Concept Mapping as a Form of Student Assessment and Instruction

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Abstract

As part of a concerted effort to improve Biomedical Engineering (BME) education, the Vanderbilt-Northwestern-Texas-Harvard/MIT Engineering Research Center (VaNTH ERC) is investigating alternative methods for assessing students' conceptual knowledge, and integrating an array of diverse competencies into the curriculum. One potentially useful tool for achieving these goals is concept mapping or the spatial representation of concepts and their interrelationships. This paper describes three studies investigating this potential. In Study One, three groups (i.e., BME undergraduates, graduate students and faculty) constructed concept maps in response to the question, "What are the 10-20 most important concepts in BME?" Group differences were consistent with expert-novice distinctions in structural knowledge. Faculty generated dense networks of higher-order principles (e.g., "the synthesis of engineering and medicine") and their applications (e.g., "interdisciplinary communication") while students generated fewer connections among concepts pertaining largely to domain content (e.g., "biotechnology," "physiology"). Study 2 conducted longitudinal and cross-sectional examinations of the development of expertise. Undergraduates in a yearlong design course responded at two different time points to the question, "What is your current conceptual understanding of what is involved in the BME design process?" Analyses revealed that, relative to maps constructed at the beginning of the course, end of the semester maps used more precise vocabulary, were more coherently constructed, and contained a greater number of connections among concepts. Student maps were also compared to a criterion map created by the course instructor. Study Three will investigate concept mapping as a form of instruction. Learning outcomes of students receiving traditional (i.e., taxonomy-driven presentation of concepts) and innovative (i.e., use of concept mapping as an advance organizer) instruction are being compared. Findings are discussed in terms of their implications for the role of concept mapping as a form of student assessment and instruction, and ultimately, a means to promoting lifelong learning.

Introduction

Biomedical engineering (BME) courses typically adopt traditional approaches to student assessment and instruction: assessment is usually a written test requiring students to provide correct answers to fact-based questions; instruction is largely a linear progression of lectures organized around the general taxonomy of the subject matter. Summaries of current research in the learning sciences, [1] however, suggest that these approaches offer students limited opportunities to develop a rich conceptual understanding of the fundamental principles and applications of a domain. As part of a concerted effort to improve BME education, the Vanderbilt-Northwestern-Texas-Harvard/MIT Engineering Research Center (VaNTH ERC) is investigating alternative methods for capturing and assessing students' conceptual knowledge, and integrating an array of diverse competencies into the curriculum. One potentially useful tool for achieving these goals, across all engineering fields, is concept mapping.

Invented during the 1970s by Novak and his colleagues at Cornell University, a concept map looks like a flow chart. However, instead of "mapping the linear or logical structure of knowledge, concept maps reflect the psychological structure of knowledge." [2] Theoretically, knowledge functions as a semantic network.[3] Thus, learning is not only the acquisition and understanding of concepts but also the construction of meaningful links among concepts.[4] Consistent with these theoretical perspectives, concept maps are composed of interrelated elements: nodes, lines and labels. Nodes represent concepts. Concepts are defined as "perceived regularities in events or objects, or records of events or objects, designated by a label."[5] For example, 'engineering' and 'experimentation' are concepts. Lines represent relations among concepts. Labels in the lines describe the nature of those relations (e.g., 'leads to') while arrowheads indicate the direction of the relationship. The combination of a pair of concepts and a line constitutes the fundamental unit of a concept map, a proposition. Each proposition, or unit of psychological meaning, is a statement "about some object or event in the universe, either naturally occurring or constructed" [5] (e.g., 'engineering leads to experimentation'). Figure 1 provides an example of a concept map and describes how concept maps can be structured.

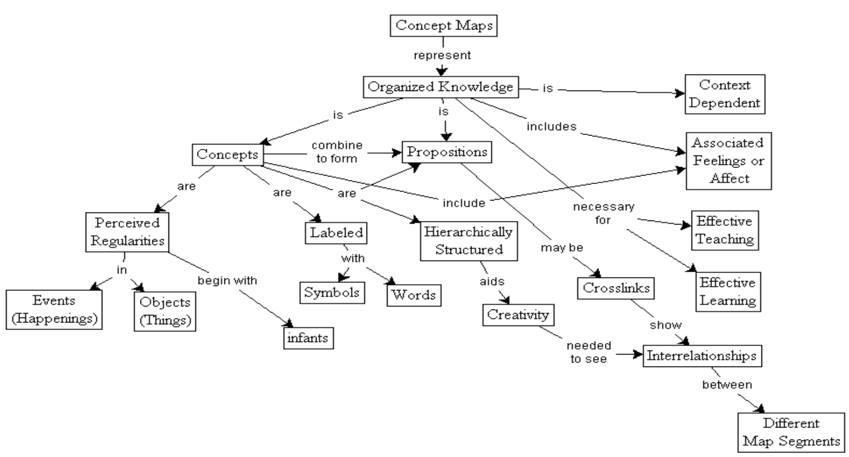

Figure 1. Example of concept map and description of how concept maps can be structured (Taken from Novak, 2000).

