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Enhancing Understanding and Retention in Undergraduate ECE Courses through Concept Mapping

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Abstract

Concept mapping is well recognized for its effectiveness in promoting deep learning and aiding students in understanding knowledge acquisition in complex subjects. In undergraduate ECE courses, instructors usually present topics one by one, followed by examples and applications. Instructors can easily navigate all course information due to their well-established understanding of the entire course and the connections between its topics. However, students face the challenge of establishing the connection between their existing knowledge and the new concepts and reinforcing those connections through repeated practice.

In this work, we introduced concept mapping as an assessment tool to help students build these links and enhance their learning experience. The goal is to improve students' comprehension, retention, and interconnectivity of complex course topics. We have systematically integrated concept mapping into four distinct courses: a freshman course about electronics (ECE 110), a sophomore course about signal processing (ECE 210), and two junior-level courses about electromagnetics (ECE 329) and green energy (ECE 333). In each course, students were asked to create their own concept maps before midterm exams. The maps were scored qualitatively by the instructor based on the number of concepts and their structures. This exercise was designed to encourage students to consolidate their knowledge and foster a deeper understanding of the course material by visualizing and summarizing the relationships between key topics. This type of active learning also empowers students to take ownership of their learning by creating and revising their concept maps.

A fundamental aspect of our course improvement work involved gathering feedback from students regarding their perceptions of the effectiveness of concept mapping in these courses. In each course, a survey was administered at the end of the semester to gauge students' experiences, opinions, and reflections. Our findings from the surveys indicate that concept mapping is perceived positively by a significant proportion of the students, especially if it's actively used as an instruction tool during the semester. Students reported that concept mapping enhanced their understanding of the course material.

Introduction

The field of electrical and computer engineering (ECE) education is always in need of dynamic and engaging teaching methods. However, traditional lecture-based approaches often fall short.

While they offer structure, their presentation of one topic at a time can make it difficult for students to form connections and logic between topics. It's difficult to 'see' the complete picture and understand the intricate connections among concepts. Furthermore, this type of passive learning through lectures may not be sufficient to engage students. It can also limit the student's active participation and negatively affect their depth of comprehension. As the field progresses and technology advances, there is an urgent demand for pedagogical strategies that foster deeper understandings and encourage active engagement among students.

Concept mapping was developed by Joseph D. Novak and his colleague Alberto J. Cañas in the 1970s at Cornell University, when Novak was seeking to understand children's knowledge of science [1, 2]. The theoretical foundation of the concept map is Ausubel's theory of meaningful learning [3, 4]. This theory emphasizes the importance of students actively linking new information to their existing knowledge [5, 6]. Concept maps serve as a visual tool that aligns with this principle, fostering meaningful learning by facilitating the connection of knowledge in a clear and structured way.

Concept maps may benefit the classroom not only as a learning tool but also as an evaluation tool [1, 6]. Concept maps typically consist of concepts enclosed in circles or boxes, connected by lines that indicate relationships, with linking words or phrases articulating the nature of these connections [1]. Figure 1 below uses a concept map to illustrate the key features of concept maps.

