121st ASEE Annual Conference & Exposition
Indianapolis, IN
June 15-18, 2014
Paper ID #10682

Utilizing Concept Maps to Improve Engineering Course Curriculum in Teaching Mechanics

Ruben Pierre-Antoine, Stanford University

Ruben is a senior undergraduate student at Stanford University studying Management Science & Engineering. He joined the Designing Education Lab in the winter of 2013. He has always had a passion for education and enjoys the integration of entrepreneurship into a curriculum. Ruben loves to play sports, videogames, and eat at new restaurants. He also explores entrepreneurship in his free time.

Dr. Sheri D. Sheppard, Stanford University

Sheri D. Sheppard, Ph.D., P.E., is professor of Mechanical Engineering at Stanford University. Besides teaching both undergraduate and graduate design and education related classes at Stanford University, she conducts research on engineering education and work-practices, and applied finite element analysis. From 1999-2008 she served as a Senior Scholar at the Carnegie Foundation for the Advancement of Teaching, leading the Foundation's engineering study (as reported in Educating Engineers: Designing for the Future of the Field). In addition, in 2003 Dr. Sheppard was named co-principal investigator on a National Science Foundation (NSF) grant to form the Center for the Advancement of Engineering Education (CAEE), along with faculty at the University of Washington, Colorado School of Mines, and Howard University. More recently (2011) she was named as co-PI of a national NSF innovation center (Epicenter), and leads an NSF program at Stanford on summer research experiences for high school teachers. Her industry experiences includes engineering positions at Detroit's "Big Three:" Ford Motor Company, General Motors Corporation, and Chrysler Corporation.

At Stanford she has served a chair of the faculty senate, and is currently the Associate Vice Provost for Graduate Education.

Dr. Mark Schar, Stanford University

Dr. Schar works in the Center for Design Research - Designing Education Lab at Stanford University. He is also a member of the Symbiotic Project of Affective Neuroscience Lab at Stanford University and a Lecturer in the School of Engineering. Dr. Schar's area of research is "pivot thinking" which is the intersection of design thinking and the neuroscience of choice where he has several research projects underway. He has a 30 year career in industry as a Vice President with The Procter & Gamble Company and Senior Vice President and Chief Marketing Officer with Intuit in Silicon Valley. Dr. Schar has a BSS from Northwestern University, an MBA from the Kellogg School of Management and his PhD in Mechanical Engineering is from Stanford University.

Utilizing Concept Maps to Improve Engineering Course Curriculum in Teaching Mechanics

Abstract

One of the most difficult tasks in teaching is evaluating how students assimilate the content; this holds at all levels of education. Tests and homework only show so much, as the performance on those evaluations may be a stronger indication of how much effort each student is putting into the course. In addition, large classes and the relative lack of communication between the instructor and his/her students make it difficult to know exactly how students are learning course material. One approach is to have students create concept maps once they have finished the course[4]. A concept map is essentially a mental web of connected terms or topics, where the centermost term is the primary learning focus and lines are used to connect related concepts. This results in a web of interconnected concepts that reflect the way students assimilate the new information.

The three main questions guiding the study reported here are:

1) How can we decode the variety of ideas and structures that students include in their concept maps?
2) How can we use discoveries from this decoding to make lectures and labs more effective?
3) What improvements can be made to the way students are assigned drawing concept maps to further increase the usefulness of concept maps in capturing their learning?

The dataset for this study focuses on concept maps developed by undergraduate students enrolled in an introductory solid mechanics course taken by many prospective engineering majors (primarily freshmen and sophomores) in the winter quarter of 2013. In the final week of the course, students were tasked with creating a concept map of the various terms and topic areas covered during the ten-week course. In analyzing these maps, terms were weighted based on their location in reference to the centermost term of the map. Information regarding the proximity of the terms to each other and which terms are connected was also drawn from the concept map dataset.

This first round of analysis indicates that students, for the most part, were drawing the expected connections between the different terms and topics. However, there were instances where students isolated topics, missed topics, or had them wrongly associated. This suggests that it may be beneficial for the teaching team to more explicitly or repeatedly connect certain topics throughout the course in lectures, class exercises and homework assignments. Suggestions for improving the concept map assignment are also discussed.

