AC 2012-3345: ENHANCING STUDENTS' UNDERSTANDING OF DYNAMICS CONCEPTS THROUGH A NEW CONCEPT MAPPING APPROACH: TREE OF DYNAMICS

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Enhancing Students' Understanding of Dynamics Concepts Through a New Concept Mapping Approach - Tree of Dynamics

Abstract

Dynamics is a sophomore-level course that many engineering students are required to take. The course is widely regarded as one of the most difficult undergraduate courses to succeed in because the course covers numerous foundational concepts. Inspired by and built upon the conventional concept mapping approach, this paper proposes a new concept mapping approach, called the “Tree of Dynamics,” to enhancing students’ understanding of dynamics concepts. In the new approach, the relationships among dynamics concepts are represented by tree structures (such as roots, trunks, branches, leaves, and fruits) rather than by linking words and phrases. The new approach enhances students’ perception (cognitive intuition) of the relationships among concepts and also adds an element of fun to student learning. This paper describes in detail how to build a tree of dynamics and provides three representative examples of student-constructed versions. The assessments from the pre-post test results have shown that the average learning gain for all student participants was 64.2%. Compared to the average pretest score, the average post-test score increased 1.45 standard deviations. Seventy-one percent of the students surveyed agreed or strongly agreed that the “Tree of Dynamics” helped them understand hierarchical relationships among dynamics concepts and associated equations.

Introduction

Dynamics is a sophomore-level course that nearly all students in mechanical, aerospace, civil, biological, and biomedical engineering programs are required to take. The course is widely regarded as one of the most difficult undergraduate courses to succeed in because the course covers a broad spectrum of foundational concepts such as force, velocity, angular velocity, acceleration, angular acceleration, work, energy, linear impulse, angular impulse, linear momentum, angular momentum, and vibration¹⁻³. Many students fail the dynamics course because they lack a solid understanding of these foundational concepts and do not know when and why to apply what concepts and associated equations⁴⁻⁶.

Concept mapping, developed upon constructivist learning theory, is a graphical representation (like a flow chart) that shows how individual concepts are related to and connected with one another to form large wholes^{7,8}. In a concept map, concepts are arranged in a hierarchical or network form, with labeled nodes (in circles or boxes) denoting concepts, and linking words or phrases specifying the relationships among concepts. Two or more concepts that are connected by linking words or phrases form a proposition (i.e., a meaningful statement). Figure 1 shows the structure and characteristics of concept maps⁸.

Since its development in 1972 by Joseph Novak and his colleagues^{7,8}, who sought to follow and understand changes in children’s knowledge of science, concept mapping has been adopted in nearly every discipline ranging from STEM (science, technology, engineering, mathematics), psychology, and medicine to business, economics, accounting, history, and literature by institutions ranging from K-12 to undergraduate education⁹⁻¹⁵. For example, Darmofal et al.¹⁰

Figure 1. The structure and characteristics of concept maps⁸

developed concept maps to identify and organize key engineering concepts in the aerospace engineering program at Massachusetts Institute of Technology. They reported that instructors at their institution also developed concept maps and associated concept questions for a variety of foundational engineering courses such as thermodynamics, structures, and signals and systems. Egelhoff et al.¹⁵ developed a concept map for a sophomore-level Mechanics of Materials course. The concept map was used as a tool to review the Mechanics of Materials course before administering a gateway exam in the junior-level Mechanisms course. The assessment results¹⁵ showed that due to the use of the concept map, the students' average score of the Mechanisms exam increased from 68% to 90%, and standard deviation decreased from 16.9 to 10.0.

Concept maps for engineering dynamics have also been developed by engineering instructors at various institutions of higher learning^{4, 16, 17}. For instance, Cornwell⁴ developed a concept map for particle kinematics, an essential topic in dynamics, to help students understand the relationships among kinematics concepts and organize the material in student's minds. He set up his concept map on a corner of the classroom front wall. When he presented new materials, he showed their location in the concept map. Ellis et al.^{16, 17} developed a course concept map and a dynamics concept map for a Continuum Mechanics I course. Their dynamics concept map focused on relating motion to its causes by Newton's Second Law and impulse-momentum relationship. The effectiveness of their concept maps was assessed through attitudinal surveys and focus-group interviews. The assessment results^{16, 17} showed that the majority of students surveyed had positive experiences with concept maps and that concept mapping is a promising pedagogical and learning tool in dynamics.