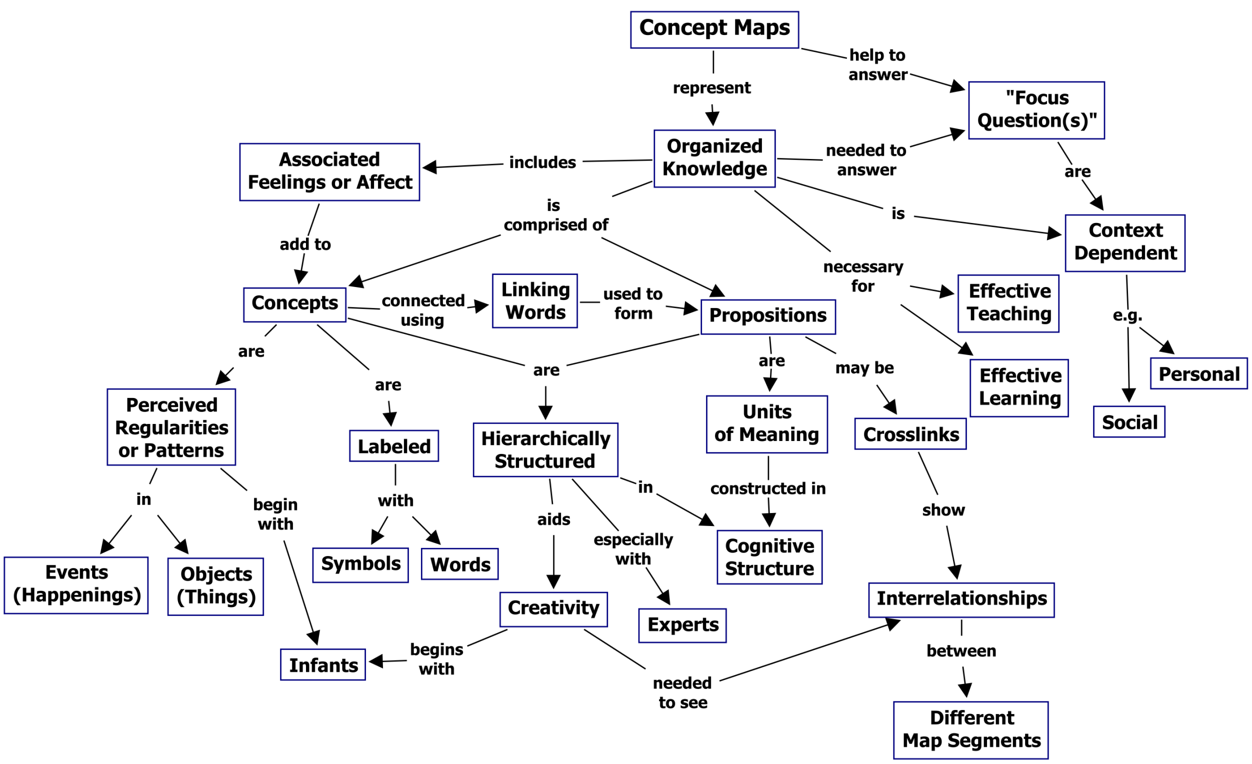


Figure 1: A concept map about concept maps [1, 7].

There are three key features of concept maps: concept selection, hierarchical structuring, and cross-links [1]. The first unique characteristic of a concept map is the selection of *concepts* or *topics*. Selecting concepts or topics for a concept map involves a thoughtful consideration of the topic. A few things that might be considered are course learning objectives, key concepts, syllabus, course content, etc.

The second notable characteristic of concept maps is their *hierarchical structure*. Some commonly used hierarchical structures include:

- Top-Down Hierarchy: In this structure, the most general concepts are placed at the top, with increasingly specific concepts branched below. This structure provides a clear and organized view of the topic.
- Bottom-Up Hierarchy: This structure starts with specific details or examples at the bottom, leading to more general concepts at the top. It is useful when you want to build understanding from concrete examples to abstract principles.
- Radial Hierarchy: Radial concept maps have a key concept in the center, with related concepts branching out in a radial fashion. This structure is useful when exploring concepts around a central idea.
- Lateral Hierarchy: In lateral hierarchies, concepts are arranged horizontally, with relationships extending from left to right. This structure is helpful when concepts have equal importance or when exploring a sequence of events.
- Nested Hierarchy: Nested hierarchies involve placing concepts within categories or nested structures. Nested hierarchy is exemplified in Russian matryoshka dolls. Each doll is nestled in another bigger doll. This structure is useful when dealing with complex topics with layers of detail.
- Circular Hierarchy: Circular concept maps arrange concepts in a circular or spiral pattern with the key topic in the center. There can be layers of circular concepts, which are then connected with cross-links between them. This structure is suitable for representing cyclically interconnected topics.
- Network Hierarchy: Networked hierarchies are a more advanced way of constructing concept maps. In this structure, connect concepts are represented as nodes and connected with lines or arrows in a network rather than in a strict top-down or bottom-up way. This structure is effective for showing the interconnections in a complex network.
- Combination Hierarchy: Some concept maps may use a combination of hierarchical structures, especially when dealing with multifaceted topics. For example, a central top-down hierarchy may have lateral or nested structures within specific branches.