Introduction

In working with college students at the early stages of their engineering studies, professors are faced with the challenge of organizing their course in a way that makes it accessible to the students, but at the same time is complex enough to illustrate core engineering concepts. In order to properly teach engineering concepts, the professor must learn how students are learning the information in the class, including what they are understanding easily and the concepts that are more difficult for them to grasp. The first goal of this paper is to learn more about how students organize the knowledge that they are exposed to in an engineering class. Second, this paper analyzes how we can use concepts maps, a visual tool discussed later in the paper, to further analyze student knowledge organization as well as the improve the tool to be even more useful to engineering educators. The final goal is to use what we learn from the students to improve the classroom experience.

Methods

In order to learn about the organization of knowledge in students, we chose to identify how students organized concepts. To do this, students were asked at the end of the course to fill out a concept map. Concept maps are graphical tools for organizing and representing knowledge[3]. Student are given either a list of terms or overall topics, and are told to link them based on their assessment of importance and relation. Based on the work of J. Turns, the concept map is an assessment tool based on nodes and arcs[4]. Nodes are the individual words or phrases that the student is associating. Arcs connect the nodes with one another, typically in an outward fashion, in which there are more nodes the further one gets from the center node. The most important and/or central part of the concept map is placed in the center node. Connected outwards from the center node are the terms that the student deems to be a subset or close relation of the center term. For example, in the case of describing what an ice cream cone is (with *ice cream cone* being in the central node), a student might place on the second level of the map a node containing the term *cone* (assuming it is the basis for the ice cream cone) and on the third level a node containing *ice cream* (since it is placed into the cone). In addition, concept maps also often make use of linking words or phrases, placed on the arcs, in order to further explain the relationship between the two terms. Examples of linking phrases and words include *help to answer*, *represent*, *includes*, *are*, and *results in*. An example of a concept map is shown in Figure 1 below.

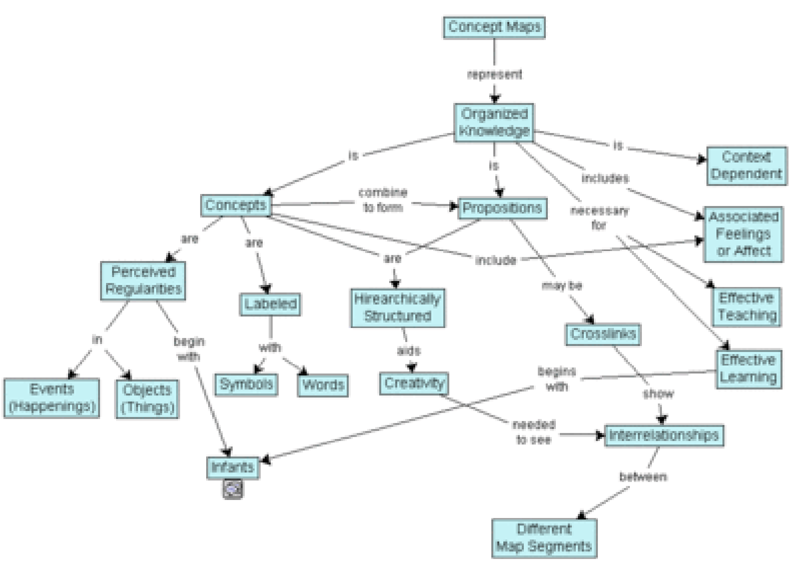

Figure 1. Example of a Concept Map[5]

By introducing the idea concept maps, we can refine the first question that this paper is addressing. By looking at the concept maps of students in this course, we can gain insight into how they organize their knowledge, then use this organization to improve the course. The concept map assignment was given the end of term in the Stanford undergraduate course Engineering 14: Introduction to Solid Mechanics (Engr 14). Engineering 14 is taken primarily by college sophomores interested in mechanical or civil engineering. For many of these students it is one of their first engineering focused classes. The course aims to set solid foundations for what is to come in future classes as well as teach the fundamentals that would be required in many mechanical and civil engineering courses. The class has lecture and lab components, and includes 80-100 students. It is taught in a 10-week period and introduces the students to real world engineering problems through case studies, problem sets, and team-oriented activities.