In the conventional concept mapping approach^{7, 8}, the relationships among concepts are indicated by linking words and phrases, as shown in Fig. 1. Students must "read" those linking

words and phrases in order to learn the relationships among concepts. Cognitively, this “learning by reading texts” activity might not be most effective. To enhance students’ perception (intuitive cognition) of the relationships among concepts and also add an element of fun to learning, the author of this paper has developed a new concept mapping approach called “Tree of Dynamics.” In the new approach, the relationships among concepts are represented by tree structures including roots, trunks, branches, leaves, and fruits, instead of by using linking words or phrases. For example, the foundation on which all concepts are built can be placed as the root of a tree. The main concept can be the trunk. Concepts that derive from the main concept can be the branches. It should be pointed out that to some extent, the “Tree of Dynamics” approach looks similar to the mind-mapping approach developed by Buzan¹⁸. Both use hierarchical structures to represent knowledge and information. However, in a mind map, the topic or subject of learning is placed in the center of the map, and all concepts are placed in a radial manner around the center. The “Tree of Dynamics” approach involves a vertical tree structure that enables students to see foundational dynamics concepts. Given that concept mapping is widely known and adopted in the engineering and technology education community, the “Tree of Dynamics” approach is categorized in the present study as a concept mapping approach.

The “Tree of Dynamics” approach was implemented in a dynamics course that the author of this paper taught. A total of 76 students worked either individually or on teams to construct a variety of trees of dynamics. This paper describes the method of constructing a tree of dynamics. Three representative examples of student-constructed trees are provided. Assessment instruments included 1) pre-post tests that measured students’ conceptual learning gains, and 2) an attitudinal questionnaire survey that determined student experiences with the tree of dynamics. The results of assessment are presented, followed by the discussion of the limitation of the “Tree of Dynamics” approach and lessons learned. The conclusions are made at the end of the paper.

Construction of a Tree of Dynamics

The quality of a tree of dynamics is measured by two factors: technical correctness and logical reasonableness. The first factor requires students to have a solid understanding of foundational dynamics concepts, particularly the hierarchical relationships among relevant dynamics concepts. The second factor requires students to place dynamics concepts in correct positions on the tree, such as roots, trunks, branches, leaves, and fruits.

For example, let us consider how to place five critical dynamics concepts in different positions of a tree. These five concepts include 1) Newton’s Second Law, 2) Principle of Work and Energy, 3) Conservation of Energy, 4) Principle of Linear Impulse of Momentum, and 5) Conservation of Linear Momentum. The hierarchical relationships of these five concepts are:

- From Newton’s Second Law, one can drive all other four principles.
- Conservation of Energy is a special case of the Principle of Work and Energy.
- Conservation of Linear Momentum is a special case of the Principle of Linear Impulse of Momentum.

Therefore, Newton’s Second Law can be placed in the position of the trunk of a tree, with the Principle of Work and Energy and Principle of Linear Impulse of Momentum being placed as

two branches. The branch of the Principle of Work and Energy has a sub-branch of Conservation of Energy. The branch of the Principle of Linear Impulse of Momentum has a sub-branch of Conservation of Linear Momentum.

Because there are more than one form (such as trunk/branch, branch/sub-branch, branch/leave, and branch/fruit) to represent the relationships among concepts, one can write a separate text to explicitly explain the the relationships.

Representative Examples of Student-Constructed Trees of Dynamics

Figures 2-4 provide three examples of trees of dynamics that were initially submitted by students. After reviewing by the instructor, some student-constructed trees were revised for technical correctness and logical reasonableness.

Figure 2. Example 1: a tree of dynamics constructed by a two-student team

Figure 3. Example 2: a tree of dynamics constructed by a two-student team

Figure 4. Example 3: a tree of dynamics constructed by a student

For the tree shown in Figure 2, the students provided the following explanation:

“The roots are math and science. It then branches into two trunks, kinematics and kinetics. You will also see a knot in the upper right of the tree that represents the triangle of kinematics. Newton’s second law connects the two trunks. They then branch into the smaller aspects of dynamics, and the formulas and equations that you can derive from Newton’s second law are shown in parenthesis. Our tree was drawn using artistic markers by my roommate who is a Landscape Architecture major.”

For the tree shown in Figure 3, the students provided the following explanation:

“This tree divided all of dynamics into rectilinear and curvilinear sections, stemming from the all-encompassing $F = ma$. Each section of the tree continues to break down, leading to the essential equations of each concept, which are the fruit of the tree. The tree demonstrates the importance of Newton’s second law while visualizing the tools necessary to solve most dynamics problems.”