The third effective characteristic of concept maps is using *cross-links*. These cross-links aren't limited to neighboring concepts but can bridge concepts across different sections or even entire domains. Creating such cross-links requires creative ideas in knowledge production, which can contribute to creative thinking and deeper insights.

Concept mapping is now a popular tool in education for enhancing teaching and learning across a range of subject areas, including science, math [8], social studies, and literature [9, 10]. Daley

[11] and Harris [12] [13] showed that concept mapping was an efficient tool for enhancing students' critical thinking skills in fields that involve complex information or multiple interrelated concepts.

Concept maps can also be used to identify the way students ”see” or understand the relationships between knowledge. Extensive research has demonstrated the effectiveness of using concept maps to promote meaningful learning [14–16] and problem-solving skills among students.

Methodology

The methodology used to evaluate the effectiveness of using concept maps is separated into two phases. Phase one was in a senior-level elective Electromagnetic Compatibility (EMC) course. The emphasis was on evaluating the effectiveness of concept maps. In phase two, three instructors across four undergraduate-level courses were involved. This expansion in scope allowed for a more comprehensive exploration of the impact of concept mapping across diverse courses and academic levels.

Methodology: Phase 1

Concept maps were actively used in the fall 2022 semester in a senior-level course about EMC. The EMC course is composed of a variety of topics, including but not limited to circuits and electronics, signal processing, power systems, electromagnetics, telecommunications, control systems, etc. Because there are so many topics involved, students may find it challenging to grasp the whole idea from such a broad spectrum, so concept maps was used to provide a structured overview.

The first step used was introducing a concept map to students in class, with the goal of helping them navigate between concepts and lectures. However, the maps were not distributed to students after the lecture. The concept map started with the fundamental EMC principle, known as the source-coupling path-victim model. It was used as the root of the concept map tree. Then the map grew in terms of different types of sources, victims, and coupling mechanisms as branches. Each branch was further divided into more specific subtopics. This bottom-up hierarchy structure of the concept map gave students a clear and structured framework of concepts, and it allowed students to quickly identify the key topics and the connections between them.

The second step was to ask students to construct their own maps before each midterm exam and revise them based on instructor feedback. The requirement for the map was to clearly illustrate the connections between topics, and the students had flexibility regarding the format and structure of the map. The instructor provided feedback for each map, and highlighted the areas that needed improvement. The students could revise and resubmit their maps to gain partial credit back. This method promoted active learning and iterative learning. Students continuously improved their understanding of the course material. During the process of building the concept maps throughout the semester, these maps could also be used as study aids for exam preparation. Students engaged in self-assessment as they revisited and refined their maps while identifying gaps in their understanding of the topics.

Methodology: Phase 2

Student feedback from phase one was positive [17], so in spring 2023, concept maps were further introduced to four undergraduate courses. In the ”Introduction to Electronics - ECE 110” course, concept maps were introduced to freshman students for the first time. This 3-credit-hour course serves as an introduction to selected fundamental concepts and principles in ECE, for example, circuits, electromagnetics, communications, electronics, controls, and computing. The course comprises 16 homework assignments, 3 midterm exams, and 1 final exam. Students were asked to construct their own concept maps before midterm exams one and two. The concept map problems were given as extra-credit problems in homework assignments. Students could use the concept map to visually organize and reinforce their understanding of key concepts.