There are several unique qualities of the Engr 14 course that may be relevant to understanding the environment and outcomes observed by the paper. First, the hands-on components in the class truly emphasize real work as a group. Students are placed into small pods, or groups, in which they work together in order to solve real problems in their labs. Instead of using typical introductory equipment, student in the labs work with materials used in skateboards and even bring in their own bikes. The class is also influenced by the attention to design and design thinking from the Stanford d.school[1] and also incorporates a lot of the entrepreneurial thought that is ever present on Stanford campus. A few of the labs incorporate business thinking into design choices, whether it is optimizing profit or identifying customer needs. A good example of all of these concepts comes in the form of the bicycle lab. In this lab, the students first learn and experiment with mechanical advantage by bringing in their own bike and working with the gear systems. Then, they have analyze the needs of a new bicycle sharing program made by a real bike company (Trek/B-Cycle) and have to determine which customer base is optimal to cater to. By making design and business choices, the students are able to be exposed to a variety of learning techniques. By using the four primary objectives of Kolb's Experiential Learning Model (feeling, watching, thinking, and doing), the unique variety of this class often allows students from different backgrounds with different skills to succeed and have interest in an introductory Engineering class[2]. In addition, the insertion of design and business into the curriculum had an impact on the associations that students made in their concept maps (as we shall see below).

We analyzed the 97 concept maps, all created by Stanford undergraduate students participating in the class. The students were also instructed to write on the lines that connect the words, using terms or short action phrases that would describe the relationship between the two. In order to assist their creation of the maps, students were given a very list of the topics and concepts that the course covered. The goals of the analysis presented here were 1) to see what concepts students included on their maps, 2) to see if some concepts were connected in complex ways (whereas others were only connected in simple ways).

In analyzing the data, we took a series of steps that simplified the complex and diverse concept maps that were created by the students. The first method was to encode the data into an

Excel file in order to count the occurrences of each word as a set towards creating a single concept map that embodied the perspectives of the class. We weighted a word based on a point system that rewarded terms that were closer to the center of the concept map. The point system was as follows:

- 4 points for the center term (Level One)
- 2 points for the terms connected to the center term (Level Two)
- 1 point for the terms connected to the Level Two terms (Level Three)

We decided not to factor in the terms or phrases that were past level three, as they varied highly between concept maps and it was very difficult to make defining conclusions. The rationale behind the point system was to give extra emphasis to the confidence that a student had in a term; we hypothesized that students would half as confident and/or associative of terms as they concept grew outwards. Therefore, level one was twice the value of level two and four times the value of level four. Once the data were encoded, we sorted all of the terms by point value. Using a combination of this information and the qualitative observations of previous concept maps (i.e., the patterns that were observed through going through a large number of concept maps), we made an initial concept map for the class (see Figure 2 – statics had the highest point total).

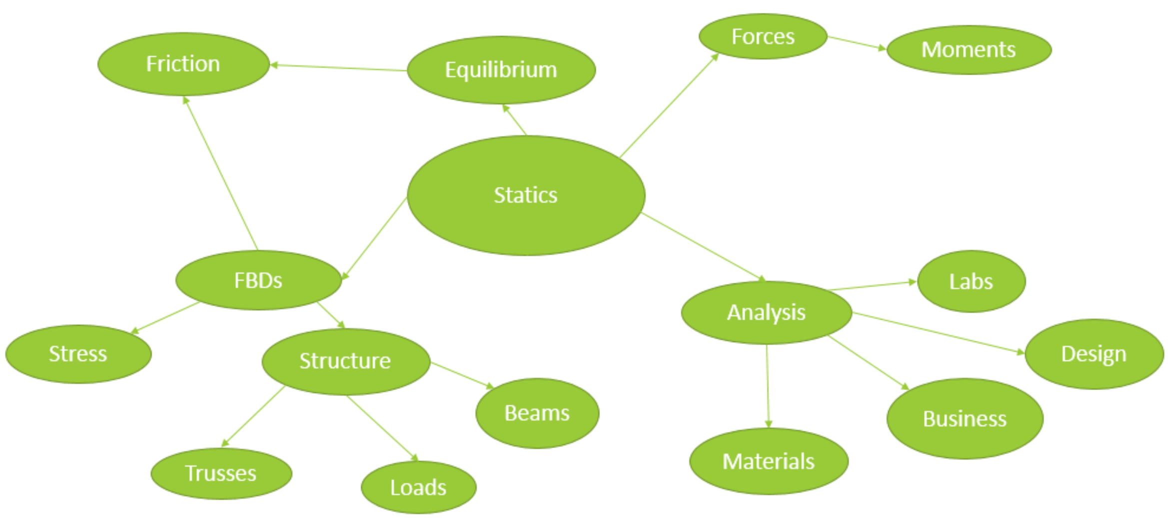

Figure 2. Draft #1 of the Class "Composite" Concept Map

From this map, we were able to draw the basic connections that the students were able to make. Since the concept map was primarily constructed through the frequency of the words appearing, we could not make any definitive conclusions regarding the relationships of the words. Although there were connections established as seen in Figure 2, we could determine whether there were accurate since the frequency of words doesn't necessarily define their associations with other words. In addition, the concept map was missing some key elements in the class (e.g., shear stress, ethics, and tension). However, it was apparent that the first level was accurate, as analysis, FBDs, equilibrium, and forces were the central concepts of a student's approach to the class.