Concept maps can be used as a learning strategy, an instructional strategy, a strategy for curriculum planning, and a means of student assessment.[6] Use of concept mapping has been associated with the enhancement of numerous student outcomes including greater focus on salient rather than irrelevant aspects of the problem to be solved, [7] transfer of problem-solving skills, [8] and better test scores. [9,10] The technique may have these effects because it facilitates the achievement of a shared conceptual understanding between teacher and student. Learning is a private and individual process, thus it is often difficult for teachers to know what students do and do not understand. Unlike traditional forms of assessment (e.g., multiple-choice tests) and instruction, concept mapping allows teachers the opportunity to both observe how extensive and integrated a student's conceptual knowledge is, and share their own conceptual understanding with students. Moreover, concept mapping as a form of assessment offers teachers the opportunity to recognize a student's misconceptions, impediments to learning that traditional assessments may not detect.

Fundamentally, "the more concepts to which a given concept is linked, the better defined or explicated that concept is."[11] Put another way, the more dense the network, the better the thinking. This argument is supported by evidence that given identical problem spaces, novices and experts structure their knowledge in ways that are quite different.[12] Experts tend to display "conceptually rich tapestries of interrelated ideas" while novices tend to possess undifferentiated, incomplete and sometimes erroneous knowledge structures. [13] Further, experts appear to make efficient use of their dense networks while novices tend to portray their thinking in disorganized arrays. [14] To construe the goal of concept mapping as convergence between students' and teachers' maps, however, is to misunderstand the constructivist origins of the task. Theoretically, the power of concept mapping does not lie in the fact that it trains students to "think just like the teacher," but rather in its ability to actively engage students in the material, and portray the process of knowledge transformation as students move from novice to expert. For example, studies of students' concept mappings over time have revealed that as expertise within a domain is developed, vocabulary becomes increasingly precise and more interconnections between concepts are created.[10, 15,16,17] Further, given the often striking differences displayed among concept maps focused on the same problem space, it has been suggested that rather than emphasizing the technique as an assessment tool, instructors might reap greater benefits by using it to make the structure of the curriculum apparent to students, and to help students become aware of and critique their own learning frameworks and those of others.[18]

This paper describes three studies investigating concept mapping as a form of student assessment and instruction within the BME department at Vanderbilt University. Study 1 explored novice-expert distinctions. Three groups (i.e., BME undergraduates, graduate students and faculty) constructed concept maps in response to the question "What are the 10-20 most important concepts in BME?" Study 2 offered a longitudinal and cross-sectional window into the development of expertise. At multiple time points during a yearlong design course, undergraduates responded to the question "What is your current conceptual understanding of what is involved in the BME design process?" Student maps were also compared to a criterion map created the design course instructor. Study 3 will investigate concept mapping as an innovative form of instruction. In the sections that follow, each of these studies is described. The paper concludes with a discussion of the studies' findings as they relate to the potential of concept mapping as a method for capturing and assessing students' conceptual knowledge, and an instructional technique that integrates an array of diverse competencies into the BME curriculum. Future studies are also identified.

Study 1

Methods

Eight undergraduates, nine graduate students, and three professors in the BME department at Vanderbilt University participated in the study during the summer and fall of 2001. All participants were told that concept mapping was of interest to the VaNTH ERC because of its potential as a tool for student assessment and instruction. Although some participants indicated they were familiar with concept mapping, most had not previously used the technique. The first author asked for permission to tape record comments made during the task and to retain all maps created. As part of a brief orientation, several figures contained in Novak (2001) [5] were presented and the three basic components of concept maps were described. Although a variety of methods for eliciting the structure of conceptual knowledge exist, recent work has suggested that exploratory methods (e.g., generating a map "from scratch") are better tools for understanding differences among knowledge structures than "fill-in-the-blank" or confirmatory methods of elicitation.[19] Given that concept maps are theorized to reflect individual meaning making such recommendations make sense. For this reason, participants were told that the procedure for constructing a map involved generating a list of concepts, writing each concept on a separate post-it note™, and then spatially arranging the concepts according to the strength of their relationships. Participants were told that their maps could be structured as a hierarchy (i.e., a superordinate concept followed by tiers of increasingly subordinate concepts and examples) or as a non-hierarchical network. Participants were told that once they had generated and arranged the concepts to their satisfaction, they should copy the arrangement onto a single sheet of paper, and connect related concepts with an arrow. Each arrow was then to be labeled in a way that described the nature of the relationship between the linked concepts. Once this general overview had been given and any preliminary questions were answered, participants were given the following focus question: "What are the 10-20 most important concepts in BME and how are they related?" Undergraduate participants constructed maps in pairs. Three graduate students created maps individually and 6 others worked in pairs. Each professor constructed an individual map. In total, 4 undergraduate maps, 6 graduate student maps, and 3 professor maps were created. All pencil-paper maps created by participants were recreated using software tools available from the Institute on Human and Machine Cognition [http://cmap.coginst.uwf.edu]. When the mapping task was completed, participants also responded to a brief structured interview.

Method of Evaluation

The nodes, lines and labels of a map are theorized to represent the breadth, depth and connectedness of knowledge structures. Thus scoring involves quantifying these components. Although a variety of methods for scoring maps exist, [20] in this study, each node and each line used to create a proposition was counted. To quantify the density of the map, a node to line ratio was also calculated. The fact that some maps were structured hierarchically while others were not prohibited our use of other common scoring methods, such as Novak and Gowin's (1984) structural scoring system (i.e., awarding points for the number of hierarchies or crosslinks among hierarchies). [13]

Results & Discussion

Results were consistent with expert-novice distinctions in structural knowledge. Faculty generated dense networks of higher-order principles (e.g., "the synthesis of engineering and medicine") and their applications (e.g., "communication with professionals outside the field") while students generated fewer connections among concepts pertaining largely to domain content (e.g., "biotechnology," "physiology"). Examples of novice and expert maps are presented in Figures 2 and 3, respectively.