Concept maps were also introduced to sophomore-year students in the ”Analog Signal processing - ECE 210” course for the first time. This course was required for Electrical Engineering and Computer Engineering majors, while students from other majors were only required to complete the first half. The full course comprises 14 homework assignments, 5 laboratory assignments, 3 midterm exams, and 1 final exam. On the other hand, the first half course comprises 8 homework assignments, 1 midterm exam, and 1 final exam. During the spring 2023 semester, 334 students were enrolled in the full course and 31 students in only the the first half of the course.

Concept maps were also introduced to junior students in the ”Green Energy - ECE 333” course for the first time. This elective course, part of the ECE curriculum in the Power and Energy Systems area, offers a comprehensive exploration of renewable energy systems, highlighting technical, economic, and environmental aspects. The course comprises 10 homework assignments, 2 midterm exams, and 1 final exam. In Spring 2023, a total of 88 students were enrolled in the course.

In the junior-level ”electromagnetic I - ECE 329” course, instructors have previously used concept maps as part of their lectures. The course comprises 14 homework assignments, 3 midterm exams, and 1 final exam. Multiple maps were seamlessly integrated into the lecture materials. However, prior to this work, we had not gathered feedback from students regarding their perspective on concept maps. In the spring of 2023, a total of 103 students were enrolled. We collected and analyzed their feedback in order to gain insights into their experiences with concept maps in the course.

In all four courses, students were asked to construct a section of a course concept map before midterm exams. The goal was to encourage the students to establish connections across the covered topics, which may reflect their understandings of the course material. Each instructor in their respective course graded these maps and provided feedback.

At the end of the spring 2023 semester, students were required to provide feedback on the usefulness of the concept Map. In ECE 110 course, student feedback was collected during class time by using iClicker [18]. In ECE 210 which had larger student enrollments, student feedback was gathered through a university feedback survey tool. In the ECE 329 and ECE 333 courses, this feedback was gathered through an anonymous survey conducted via Google Forms. Students were instructed to submit a screenshot demonstrating their completion of the survey to receive credit.

Design survey questions

The survey questions for this work were designed to explore the impact of concept mapping across diverse courses and examine student perceptions in different engineering course settings. The five questions we tried to understand were:

1. In what ways do students believe concept maps are beneficial for gaining a comprehensive understanding of the course content, and how does this perception differ across the range of courses involved?
2. In students' view, are concept maps helpful with their understanding of the interconnections of various concepts in different courses?
3. To what degree are concept maps useful for students who prefer visual learning methods, and how does this perception vary among courses?
4. To what extent do students consider concept maps as helpful tools in preparing for exams across all courses in the study?
5. Finally, if there're statistically significant different mean values of each survey question across the courses, how can these variances be attributed to differences in course setup, content complexity, or other course-specific factors?

To answer these questions, we considered the following survey questions:

1. Are concept maps a beneficial tool for gaining a comprehensive understanding of the course content?
2. Whether concept maps were helpful in preparation for exams?
3. Does concept maps help the students to better understand how different concepts in the course are interconnected?
4. Are concept maps useful for students who learn best through visual methods?

All of the questions were rated on a 5-point Likert scale, ranging from Extremely Not Helpful/Disagree (1) to Very Helpful/Agree (5).

Results

A total of 479 students participated in the survey, in which 26 students were from freshman course ECE 110, 300 students were from sophomore year course ECE 210, and 72 and 81 were from two junior year courses, ECE 329 and ECE 333 respectively.

Figure 2 shows the mean value and standard derivation (SD) for survey question 1, which shows students' perception about whether concept maps is beneficial for gaining a comprehensive understanding of the course content and how this perception differs across courses.