	FBDs				
Statics		Joints	Forces	Friction	Drawing
Statics		Assumptions	Axes	External Forces	
Statics		Vectors	Systems		
Equilibrium		Assumptions			
Statics		Bearings	Joints	Planar	NonPlanar
Statics		Moments	Forces		
		Equlibrium	Forces	Pins	
Moments		Equlibrium			
Equilibrium		Joints			
Forces		Systems	Shear	Tension	
Equilibrium		Trusses	Bearings	Joints	
Statics		Assumptions	Forces		

Figure 3. Analyzing Level 2 Terms

In order to gain further insights into student thinking represented by the concept maps, we wanted to figure out how second and third level terms were related and what they connected to. In order to do this, we undertook a second analysis that involved encoding 20 concept maps, selected based on their completeness, quality of effort, and use of simple terms. Coding involved finding the terms both on the level below and above of the "target term". Figure 3 shows how the data were encoded on excel. We began by isolating each of the target terms used in the concept maps (in this example, free body diagrams) on a black centered column. Terms that were assigned a higher point level than the isolated term were considered to be preceding and terms that were assigned a lower point level than the isolated term were considered to be following. The terms that preceded free body diagrams were placed to the left of the black column and the terms that followed free body diagrams were placed to the right of the black column. In this case, the term statics consistently appeared to the left of the free body diagrams, resulting in statics appearing one level closer to the center. Therefore, since we learned that statics was a more central term, it was evident that free body diagrams would have to be included on the second level. In addition, free body diagrams had a unique relation to equilibrium. Equilibrium was observed to be one level above or below free body diagrams at about the same rate. Since it was constantly present, but did not consistently appear in the same fashion, we determined that these two concepts were co-dependent in the minds of the students. This means that students would think about free body diagrams and Equilibrium on the same plane, therefore placing both interconnected on the second level of the concept maps. Ultimately, this proves to be logical as the primary goal of free body diagrams in a Statics class is to ensure that equilibrium is maintained. By doing this, we were able to create a much more comprehensive concept map (see Figure 4) that gave a solid impression of how the class was structured from the viewpoint of a young engineering student.

Page 24.1353.6

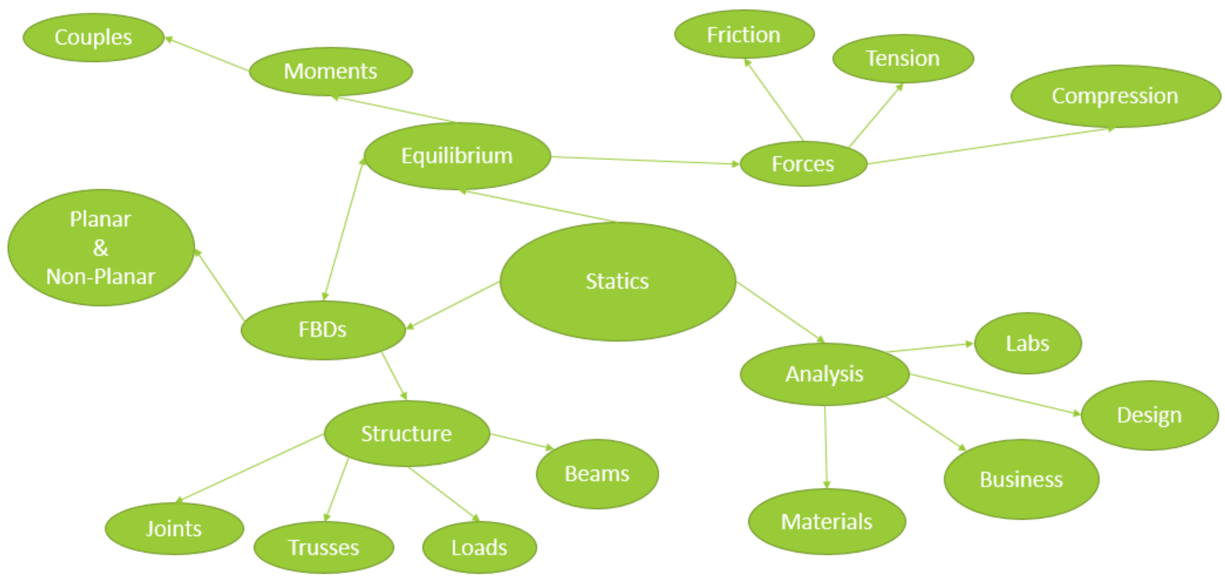

Figure 4. E14 Concept Map Created by Level Analysis. Three level analysis represented here. Double-headed arrows indicate co-dependent terms.

