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Using Concept Maps to Illustrate the Evolution of Key Concepts: Student Learning Experience in a Foundational Undergraduate Engineering Course

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Abstract

As a graphical tool for knowledge organization, representation, and elicitation, concept mapping has received growing attention and application in STEM (science, technology, engineering, and mathematics) disciplines as an effective instructional strategy to improve student conceptual understanding. This paper reports how the concept mapping approach was employed in a foundational undergraduate engineering dynamics course. In this course, students (rather than the instructor) developed their concept maps to illustrate the evolution of key concepts in engineering dynamics. Data were collected from students who took an engineering dynamics course in recent two semesters: Semester I when concept mapping was not employed and Semester II when concept mapping was employed. The results show that as compared to Semester I, students developed better conceptual understanding in Semester II. Four representative examples of concept maps generated by students in Semester II are presented in this paper. A representative set of student comments are also presented, which demonstrate how the concept mapping approach helped students develop better conceptual understanding.

Introduction

Concept mapping is a graphical tool for knowledge organization, representation, and elicitation. It has received growing attention and application in STEM (science, technology, engineering, and mathematics) disciplines as an effective instructional strategy to improve student conceptual understanding. [1, 2] In concept mapping, concepts are often arranged based on their hierarchical relationships to form a map, so students can visualize relationships among different concepts and understand the "big picture" of relevant topics. As such, concept maps have long been employed as an instructional tool to assess student conceptual understanding in a variety of academic disciplines [3-6], including engineering [7, 8]. For example, Robert et al. [7] employed concept maps to assess student learning in an undergraduate civil and environmental engineering course. The course aimed to develop student understanding of infrastructure and interconnected systems in the civil and environmental engineering course curriculum. Watson et al. [8] employed concept maps to assess student sustainability knowledge. Their ultimate goal was to incorporate sustainability into engineering curricula.

A significant amount of research has been conducted to study how to use concept maps to enhance teaching, learning, and assessment in various courses [9-11], including engineering courses [12-16]. For instance, Pierre-Antoine et al. [12] suggested two approaches that an instructor could use. One approach is to "focus on the overall content of the course and have students outline their overall understanding of the course," and the other approach is to "go after one topic." [12] Triplett et al. [13] suggested a Concept-in-Context approach in an introductory materials course. In their approach, learning topics are characterized and articulated with multiple representations, including "equations, graphs, charts, macroscopic images, microscopic images, engineering components, and historical facts." [13]

Engineering mechanics (including statics, dynamics, and strength of materials) involves numerous foundational concepts and problem-solving procedurals. The objectives of an engineering mechanics course often include conceptual and procedural understanding of course content. For example, for an engineering dynamics course, an important course objective is for students to develop a solid understanding of fundamental concepts, such as Newton's Second Law, the Principle of Work and Energy, the Principle of Linear Impulse and Momentum, and the Conservation of Linear Momentum.

To help students to understand fundamental concepts, a variety of instructional approaches and assessment tools, such as concept inventories [17], computer simulation and animation [18], video games [19], and concept mapping [12, 20-23] have been developed and employed. For instance, Cornwell [23] developed concept maps for students in his dynamics class. He hung concept maps on the classroom wall whenever he gave lectures, so students could see how the concepts fit into the entire course curriculum.

In the present study, students developed concept maps to illustrate the evolution of key concepts in an engineering dynamics course. This second-year undergraduate engineering course is a foundational course that nearly all students in mechanical, aerospace, civil, biological, and biomedical engineering programs are required to take. The course involves numerous fundamental concepts in physics and engineering mechanics and requires students to have solid conceptual understanding in order to solve relevant problems. [24, 25]

This paper is organized as follows. Described first is the method of data collection, which involved two semesters: Semester I when concept mapping was not employed and Semester II when concept mapping was employed. Then, it is described how students in Semester II constructed their concept maps with the aid of a computer software tool. Four representative examples are presented to demonstrate how students in Semester II illustrated the evolution of key concepts on their concept maps. Next, student conceptual understanding is compared between Semesters I and II, followed by representative student comments on their learning experience. Finally, conclusions are presented at the end of this paper.