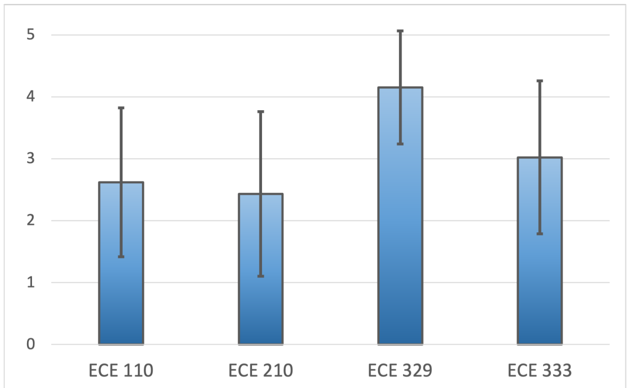


Figure 2: Mean value and SD for survey question 1.

The analysis was carried out using the IBM SPSS Statistics tool [19]. The one-way ANOVA test revealed significant differences in students' responses to this question, with a *p*-value less than 0.01. ECE 329 stood out with the highest mean value of 4.15, indicating that students in this course strongly believed that concept maps were useful tools for comprehensive understanding of course material. This potentially reflected the integration of example concept maps within ECE 329 lectures, which aligned with the course material and potentially created a stronger influence for students. The sample maps were extensively used when summarizing existing topics, explaining the logic of how to solve example problems, as well as introducing new topics. However, ECE 110 and ECE 210 had lower mean values of 2.62 and 2.43, respectively, which suggested a lower perceived benefit compared to the two junior-level courses.

Figure 3 shows the mean value and SD among the four courses to survey question 2: whether concept maps were helpful in preparation for exams.

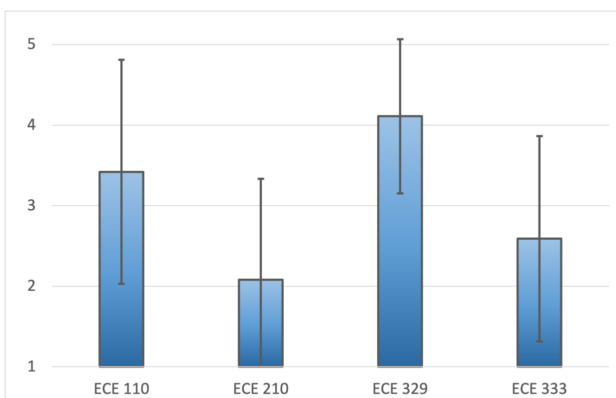


Figure 3: Mean value and SD for survey question 2.

The data indicated significantly different levels of perceived helpfulness in exam preparation across courses. ECE 329 demonstrated the highest mean (4.11), suggesting that students in this course found concept maps significantly helpful for exam preparation. ECE 329 also had a relatively low SD of 0.958, which suggested a more uniform agreement among students that concept maps were helpful for getting ready for exams. All other courses had a similar SD, from 1.255 (ECE 210) to 1.391 (ECE 333). This indicated that students had more diverse opinions regarding utilizing concept maps for exam preparation. In particular, ECE 210 exhibited the lowest mean of 2.08, indicating a lower perceived impact on exam preparation in this course.

Figure 4 shows the mean value and SD among four courses to survey question 3: how useful are concept maps in understanding the interconnection of various concepts in the course?

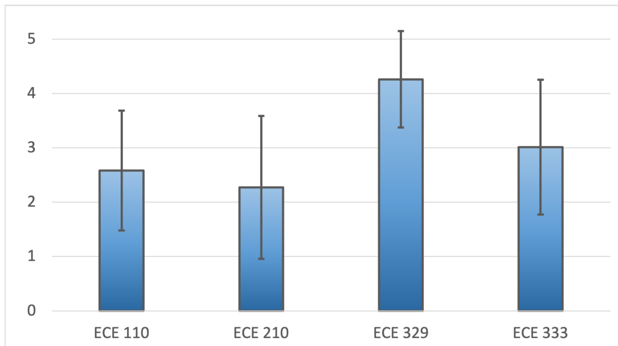


Figure 4: Mean value and SD for survey question 3

ECE 329 stood out with the highest mean value of 4.26 and a low SD of 0.888. This suggested a strong consensus among students that concept maps were useful in illustrating the interconnections of concepts within the course. Conversely, the other three courses exhibited lower mean values with a higher SD from 1.102 (ECE 110) to 1.315 (ECE 210). This indicated a less unanimous perception among students regarding the usefulness of concept maps in understanding interconnections in these courses. The higher SD values implied some variability in student opinions, suggesting a mix of perspectives, especially in the ECE 210 course.