From this concept map, we had some interesting observations, some of which revealed more about how the class could be refined. One positive note was the prevalence of the analysis portion of the class, which is important as one of the class's primary foci is to begin to teach engineers how to analyze a problem. The levels of analysis that stuck with the students included labs, design, business, and materials. One level that was not present often was ethics. We attributed that to a combination of factors. First, many students may have not considered ethics as a concept that they should include in their concept map because it is not the first thing that comes to mind when doing a homework assignment for an engineering class.

One other important observation from the Figure 4 map is that moments seem to be isolated from the rest of the concepts. It seems that students struggled to connect moments with the rest the concepts, perhaps because it is a difficult concept that often gets introduced without much pretense. An encouraging aspect of this map is that students did do a successful job grasping a large majority of the concepts. Finally, in order to ensure the validity of the data, we cross-referenced several randomly selected concept maps that were not in this sample. We learned that organization of terms on the map were relatively consistent, although different terms were often used for the same ideas (i.e. Statics & ENGR 14 or Equilibrium & Balanced Forces).

A third analysis was undertaken to better understand the connector words. We note that only 12 percent of the students used connector words in their concept maps. One of these student-created concept maps was transferred into paragraph form, as show in Table 1. Note that the terms are underlined, the connecting words are italicized. Normal text are words inserted in to make the sentence structure flow better are indicated in brackets []. From this table, a summary of the class can be extracted. Professors can note areas of inaccuracy that they can attempt to solve in future classes or note areas of accuracy that can further emphasize.

Table 1: A Concept Map Turned into a Narrative

Engineering analysis *involves* forces *found using* math *like* dot product and vector product. [These] forces *are found using* formulas, equilibrium equations, [or] moments. Forces *consider* friction, [which are either] kinetic [or] static. Engineering analysis [is] *done in reference to* design, [which is] *created for* business plans. Design [is] *usually of* structures *such as* trusses [and] cantilevers. Structures [can be] *analyzed by* methods of joints, methods of sections, [and] rechecks. Structures *must be* ethically sound (*meaning* oversight and approval of licensed engineers [and using] safety factor above legal obligation), well-designed *so* [it] holds up given physical stress/strain [and] in equilibrium, [and] statistically determinant.

Discussion and Implications

The concept maps proved to be a great way to learn how the class could be improved as a whole. Teachers can use this tool in order to learn how their students are reacting to the curriculum. However, throughout the experimentation and the observation of results, we learned that are several ways to improve on the shortcoming of concept maps in order to make them even more useful. Based on the results obtained, we recommended several changes to both the class and future iterations of the assignment. For the class, as stated earlier, an increased emphasis on moments and their relationship to Statics as a whole could increase student's ability to associate it with other concepts. This same sort of connection may also be needed regarding ethics so that students see its connection to almost every aspect of the course (and every decision an engineer makes).

As for the assignment, more overall structure is needed. In the first iteration, the concept map was on done on the back of the assignment paper without any guidance from the instructor. We recommended that the assignment be placed completely within its own side. In addition, the instructor doing an example of creating a concept maps for the students on a topic other than statics would help students that are confused as to how they should display the data. While looking through the concept maps, we realized that the center term differed often and students did not know where to start, occasionally creating two center terms or having concept maps that were concentrated away from the center node. When students started from different points, it became difficult to analyze the second level of nodes. In addition, the use of possible synonyms made coding challenging, since we did not actually know if students were using different words to describe the same concept.