Data collection

Data were collected from students who took an engineering dynamics course in recent two semesters: Semester I (n=82) when concept mapping was not employed and Semester II when concept mapping (n=71) was employed. The same instructor (i.e., the author of this paper) taught the dynamics class in both semesters I and II, using the same textbook and syllabus. Prior to data collection, all student participants signed a Letter of Informed Consent approved by an Institutional Review Board. In both semesters, students responded to in-class clicker questions after students completed the learning of relevant concepts. Clickers are electronic classroom management systems that provide real-time in-class assessments of student conceptual understanding [26, 27]. In Semester II, students submitted their own concept maps for evaluation and analysis. A questionnaire survey was also administrated at the end of semester II to ask for students' experiences with concept mapping.

Construction of concept maps

In semester II, students constructed their concept maps using IHMC Cmap Tool, a computer software program that is particularly designed for creating concept maps and can be downloaded for free from http://cmap.ihmc.us. [28] The tool has a friendly graphical user interface as shown in Figure 1. It takes only 10-30 minutes for a student to teach him/herself how to use this tool to create and modify his/her concept maps. Graphics and mathematical formula can also be easily added to concept maps.

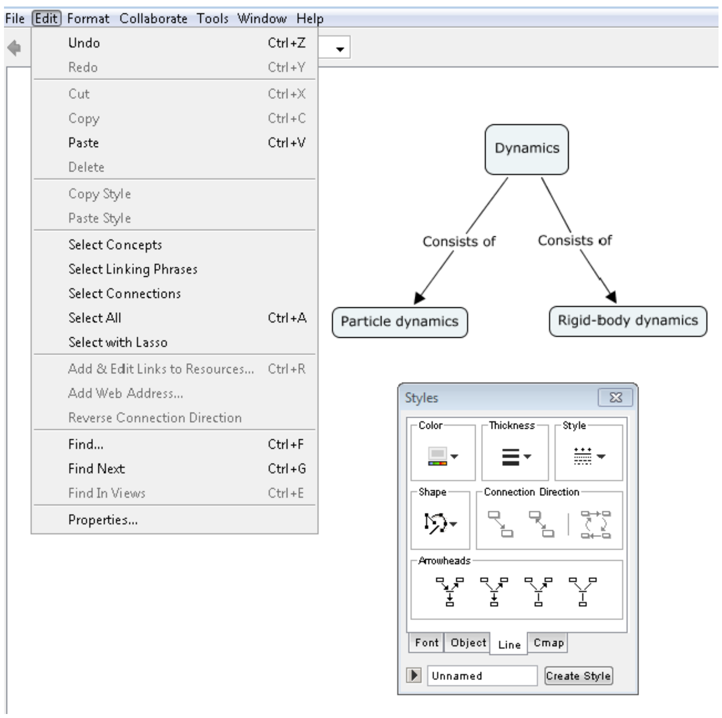

Figure 1. The graphical user interface of the IHMC Cmap Tool [27]

At the beginning of Semester II, the instructor showed example concept maps to the students and explained how the IHMC Cmap Tool could be used to create and modify concept maps. After students learned each textbook chapter, they developed and submitted their concept maps for assessment at the end of each chapter. A questionnaire survey was administrated at the end of the semester to ask about student learning experience with concept mapping. Pretests and posttests were also administrated to assess student conceptual understanding. Pretests were administrated before students learned relevant concepts; and posttests were administrated after students learned relevant concepts and submitted the corresponding concept map that included relevant concepts. To encourage participation, a small course credit was provided to students for each concept map they submitted.