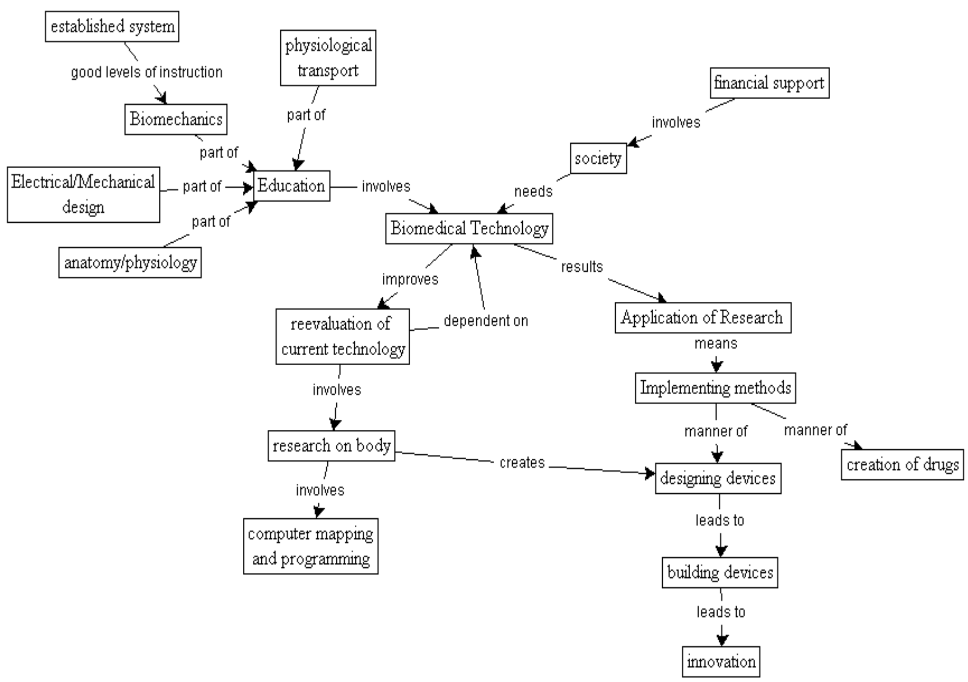

Figure 2. Undergraduate concept map constructed in response to the focus question, "What are the 10-20 most important concepts in BME?"

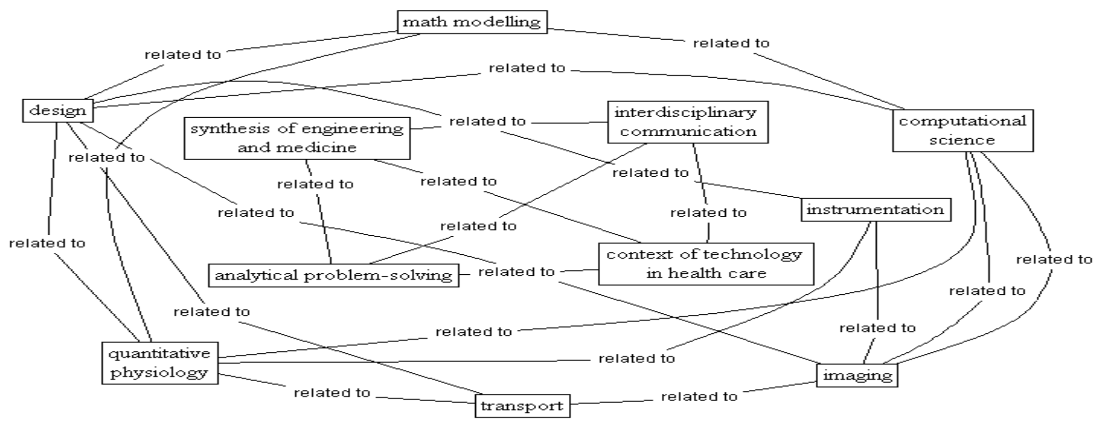

Figure 3. Faculty concept map constructed in response to the focus question, “What are the 10-20 most important concepts in BME?”

Specifically, analyses of responses to the question “What are the 10-20 most important concepts in BME?” revealed that undergraduates used an average of 20 concepts and 25 lines to represent the domain of BME (nodes, M = 20, range = 14 to 24; lines, M = 24.50, range = 15 to 34; node:line = .82). Graduate student maps contained a smaller average number of nodes and lines (nodes, M = 16.67, range = 11 to 21; lines, M = 19.83, range = 12 to 26). However, these differences did not create a difference between undergraduate and graduate students in terms of node:line (graduate student, node:line = .84). Faculty maps had a much lower node:line than student maps (nodes, M = 16, range = 11 to 24; node:line = .62). These results are summarized in Table 1.

Table 1. Mean number of nodes and lines, node:line, and range in BME undergraduate, graduate student and faculty concept maps.

Group	Nodes	Lines	Node:Line	Range
Undergraduate	20.00	24.50	.82	14-24
Graduate	16.67	19.83	.84	11-21
Faculty	16.00	25.67	.62	11-24

While the quantitative novice-expert differences in terms of density are notable, important qualitative distinctions were also found. First, experts mentioned not only domain knowledge, but also the importance of core competencies or the application of domain knowledge (e.g., “persuasiveness,” “understanding the context of technology in health care”). References to these competencies were rare among student maps. Fundamentally, this difference suggests that students either do not consider, or do not know how to consider, the practical applications of their domain knowledge, even at the graduate level.

