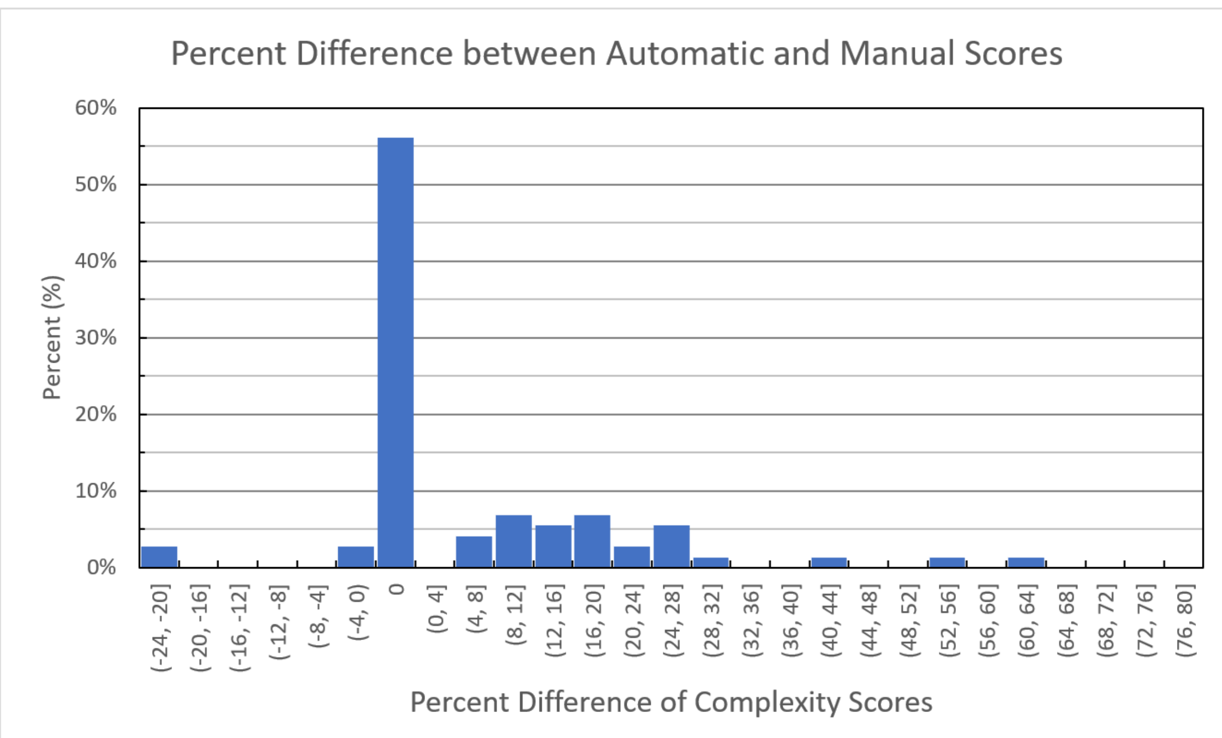

Figure 3: Histogram of Differences between Automatic and Manual scoring methods

While the automatic scoring did not always match the manual scoring, it still has potential use for instructors wanting to score concept maps their students make. Manual scoring took much more time for both researchers to score 80 concept maps and come to a consensus on each score. Automatic scoring was able to be completed in a fraction of the time and could scale for even larger classes with more students much better than manually scoring each concept map. Because the purpose of scoring these concept maps is to get an idea of how complex someone's understanding of a concept is and how different related concepts connect, the automatic scoring method could be used to have an efficient way to calculate a complexity score for concept maps.

Conclusions & Future Work

First, we explored the understanding of EM between first-year engineering and multidisciplinary engineering capstone students to examine how well students understand the concept of EM. There was not a statistically significant difference between the two courses despite the first-year students having a slightly higher complexity score. We cannot conclude why this difference existed and it may be helpful for future research to more specifically measure EM understanding through other methods or to examine EM understanding longitudinally to examine how it may change throughout an undergraduate engineering program.

Additionally, we explored how accurately an automatic scoring program was in calculating the concept map scores compared to our manual scoring. The automatic scoring program had a statistically significant difference to the manual scores, tending to score the concept maps higher than the manual scores. The automatic scoring tool provided a decent estimate to how complex each of the maps were, allowing us to estimate the scores with an average difference of 8%. A tool that can automatically score concept maps could still be very useful to instructors that either score concept maps from many students or score concept maps at multiple occasions during a course.

Faculty members can use concept mapping to both measure their students' understanding of course topics by having them draw and explain how the concepts connect. This tool can help instructors identify what concepts and connections students understand well and which need additional clarification as to how they connect to course material. While the complexity score does not help measure accuracy of maps, it can allow instructors to measure growth from the start to the end of a course or topic within a class or to measure differences in courses as they make adjustments to their course between semesters. Instructors may use average complexity scores to determine if a review session or additional lecture on how the course material connects to topics may be necessary, and if the class size is large or the professor does not have the resources to individually grade each of the concept maps, the automatic scoring method is a quick and simple way to get a general understanding of the class's understanding as a whole. We would not recommend using concept map scores in a way where a specific score matters, so having a tool that can estimate the score could still be useful. For future research, it may be useful to reexamine this tool to determine the bugs that prevented it from scoring some of the maps or in exploring other methods to automatically score concept maps and comparing its results to manual scoring to ensure it is accurate in calculating the complexity score.

One limitation of this study is that the complexity of the concept maps that students created depends on the effort they put into the assignment. One set of students may have put more or less effort into the assignment than the other, however this study was not designed to measure how much effort they put into the assignment. Future work could implement other forms of concept mapping (such as fill-in-the-blank concept maps, e.g., [13]) that may have a more uniform amount of effort put in due having a specific number of concepts that students need to fill in without being able to add additional concepts. Another limitation is that the two sets of students may have been introduced to EM at different times before the concept map assignment. This limitation may cause some students to remember or understand EM more or less depending on the timing of the material. Future work could look at growth over time through a longitudinal study to measure how the complexity of understanding EM develops over time.

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