For the tree shown in Figure 4, the students provided the following explanation:

“This tree of dynamics is split into two parts. Stemming from the left side of the trunk are the equations related to kinematics. The right side of the tree is everything from chapters 13 to 15 that stem from Newton’s second law. Many of the letters in the equations are explained on leaves. The equations are placed in the clouds next to the principles and laws that they stem from. Because absolute motion of two particles doesn’t have a set equation, I placed a system of pulleys from which I derived its equations to explain the concept. Trailing behind the falling apple I place the two constants of acceleration from gravity and the equation for weight.”

Pre-Post Tests for Assessing Students’ Conceptual Learning Gains

A total of 76 students who took dynamics from the author of this paper participated in the activities of constructing trees of dynamics. Among the 76 student participants, 45 (59.2%) students were mechanical and aerospace engineering majors, and 19 (25%) of the students were civil and environmental engineering majors. Sixty-seven (88.2 %) students were male, while only 9 (11.8%) students are female.

Before students constructed their trees, the instructor provided a lecture explaining the general idea of tree concepts and how to build trees. The students were allowed to work either individually or in teams. Among the 76 student participants, 35 (46%) students chose to work individually, and 41 (54%) students chose to work in teams of two to four students, forming 15 teams. Therefore, a total of 50 “trees” were generated, including 35 “trees” generated by individual students and 15 “trees” generated by student teams. All student-generated trees were graded by the instructor using a scoring rubric. The rubric contains a set of criteria that check the technical correctness and logic reasonableness of student-generated trees. For example, two criteria were: If the tree correctly shows that all six dynamics principles stem from Newton’s second law, the student earns 2 points. If the tree correctly shows the hierarchical relationship

between the “Principle of Work and Energy” and the “Principle of Conservation of Energy,” the student earns one point.

Among the 76 student participants, 53 students chose to take a pretest and a post-test that measured their conceptual understanding of the hierarchical relationship among the following seven critical dynamics concepts: Newton’s Second Law, Principle of Work and Energy, Conservation of Energy, Principle of Linear Impulse and Momentum, Conservation of Linear Momentum, Principle of Angular Impulse and Momentum, and Conservation of Angular Momentum. The pre-test occurred two weeks before students constructed their trees. The post-test occurred one week after students completed their trees. Students built their trees after they completed the study of particle dynamics and were in the initial stage of learning rigid-body dynamics. The following paragraphs provide three example pre-post test questions:

Question #1: Who is a “grandparent” from which all other law/principles can be derived?

- A) Principle of Work and Energy
- B) Conservation of Energy
- C) Principle of Linear Impulse and Momentum
- D) Newton’s Second Law
- E) I do not think that “grandparent” exists

Question #2: “Conservation of Linear Momentum” is the immediate descendant of

- A) Newton’s Second Law
- B) Principle of Work and Energy
- C) Conservation of Energy
- D) Principle of Linear Impulse and Momentum
- E) Principle of Angular Impulse and Momentum

Question #3: Which of the following statements is true?

- A) “Principle of Work and Energy” can be derived from “Conservation of Energy.”
- B) “Principle of Linear Impulse and Momentum” can be derived from “Conservation of Linear Momentum.”
- C) “Principle of Angular Impulse and Momentum” can be derived from “Conservation of Angular Momentum.”
- D) “Principle of Angular Impulse and Momentum” can be derived from “Principle of Linear Impulse and Momentum.”
- E) None of the above statements is true.

Student responses to the above three assessment questions are summarized in Table 1, where the correct answer choice (D) for each question is highlighted in bold.

Table 1. Percentage (%) of student responses to assessment questions

Multiple answer choice	Question #1		Question #2		Question #3	
	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test
A	5.9	1.9	18.9	9.4	17.0	3.8
B	5.7	0	11.3	1.9	11.3	5.7
C	0	1.9	50.9	7.5	1.9	1.9
D	86.8	96.2	18.9	79.2	60.4	79.2
E	1.9	0	0	1.9	9.4	9.4

The following observations can be made from Table 1:

- Significant learning gains were achieved for question #2 that assessed students' understanding of the relationship between "Conservation of Linear Momentum" and "Principle of Linear Impulse and Momentum." The percentage (%) of student responses to question #2 in pre-post tests increased from 18.9% to 79.2%.
- Moderate learning gains were achieved for question #3 that assessed students' understanding of the relationship between "Principle of Angular Impulse and Momentum" and "Principle of Linear Impulse and Momentum." The percentage (%) of student responses to question #2 in pre-post tests increased from 60.4% to 79.2%.
- Students' learning gains for question #1 were insignificant due to high pre-test scores of students. This implies that question #1 is an easy question. Therefore, no education intervention is necessary in order to help students correctly answer question #1.