Another striking difference between students and faculty was the amount of time it took to complete the task. For students, the mapping task took approximately 30-45 minutes.

For professors, the task took about 10-15 minutes. Of course, this difference could be due to the fact that students worked in pairs and thus spent time discussing the content and coordinating procedures. Another interpretation consistent with the literature, however, is that experts make efficient use of their semantic networks. This efficiency is evinced in the following description of how one professor constructed his map. After receiving a brief verbal explanation of the task, Professor 3 asked whether the map's content should include knowledge or skills or both. He was told the map should contain whatever he thought was most relevant, and if that meant knowledge *and* skills, then both should be included. He quickly generated a list of concepts, writing each on a separate post-it note™. He then arrayed the notes on the surface of a coffee table. After moving them around a bit, he settled on a non-hierarchical map: Four central competencies surrounded by seven sub-areas (see Figure 3). As he explained it, each of the four central nodes was necessary for success as an engineer, however, not all of the sub-areas were necessary.

Other qualitative data was gathered from structured interviews with the participants. For example, when students were asked how concept mapping might be useful in their BME education most said the technique would be helpful in organizing and presenting the curriculum. In the words of one graduate student, “I think everyone would benefit from a more organized teaching style—it makes it hard to see the overall picture in academics sometimes when the professor doesn't link the material together." Professors and students alike expressed concern about the broad nature of the focus question (e.g., “I think these types of concept maps are less useful for understanding concepts such as ‘What is Biomedical Engineering?’ and more useful for understanding complex systems with multiple parts that interact in multiple ways (i.e. systems of the body, biochemical reactions, etc.)."

In sum, while the mapping task succeeded in giving a cross-sectional view of the development of expertise, the broad focus question may have limited our ability to make substantive inferences about students’ conceptual understanding on the basis of how their maps compared to those of faculty. For this reason, in Study 2 we selected a more specific focus question. We also expanded our work to include longitudinal and cross-sectional assessments. We did so by assessing the knowledge structures of undergraduates over time and comparing those structures to a criterion map.

Study 2

Methods

Participants included four students enrolled in a yearlong senior level design class and the design course instructor. Orientation and methods of elicitation were the same as in Study 1. Working in pairs, undergraduates responded to the question: “What is your current understanding of what is involved in the BME design process?” Maps were constructed at two time points: shortly after the beginning, and during the final week of the fall semester of 2001. (Undergraduates will construct a third map at the end of the spring semester of 2002.) The instructor constructed a criterion map pertaining to the same focus question at the end of the fall semester of 2001.

Method of Evaluation

As in Study 1, each node and each line used to create a proposition was counted. To quantify the density of the map, a node to line ratio was also calculated. Additionally, student maps were rated for their validity according to McClure and Bell's (1990) relational scoring method.[21] Specifically, the validity of each proposition was rated for correctness based on the line label: 0 points were given for an invalid or misconceived link; 1 point was given for a partially valid, general or imprecise link; 2 points were given for a moderately valid or correct but incomplete link; 3 points were given for a valid, precise, and clearly stated link. A mean validity score was calculated by dividing the total number of these points by the total number of propositions.

Results & Discussion

Consistent with previous findings in the literature, analyses showed important qualitative differences between each pair's Time 1 and Time 2 maps. Specifically, later maps used more precise vocabulary, were more coherently constructed, and contained more connections among concepts. At time 1, Pair 1 generated a map containing 14 nodes and 14 lines (node:line = 1.00). At time 2, their map contained 22 nodes and 26 lines (node:line = .81). Relative to the first pair, the second pair of students generated a greater number of nodes and lines at both time 1 (nodes = 27, lines = 30; node:line = .90) and time 2 (nodes = 35, lines = 39; node:line = .90). The criterion map had 74 nodes, 85 lines and a node:line of .87. These results are summarized in Table 2. The validity of each proposition contained in the student maps at Time 1 and Time 2 was also rated. These results are summarized in Table 3.

Table 2. Number of nodes and lines, and node:line in undergraduate and instructor criterion maps of the BME design process.

	Time 1			Time 2		
Group	Nodes	Lines	Node:Line	Nodes	Lines	Node:Line
Pair 1	14	14	1.00	22	26	.85
Pair 2	27	30	.90	35	39	.90
Instructor	--	--	--	74	85	.87

Table 3. Validity ratings of undergraduate maps of the BME design process.

	Pair1		Pair 2	
Validity	Time 1	Time 2	Time 1	Time 2
Number of invalid links (0 points)	3.00	0.00	0.00	0.00
Number of partially valid links (1 point)	6.00	2.00	0.00	1.00
Number of moderately valid links (2 points)	5.00	11.00	12.00	12.00
Number of valid links (3 points)	0.00	8.00	16.00	20.00
Mean validity score	1.14	2.28	2.59	2.58

Figures 4 and 5 depict the conceptual understanding of the first pair of students at Time 1 and Time 2, respectively. Figures 6 and 7 depict the conceptual understanding of the second pair of students at Time 1 and Time 2, respectively. The instructor criterion map is presented in Figure 8.