The present study focuses on how students employed concept maps to illustrate the evolution of key concepts in engineering dynamics. The following key concepts are paid particular attention:

- Displacement, velocity, and acceleration
- Newton's Second Law
- Principle of Work and Energy
- Conservation of Energy
- Principle of Linear Impulse and Momentum
- Principle of Angular Impulse and Momentum
- Conservation of Linear Momentum
- Conservation of Angular Momentum

Note that the first three concepts (displacement, velocity, and acceleration) are within the topic of engineering kinematics. All other concepts listed above are within the topic of engineering kinetics. Kinematics and kinetics are two essential components of engineering dynamics. [24, 25]

Representative examples of student-generated concept maps

Four representative examples (Figures 2-5) are presented in this section to demonstrate how students illustrated the evolution of key concepts on their concept maps.

Kinematics

Three important concepts – displacement, velocity, and acceleration – lay a foundation for kinematics. By definition, velocity is the displacement over time (in other words, the time rate change of displacement), and acceleration is the change of velocity over time (in other words, the time rate change of velocity). Figure 2 shows part of a concept map developed by a student that shows evolutionary relationships among displacement, velocity, and acceleration. Mathematical formulas (v = ds/dt and a = dv/dt) are also included in Figure 2.

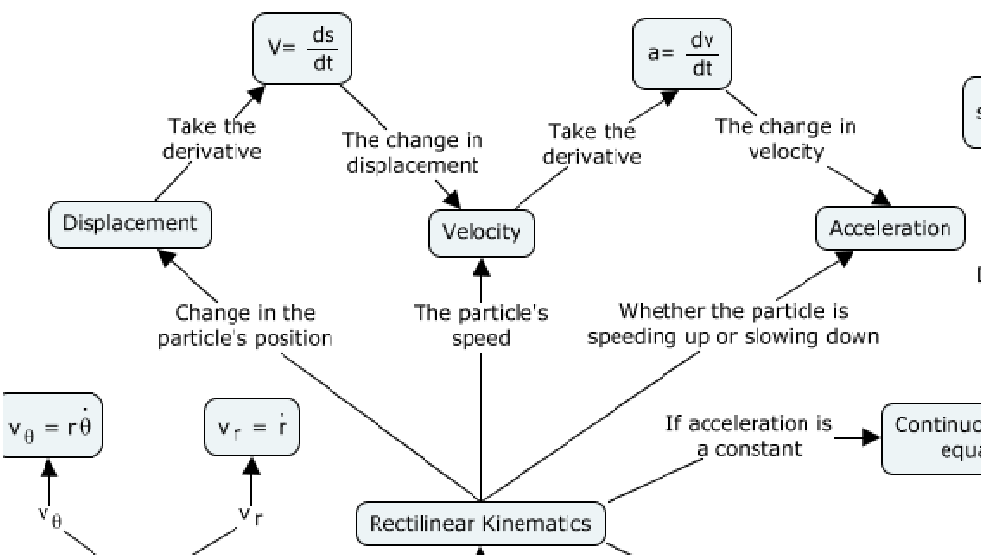

Figure 2: A student-generated concept map example 1: kinematics

Force and acceleration

Newton's Second Law forms the foundation of kinetics because all other principles in kinetics can be derived from Newton's Second Law. It can be applied in three coordinate systems: Cartesian (rectangular) coordinate system, normal and coordinate system, and cylindrical coordinate system. Figure 3, part of a concept map developed by a student, clearly shows the relationship among the three coordinate systems. Mathematical formulas are also included in Figure 3.