The average pre-test score and post-test score were calculated for each student on all pre-post test questions. The following equation ¹⁹ was used to calculate the average learning gain for each student:

$$\text{Learning gain} = \frac{\text{Post-test score (\%)} - \text{Pretest score (\%)}}{100 (\%) - \text{Pretest score (\%)}} \quad (1)$$

Figure 5 shows the learning gain for each student on all pre-post test questions. As seen from Figure 5, the majority of students demonstrated positive learning gains. Three students had negative learning gains because their average post-test scores were lower than the average pre-test scores.

For all students on all assessment questions, the average pretest score was 54.1%, and the average post-test score was 83.6%. Based on Equation (1), the average learning gain for all student participants on all assessment questions was 64.2%. Compared to the average pre-test score, the average post-test score increased 1.45 standard deviations. These two numbers (64.2% and 1.45) validate the effectiveness of the "Tree of Dynamics" in improving students' conceptual understanding in dynamics.

Figure 5. Learning gain for each student on assessment questions

Attitudinal Questionnaire Survey

An attitudinal questionnaire survey was administrated to determine students' experiences with the tree of dynamics. The questionnaire survey included both Likert-type and open-ended questions. The Likert-type question is:

Please rate the following statement: The "Tree of Dynamics" helped me understand the hierarchical relationships among dynamics principles and associated equations

- A) Strongly disagree
- B) Disagree
- C) Neutral
- D) Agree
- E) Strongly agree

Figure 6 shows the percentage of students responded to the above question. A total of 71% of the students agreed or strongly agreed that the "Tree of Dynamics" helped them understand the hierarchical relationships among dynamics principles and associated equations.

Figure 6. Student responses to the survey question

Representative student comments are listed below:

- “I think the tree helped clarify the relationships between all the principles and created an easy visual organization of the relationships. I feel the tree helped me study for the test. I feel I better understand the physical meaning behind the equations and can therefore better use them because of the assignment. Doing the assignment was much better than looking at a tree.”
- “The tree of dynamics helped me understand more fully how all aspects, principles, and theories of dynamics are inseparably connected to one another. It helped me understand this more clearly by providing a visible/tangible example of how equations of dynamics are related.”
- “It helped review everything we had learned, & better understand the relationships of the equations. I even took a tree with me on the exam.”
- “It helped me to organize what we have learned into a logical way of approaching problem. I enjoyed it a lot. I am a visual learner and this activity gives me a visual approach.”
- “The tree of dynamics helped me see how everything was related. It helped me organize everything we learned in a meaningful way.”
- “I can tell this is really helpful for connecting all dynamics concepts. It lets me know dynamics is just the basis concept of Newton’s Second Law. Everything can be derived from that.”

Limitation of the “Tree of Dynamics” Approach and Lessons Learned

The Tree of Dynamics is an effective visualization tool to help student learn and organize the course material in a meaningful way. However, it should be pointed out that the tree architecture is achieved at a cost. The cost is that some relationships among concepts are hidden (but not eliminated) because tree branches do not directly relate to each other, except through the trunk. For example, kinetics and kinematics are two essential components of dynamics. They can be placed as two branches on a “tree.” In reality, however, the solution of dynamics problems often requires relating kinetics and kinematics. That interaction is lost in the tree architecture.

It was also found that many students did not have much prior experience with construing concept maps or trees of dynamics. The instructor must spend time in teaching about concept maps or trees, and in demonstrating example maps or trees to students. In the present study, the instructor provided one lecture explaining the general idea of tree concepts and showing students example trees. Without teaching from the instructor and subsequent interactions between the instructor and students, it is difficult for students to construct quality maps or trees.

Conclusions

This paper has presented a new concept mapping approach – “Tree of Dynamics” – in which the relationships among concepts are represented by tree structures including roots, trunks, branches, leaves, and fruits, instead of by using linking words or phrases. The new approach enhances students’ perception (intuitive cognition) of the relationships among concepts and also adds an element of fun to student learning. The paper has provided three representative examples of student-constructed trees of dynamics. The assessments from the pre-post test results have shown that the average learning gain for all student participants was 64.2%. Compared to the average pretest score, the average post-test score increased 1.45 standard deviations. Seventy-one percent the students surveyed agreed or strongly agreed that the “Tree of Dynamics” helped them understand hierarchical relationships among dynamics concepts and associated equations.

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