Figure 5 shows the mean value and SD among four courses to survey question 4: Were concept maps useful for students who learn best through visual methods?

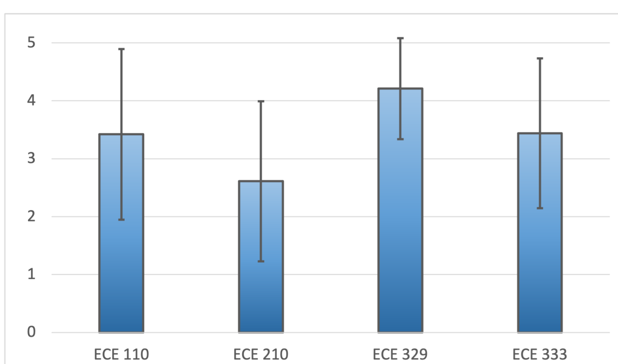
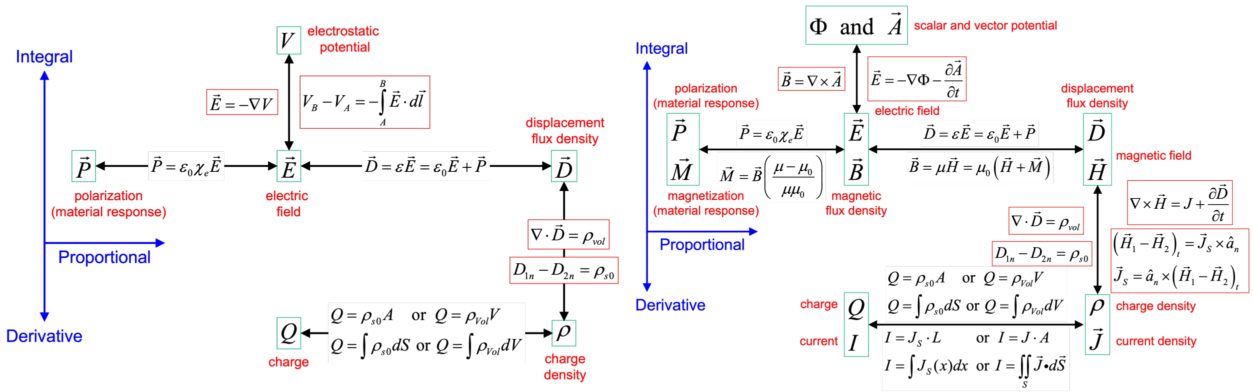


Figure 5: Mean value and SD for survey question 4

ECE 110, ECE 329, and ECE 333 had relatively higher mean values, which suggested that



(a) Electrostatic map

(b) Electrodynamic map

Figure 6: Concept Map used in ECE 329 [20].

concept maps are considered beneficial for individuals who prefer visual learning methods. Conversely, students in ECE 210 gave a lower mean value. This might be influenced since ECE 210 was a heavily math-involved course; thus, the topics may not align seamlessly with visual learning preferences.

Observations

The statistical analysis showed that students' feedback to all four survey questions was significantly different between courses with p-values<0.01. The differences in perceptions across courses may be attributed to variations in course content, structure, teaching methods, etc. ECE 110 and ECE 210 courses were required courses about engineering fundamentals. The lower mean values in ECE 110 and ECE 210 could be attributed to multiple factors. On one hand, freshman and sophomore students might lack experience in how to create and utilize concept maps. Without prior exposure or guidance, it could have impacted their ability to get the maximum benefits from using the concept maps. On the other hand, the instructors didn't provide sample concept maps that related to the course material before giving the assignments. Without explicit guidance from instructors, it might further impact students' ability to utilize it effectively in these courses. Providing a model concept map and clearer instructions could enhance students' understanding and utilization of concept maps in future implementations of these assignments.