One issue that was prevalent in the analysis was the vast variety of words used to describe the topics of the course. A general term such as forces would have many different ways of being described. Some students would write equations, some would write the types of forces, and others would incorporate it within multiple nodes throughout the concept map. This forced the combination of similar nodes when calculating the frequency and location of nodes on the maps. In order to prevent this, concept map assignments could benefit from having a general list of terms that students must include in their diagram. Regardless of whether the student decides to add additional terms or not, every map will have a common ground upon which it could be compared. Another issue in the analysis was that we wanted to use connector words in order to learn more about what linked terms together on an organizational basis. Unfortunately, very few of the students actually used the connector words, and among those that did, there was high variety in the way that they were used. Some students used advanced connector phrases such as "is as a result of" or "done in reference to", and others stuck to one word linking verbs such as "is" or "as". To improve this situation, we concluded that sample connector words and phrases should also be provided. We assembled a list of connector words that could be used by students. By displaying these, it reminds students while they complete their maps to continuously use them.

After the work done to analyze the concept maps and how they could be improved, the recommendations were implemented in the next quarter (Fall 2013). The new assignment used *Engineering Analysis* as the central node and was isolated into its own part on the page. As an explanation as to how the assignment was done, an example of a concept map done with "how a car works" was done during class. In addition, students were given a table of concepts they could use and check off the ones that they did use. Finally, a list of connector words were placed on the right in clear sight. An example of the new assignment can be found in Appendix A.

After the assignment, we took a small sampling of 20 of the assignments and did a brief analysis similar to that of the original assignment. The first thing we realized was that the new recommendations made the maps significantly easier to analyze. All of the students analyzed used connector terms to link their nodes and a majority stuck to the concept terms listed in the instructions. The moment node was also no longer placed on its own in a seemingly random place. In most of the cases, the moment's node was a connected outwardly or on the same level as the force's node. Another significant trend was the proximity of three terms on nearly every assignment: business, design, and ethics. Many students perhaps believed that ethics involved sacrificing the best monetary decision for what is good for the customer and the significance of design was to provide the customer with most intuitive and easy-to-operate product. In future engineering classes, using business to discuss design and ethics may be a sound strategy, as most ethics discussions often do not expand past simple and obvious situation in which lives are in danger.

Conclusion

We can conclude from the analysis of concept maps, that organizational tools can be significant in assessing whether students have learned what is desired of them throughout a course. By using concept maps in engineering courses, professors can gain insight into what it is like to be a student of their class. Based on this paper, are two main concept map approaches that instructors can use to improve teaching and learning. The first is to focus on the overall content of the course and have students outline their overall understanding of the course. Through this method, instructors can find unexpected areas that students struggle with, perhaps in gray areas such as moments. In addition, by figuring out that certain terms are naturally related, future labs and assignments can be tailored to make the learning process easier and more enjoyable for students. The second approach is to go after one topic. For example, if a professor notices that students struggled on an exam about free body diagrams, they can assign a concept map to students primarily on that topic. Then, by analyzing a selection, the professor could potentially notice that many students wrongly associate a certain equation or subtopic. Regardless of what approach an instructor chooses to use, it is evident that concept maps are a useful tool in assessing student knowledge and knowledge organization. Further analysis of concept maps can reveal more about the natural organization of engineering knowledge and universally improve college curriculums.

Acknowledgments

In creating this paper, I would like to thank Professor Sheri Sheppard for being a great advisor, a great person, and an excellent teacher of Engineering 14 who truly puts incredible effort into what she does on a daily basis. In addition, the continuous help I received from Dr. Mark Schar was instrumental and he introducing me to the Designing Education Lab was life-changing. I would like to thank Helen Chen, Shannon Gilmartin, and the rest of the Designing Education Lab for providing feedback, editing my papers, and helping me understand more about research and academia. Finally, I would thank the Mechanical Engineering department's research program (SURI) for providing the opportunity to spend my summer researching how to improve the engineering curriculum.

Bibliography

1. Faste, R. A., Roth, B., & Wilde, D. J. (1993). *Integrating Creativity Into The Mechanical Engineering Curriculum.* Stanford University, Mechanical Engineering Department. Stanford: Design Division, Mechanical Engineering Department.
2. Kolb, D. (1984). *Experiential learning: experience as the source of learning and development.* Englewood Cliffs, NJ: Prentice Hall.
3. Novak, J. C. (2008). *The Theory Underlying Concept Maps and How to Construct Them.* Pensacola: Institue for Human and Machine Cognition.
4. Turns, J. (2000). Concept Maps for Engineering Education: A Cognitively Motivated Tool Supporting Varied Assessment Functions. *IEEE Transactions On Education*, 164-173.
5. Weber State University. (2009, November). *Using Inspiration Software for Concept Mapping*. Retrieved from Weber State University: http://faculty.weber.edu/vnapper/3110/asgnConceptMaps.htm