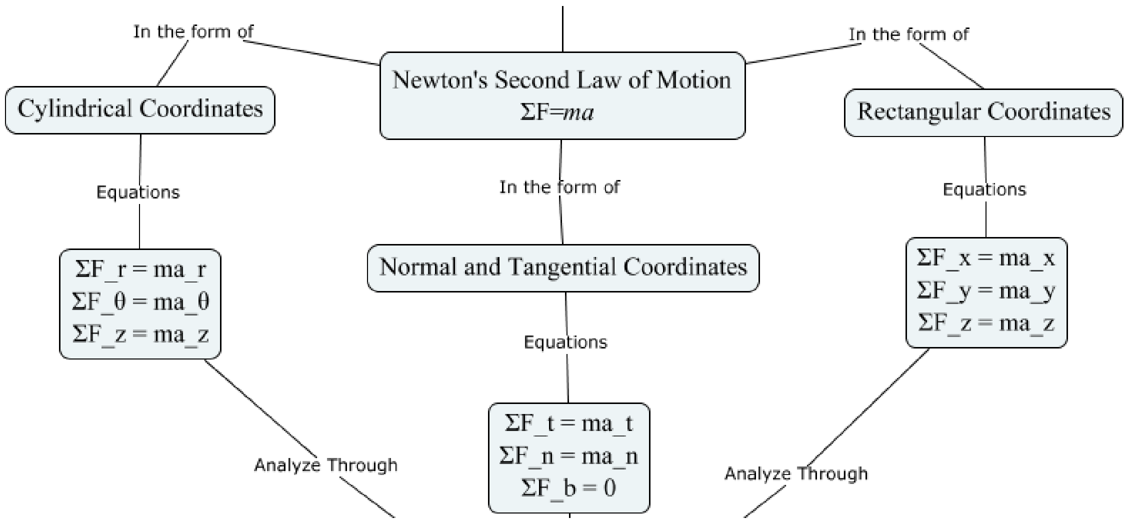

Figure 3: A student-generated concept map example 2: force and acceleration

Work and energy

The Principle of Work and Energy is an important principle in kinetics. This principle can be derived based on Newton's Second Law, along with the formula of $a \cdot ds = v \cdot dv$. Figure 4, part of a concept map developed by a student, clearly shows the evolutionary relationship between the Principle of Work and Energy and Newton's Second Law.

Impulse and momentum

Four principles are often used to solve problems involving impulse and momentum: the Principle of Linear Impulse and Momentum, the Principle of Angular Impulse and Momentum, the Conservation of Linear Momentum, and the Conservation of Angular Momentum. In cases in which a system of particles are involved, the Conservation of Linear Momentum can be derived from the Principle of Linear Impulse and Momentum. This is because impulses between particles are internal impulses and can be cancelled out. Figure 5, part of a concept map developed by a student, clearly shows the evolutionary relationship between the Principle of Linear Impulse and Momentum and the Conservation of Linear Momentum.