On the contrary, ECE 329 and ECE 333 have higher mean values, which suggests a higher perception of concept maps. One key difference in these junior-level courses may be that junior students have prior exposure and training in creating concept maps. Another fact that may contribute to the higher mean values of ECE 329 was that the instructors actively utilized concept maps in teaching concepts throughout the semester. ECE 329 is about electromagnetics and Maxwell's equations. The instructors sequentially introduce concept maps for electrostatic and electrodynamic quantities, followed by incorporating additional elements. Two sample concept maps used in the ECE 329 are shown in Figure 6.

Both maps are built on potential V and **A**, electric field **E**, magnetic field **H**, electric flux density **D**, magnetic flux density **B**, charge density ρ/current density **J**, polarization **P**, etc. The cross-links of the concept maps were represented by the equation between the corresponding concepts. The concept maps utilized the top-down hierarchy structure. Moving from the upper layers to the lower layers, it involved taking derivatives of the quantities. Conversely, when moving from the bottom layers to the top, it utilized integration operations. The concepts at the same level are proportional, in which the proportional constants were related to material properties.

From the students' comments in ECE 329 course, Figure 7 was generated using word frequency analysis. Students in general liked using concept maps and believed they were helpful in active thinking. Many students also mentioned that they would like to have the concept maps in formula sheets, since the instructors provided students with formula sheets during exams. Students had been using the concept maps to study and prepare with them for exams, and they still wanted to have access to them in the exams.

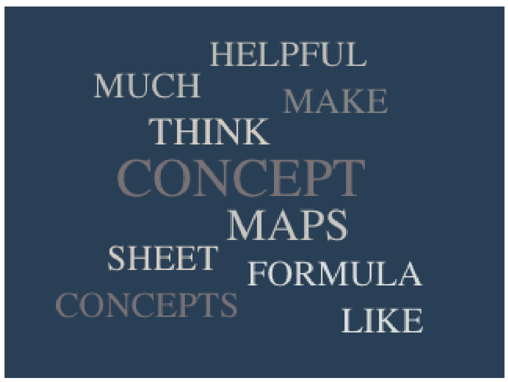


Figure 7: Data visualization based on students' comments in ECE 329 course.

Students also suggested that the instructors had put lots of emphasis on using concept maps before the first two midterm exams, but not much on the rest of the semester. One student commented that they enjoyed the concept map more for the first half of the class and less for the second half where there weren't as many maps provided, and they felt that they understood how various concepts related to each other at the beginning of the semester more than they did towards the end. This implies that increased use of concept maps may contribute to a better understanding of the interconnections between concepts throughout the course. Also, it suggested that there may be a perceived benefit to use concept maps more frequently, particularly during the later stages of the course.

Conclusions

In this work, we evaluated the students' perspectives on using concept maps as a learning and instruction tool over five different courses. Student's feedback on foundational courses like ECE 110 and ECE 210 had lower mean values, suggesting a need for systematically introducing concept maps to freshman and sophomore students. It's possible that these students' ineffective use of concept maps was because of their lack of prior exposure or unclear instruction. It is recommended that instructors offer sample concept maps and more detailed instructions for how to create and use them.

In addition, our results showed that students' feedback in two junior-level courses had higher mean values, especially in the ECE 329 course. The prior training and detailed guidance possibly contributed to the students' enhanced ability to appreciate and leverage concept maps for gaining a comprehensive understanding of the course contents. Particularly, the active integration of concept maps into the instruction process in ECE 329 may contribute to the highly positive perception. The structured approach of introducing concept maps sequentially, accompanied by clear hierarchical structures and detailed cross-links, likely facilitated students' comprehensive understanding of complex topics in the ECE 329 course. These results highlight how customized strategies, previous experience, and clear guidance may maximize the effectiveness of concept maps across diverse engineering courses.

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