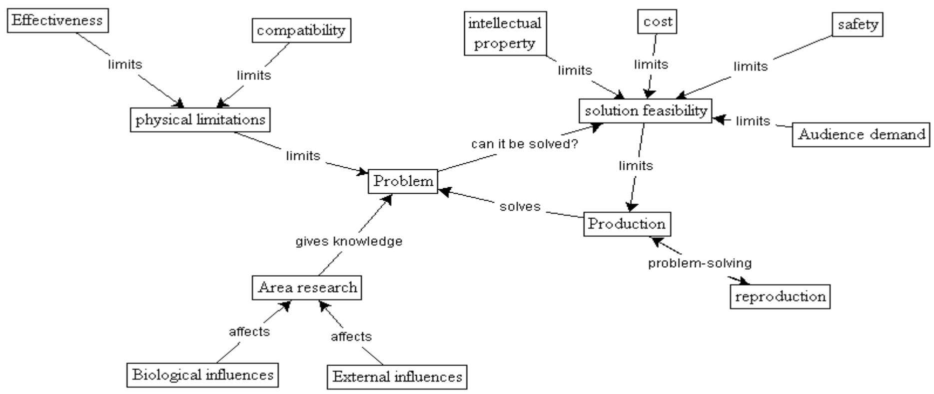

Figure 4. Concept map constructed by Pair 1 at Time 1 in response to the focus question, “What is your current conceptual understanding of what is involved in the BME design process?”

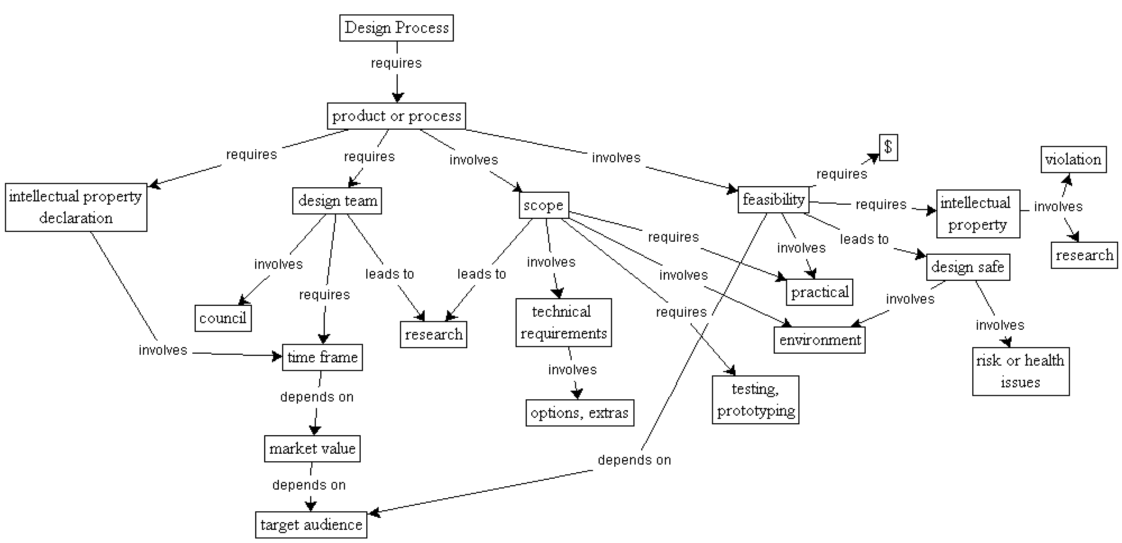

Figure 5. Concept map constructed by Pair 1 at Time 2 in response to the focus question, “What is your current conceptual understanding of what is involved in the BME design process?”

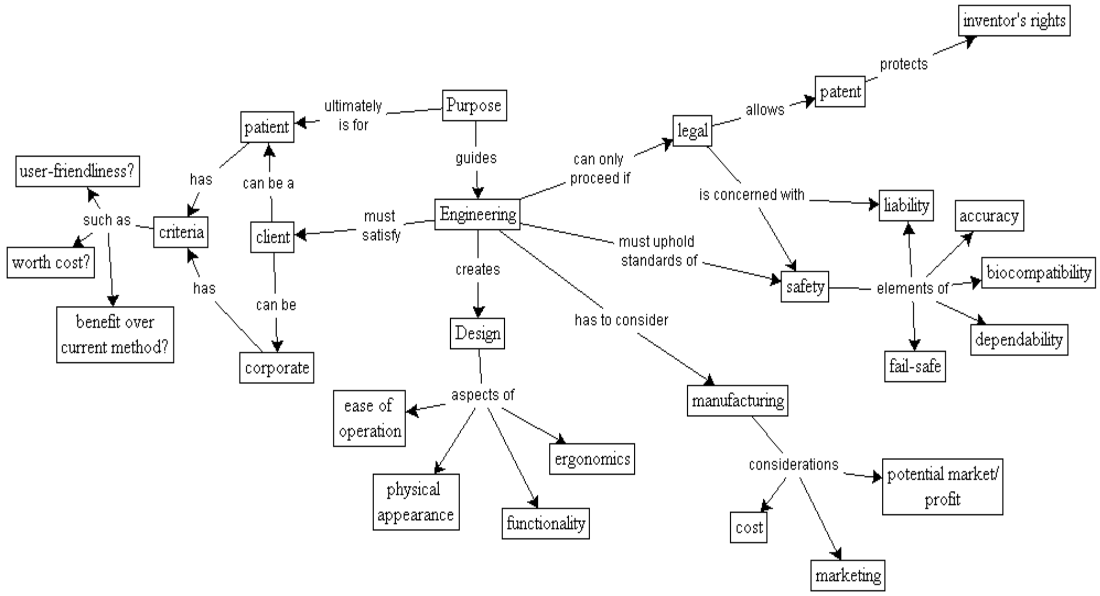

Figure 6. Concept map constructed by Pair 2 at Time 1 in response to the focus question, "What is your current conceptual understanding of what is involved in the BME design process?"