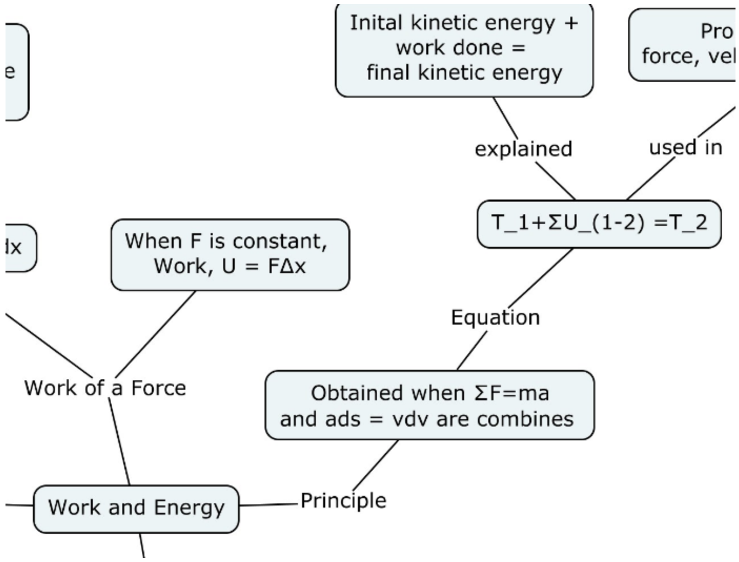

Figure 4: A student-generated concept map example 3: work and energy

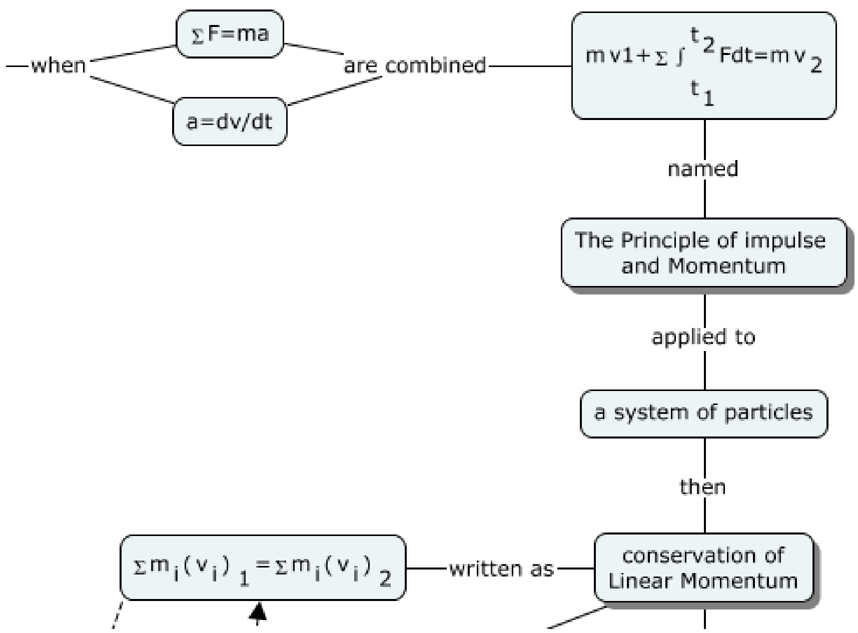

Figure 5: A student-generated concept map example 4: impulse and momentum

Comparison of student conceptual understanding

Student conceptual understanding was compared between Semester I (when concept mapping was not employed) and Semester II (when concept mapping was employed). The data were collected via in-class clicker questions after student completed the learning of relevant concepts. Throughout the semester, more than 30 particular clicker questions were developed and employed to assess students' conceptual understanding on a variety of learning topics. The following paragraphs provide two representative examples of in-class clicker questions.

Conceptual clicker question example 1: Newton's Second Law, along with which of the following equations, can be used to derive the Principle of Work and Energy?

A) $v = ds/dt$
B) $a = dv/dt$
C) $a \cdot ds = v \cdot dv$
D) $T = \frac{1}{2} m v^2$

Conceptual clicker question example 2: Newton's Second Law, along with which of the following equations, can be used to derive the Principle of Linear Impulse and Momentum?

A) $v = ds/dt$
B) $a = dv/dt$
C) $a \cdot ds = v \cdot dv$
D) Impulse $I = \int \sum F \cdot dt$

Figures 6 and 7 show the comparison of students' responses to both questions in semesters I and II, respectively. As can be clearly seen, students improved their conceptual understanding in semester II when they developed their own concept maps. These results imply that learning by doing (i.e., developing their own concept maps) is more effective than learning by simply listening to lectures.

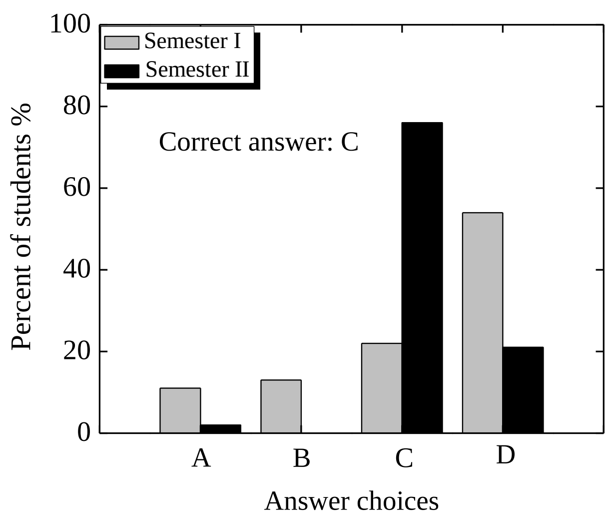

Figure 6: Comparison of students' responses to conceptual clicker question example 1