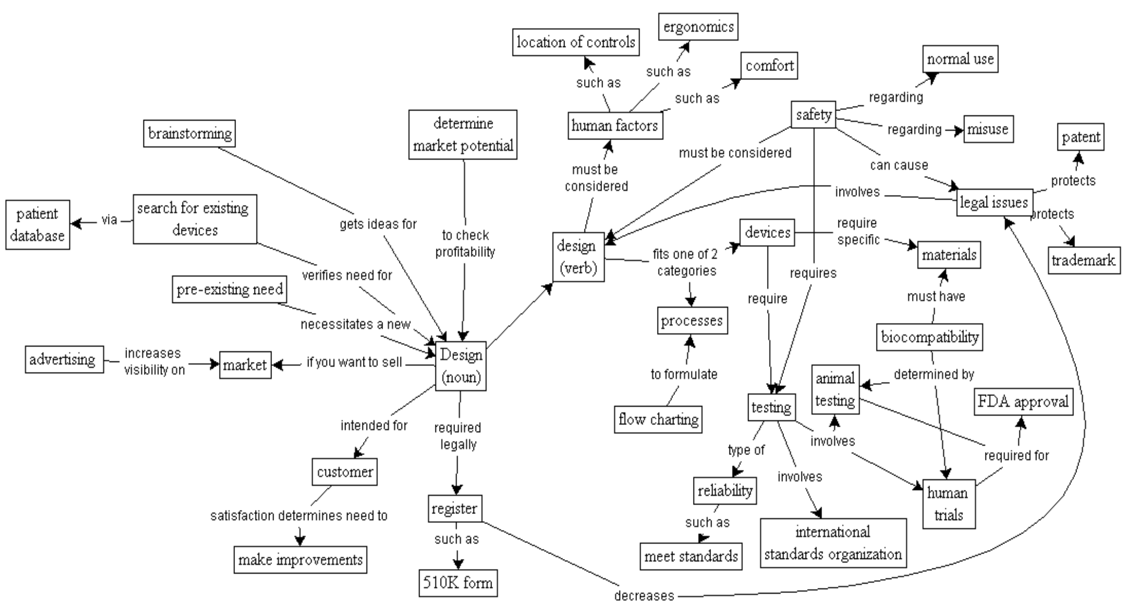

Figure 7. Concept map constructed by Pair 2 at Time 2 in response to the focus question, "What is your current conceptual understanding of what is involved in the BME design process?"

Upon completing their Time 2 maps, both pairs were asked to compare and comment on differences between their own and one another's mappings of the BME design process. Pair 1 was highly critical of their first map, both in quantitative and qualitative terms. They complained about the simple structure (i.e., small number of nodes and lines) of their first map and the fact that it failed to contain the word "design." This pair's later map contained more nodes and links, and was more coherently structured. It contained a superordinate concept (i.e., "design") followed by tiers of increasingly subordinate concepts (i.e., "process or product," "feasibility", "scope") and examples. The students articulated the qualitative difference between their early and late work as "reactive vs. proactive." For example, labels describing the nature of the relationships among concepts at Time 1 largely expressed limitations or constraints on the design process. The later map focused more on generating solutions or the creative aspects of design. These observations are consistent with the doubling of this pair's validity score between Time 1 and Time 2. While some concepts may have been absent from the early map because those topics had not yet been covered in class, this pair's later map also failed to represent important aspects of design that had been stressed during the semester. For example, the iterative nature of the design process was not represented: Few crosslinks were created between hierarchies or important subordinate concepts. Additionally, limited reference was made to issues of licensing or outside influences, safety and institutional matters such as FDA approval.

Although Pair 2's density and validity scores did not change between Time 1 and 2, the coherency of their maps differed considerably. At Time 1, this pair created a map with two central propositions: "purpose guides engineering" and "engineering creates design." They characterized the structure of this map as an "explosion" focused on the motivation for design (e.g., "client needs"). Further, in the early map, the node labeled as "design" was linked only to surface features such as "physical appearance" and "ease of operation." The majority of links emanated from the node labeled "engineering." At Time 2, this pair constructed a non-hierarchical, iterative map focused on differentiating design as a noun from design as a verb. Design as a noun related to market concerns. The noun concept of design led to two categories of design as a verb (i.e., "processes" and "devices") involving issues of human factors, safety, materials, testing, and liability. These concepts in turn, fed back into issues of manufacturing and marketing. These connections created small feedback loops among various BME design concepts.

Finally, differences between Pair 1 and Pair 2 at both time points demonstrate the wide variability often observed among concept mappings, even among students who are at the same level of professional development. For example, Pair 1 pointed out that relative to their own mappings, Pair 2's maps gave greater consideration to the needs of the client (e.g., "ergonomics") and legal issues. It is possible, however, that improvements in both pairs' mappings were due to practice with the concept mapping technique. While unlikely, future studies should control for this possibility by eliciting first-time maps from other design course students at similar time points across the semester.