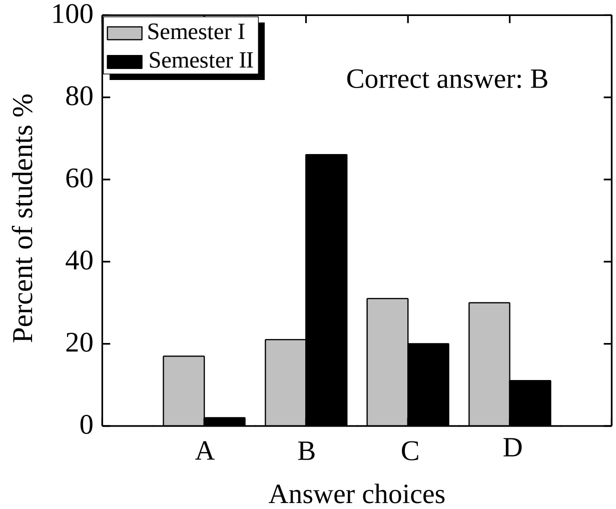

Figure 7: Comparison of students' responses to conceptual clicker question example 2

Students' experiences and representative comments

A questionnaire survey was administrated at the end of semester II after students developed their own concept maps. The survey included both Likert-type scale questions and open-ended questions. The Likert-type scale questions asked students to rate their overall learning experience and to rate the level of improvement on conceptual understanding due to concept mapping. The open-ended questions asked students to provide in-depth, written explanations of why students chose a particular answer to a Liker-type scale question.

An example Likert-type scale question is, "Please rate your overall experience with developing your own concept maps:

A) Highly negative
B) Negative
C) Neutral
D) Positive
E) Highly positive"

The results showed that 4% of students (n =71) rated their experiences as "highly positive," 35% as "positive," 48% as "neutral," 10% as "negative," and 2% as "highly negative." This means that 39% of students has positive or highly positive experiences. Those students with "negative" rating indicated that developing quality concept maps required time they did not have, as many students took five classes (15 credits) per semester and also worked part time (20-30 hours per week) outside campus to help pay for tuition and/or support their families.

An example open-ended question is, "Please describe in detail how the concept maps helped, or did not help, with your conceptual understanding of dynamics concepts, laws, and principles as well as their relationships." Students provided written comments to respond to this question.

Their comments were then analyzed using the method of content analysis [29]. In content analysis, textual (written) information was analyzed to identify its properties such as the frequency of most frequently used keywords. The textual (written) information can also be categorized (i.e., coded) for a qualitative research study.

In the present study, it was found that the word most frequently used in student comments is "organization." The other words students also often used in their comments include "visualization," "thinking," and "connection." The following paragraphs provide a representative set of student comments, which demonstrate how the concept mapping approach helped students develop better conceptual understanding.

"As I developed concept maps for each chapter, it helped me see how all the concepts we'd learned were connected. It helped organize a bunch of ideas, laws, and equations into one nice stream/plot of information. I felt the content of each chapter became "simpler," especially as I drew the connections from the beginning chapters to what we learned about rigid bodies. That material could be pretty crazy, but once you realize that it's the same as particle kinematics and kinetics with a few tweaks, it's so simple."

"It helped to organize things into categories and see how things related to one another. More than anything, it gave me a way to make a direct line from the theories to the equations, which is something I struggle with usually."

"The concept maps were a huge help in keeping track of all the principles we learn. It helped organize my materials and what tools I had and where these tools could apply. In addition, it helped me step back and see why it was important to keep all of these things in perspective and the importance of the concepts and why I needed to understand them."

"It helped me to organize the equations and ideas in a way that was easier to remember and understand. Often, in just taking notes my thoughts become disorganized, but the concept map helped me to review the things we learned in class and organize them more effectively."

Conclusions

As a graphic tool for knowledge organization, representation, and elicitation, concept mapping has received growing attention and application in STEM disciplines. This paper has reported the most recent results of how students developed their concept maps to illustrate the evolution of key concepts in engineering dynamics, a foundational undergraduate engineering course. The results show that as compared to Semester I, when concept mapping was not employed, students developed better conceptual understanding in Semester II when concept mapping was employed. It is revealed that concept maps help students to organize their knowledge and understand how key concepts in engineering dynamics evolve.

Acknowledgements

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