Interestingly, before beginning their second maps, both pairs said they thought they had not learned a great deal since constructing the first map. In fact, they wondered if their later maps would contain as many concepts. At the beginning of the semester they had been "cramming things in." Of late, they had been focusing more on application. Thus, it was gratifying to observe the students' surprise and pleasure at the tangible evolution in their thinking. Such reactions gave clear evidence that the mapping task offered students a valuable window into their own conceptual understanding, and provided a form of feedback that traditional summative forms of assessment (i.e., final exams) had not. At the end of the yearlong course, these students will complete a third and final map. We expect that these maps will reflect even greater conceptual integration (i.e., connectedness) and differentiation (i.e., precision in vocabulary) once students have applied their domain knowledge to the design process.

As in Study 1, we were interested in novice-expert distinctions. Comparison of student maps to a summative criterion map created by the course instructor at the end of the fall semester (see Figure 8) revealed findings both different from and consistent with Study 1. Unlike Study 1, node:line scores did not differ strikingly between novice and expert mappings (see Table 2). Consistent with Study 1, however, there were notable differences between novices and experts in terms of the degree to which concepts were explicated. For example, Pair 1's superordinate concept "design" was linked to only one other concept, "product or process." This node was, in turn, linked to 4 other concepts. Pair 2's "design as a noun" concept was linked to 8 other nodes while "design as a verb" was linked to 6. By contrast, the criterion map's central node of "BME design" was linked to 4 nodes. One of these, "the design process," was linked to 11 other nodes. These differences created numerous dead ends among student maps while the criterion map contained multiple feedback loops, a hallmark of the design process.

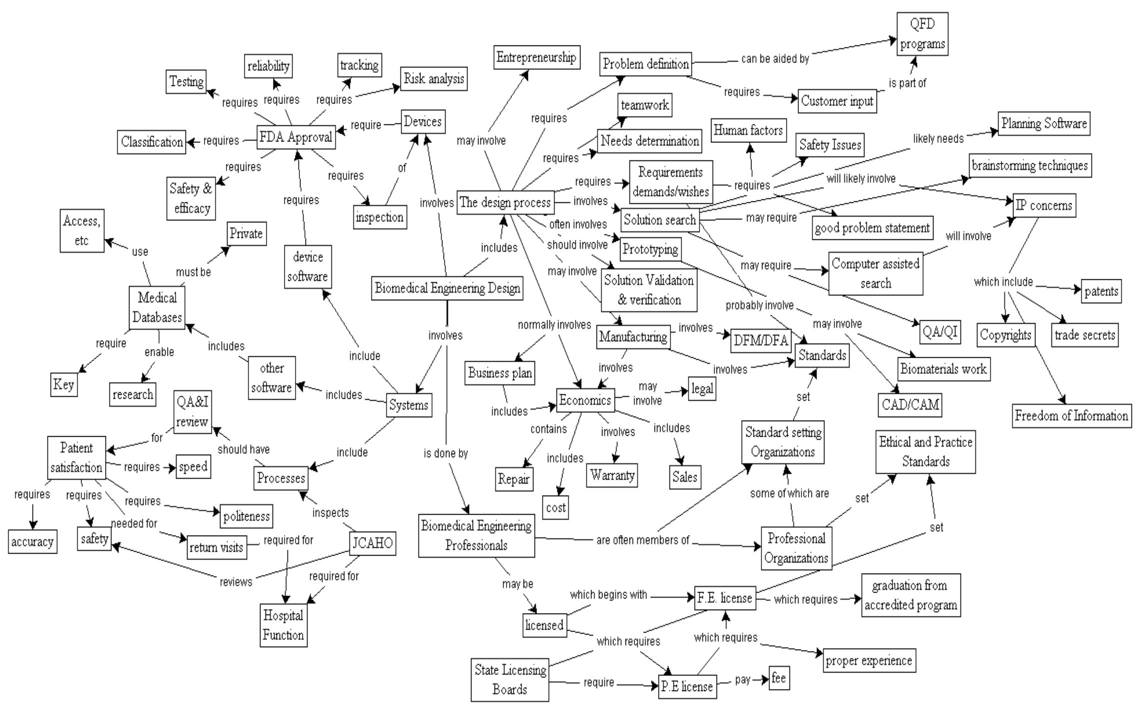

Figure 8. Criterion map created by the design course instructor in response to the focus question, "What is your current conceptual understanding of what is involved in the BME design process?"

In sum, the longitudinal findings suggest that concept mapping offers important benefits to students at little cost to the instructor. Unfortunately, as in Study 1, our ability to make meaningful comparisons between novice and expert mappings was hampered by differences in the maps' structures (i.e., comparability of hierarchical and non-hierarchical maps). Because students expressed enthusiasm for the technique not only as a means to seeing their own intellectual growth but also as an instructional tool that "hooks things up," in the next study we examine concept mapping as an innovative form of instruction.

Study 3

Methods

Study 3 has not yet been completed. All students (n = 61) currently enrolled in the traditionally taught yearlong design course are serving as a control group. Next year, the instructor will use concept mapping as an instructional tool (i.e., advance organizer). These two groups, Traditional and Innovative, will be compared in terms of their performance on parallel exams, course evaluations, and measures of intrinsic motivation, study strategies, and career goals and preferences. To control for pre-existing group differences that might obscure the influence of instructional change, students in the Traditional and Innovative groups will also be compared in terms of individual differences (e.g., GPA, SAT scores). Additionally, a small number of students within the Innovative group will be asked to create mappings of their conceptual understanding of design at three time points parallel to those in Study 2. Thus, Study 3 offers not only data on the effects of concept mapping as a form of instruction, but also a replication of Study 2, testing concept mapping as a form of student assessment. In general, we expect to find that relative to the Traditional group, Innovative students will perform better on exams, give more positive course evaluations, and have greater intrinsic motivation for their assignments. Further, we expect that because of the students' exposure to concept mapping as a form of instruction, relative to the sample of Traditional design students observed longitudinally in Study 2, Innovative students will consistently construct more coherent concept maps.

General Discussion

Studies 1 and 2 examined two approaches to using concept maps as a form of student assessment; criterion-referenced (i.e., novice-expert comparisons) and norm-referenced (i.e., comparison among students). Results for Study 1 were consistent with expert-novice distinctions in structural knowledge: Advanced engineers generated dense networks of higher-order principles and their applications while students generated fewer connections among concepts pertaining largely to domain content. These findings suggest that concept maps are a useful means to portraying the process of knowledge transformation from novice to expert. Given the stark differences in expert-novice mappings in both studies, however, we find it difficult to recommend that students be evaluated in terms of how well their maps converge with those of faculty. It is possible, however, that given a more tightly focused question about a specific issue or process (e.g., ethics), comparison of student maps to criterion maps might prove a useful form of summative assessment. Future work should address this possibility. For example, replications of these studies might constrain the structure of maps to hierarchical formats only. Structural consistency among maps would allow for the use of a richer scoring system. Additionally, rather than asking students to generate a list of concepts, students might be asked to spatially array a list of concepts generated by faculty during the creation of a criterion map. Such a constraint might enhance our ability to compare student and faculty concept mappings. Finally, when observing students' conceptual understanding longitudinally, rather than constructing a new map each time students might use their earlier map as a base for construction. This might allow a more definitive metric of differences between maps across time.

In general, we find that these results best support the use of concept mapping as a norm-referenced form of assessment. Study 2 revealed growth in individual students' conceptual understanding across time: Compared to earlier maps, maps constructed at the end of the semester were more integrated (i.e., contained a greater number of connections), and more differentiated (i.e., used more precise vocabulary, were more coherently constructed). Moreover, capturing these differences in concept mapping form allowed students to observe and critique their intellectual growth in a way that traditional summative assessments had not. This suggests that concept mapping is a valuable formative assessment that provides substantial benefits to students, in terms of motivation and critical thinking skills, while exacting minimal cost from the instructor in terms of time and materials. One could easily envision instructors giving students a brief orientation to the technique, and then asking them to construct maps (either individually or in pairs) at multiple time points during the semester. Students could then critique one another's concept maps or compare their maps to a criterion map created by the instructor. Used in such a way, concept mapping exemplifies classroom instruction that promotes active engagement in learning. [22] Specifically, it emphasizes four interrelated attributes of optimal learning environments: 1) acknowledgement of the learners' prior knowledge, 2) demonstration of knowledge or what mastery looks like, 3) assessment that makes thinking visible, and 4) establishment of community norms that support learning.[1]

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Bibliography

1. Bransford, J. D., Brown, A. L., & Cocking, R. R. (Eds.). (1999). How people learn: Brain, mind, experience, and school. Washington, DC: National Academy Press.
2. Wandersee, J. H. (1990). Concept mapping and the cartography of cognition. Journal of Research in Science Teaching, 27(10), 923-936.
3. Collins, A. M., & Quillian, M.R. (1969). Retrieval time from semantic memory. Journal of Verbal Learning and Verbal Behavior, 8(2), 240-247.

4. Ausubel, D. P. (1968). Educational psychology: A cognitive view. New York: Holt, Rinehart and Winston.
5. Novak, J. D. (2000). The theory underlying concept maps and how to construct them. [http://cmap.coginst.uwf.edu/info/]
6. Novak, J. D. (1990). Concept mapping: A useful tool for science education, Journal of Research in Science Teaching, 27(10), 937-950.
7. Okebukola, P. A. (1992). Can good concept mappers be good problem solvers in science? Research in Science and Technological Education, 10(2), 153-170.
8. Ault, C. R. (1985). Concept mapping as a study strategy in earth science. Journal of Science College Teaching, 15(1), 38-44.
9. Pankratius, W. J. (1990). Building an organized knowledge base: Concept mapping and achievement in secondary school physics. Journal of Research in Science Teaching, 27(4), 315-333.
10. Wallace, J. D., & Mintzes, J. J. (1990). The concept map as a research tool: Exploring conceptual change in biology. Journal of Research in Science Teaching, 27(10), 1033-1052.
11. Jonassen, D. H., Reeves, T. C., Hong, N., Harvey, D., & Peters, K. (1997). Concept mapping as cognitive learning and assessment tools. Journal of Interactive Learning Research, 8(3/4), 289-308.
12. Chi, M. T. H., Glaser, R. & Farr, M. J. (1988). The nature of expertise. Hillsdale, NJ: Lawrence Erlbaum.
13. Novak, J. D., & Gowin, D. B. (1984). Learning how to learn. New York: Cambridge University Press.
14. Stevens, R. H., Lopo, A. C., & Wang, P. (1996). Artificial neural networks can distinguish novice and expert strategies during complex problem-solving. Journal of the American Medical Informatics Association, 3, 131-138.
15. Beyerbach, B. (1988). Developing a technical vocabulary on teacher planning: Pre-service teachers' concept maps. Teaching and Teacher Education, 4(4), 339-347.
16. Hoz, R., Tomer, Y., & Tamir, P. (1990). The relations between disciplinary and pedagogical knowledge and the length of teaching experience of biology and geography teachers. Journal of Research in Science Teaching, 27(10), 973-986.
17. Turns, J., Atman, C. J., & Adams, R. (2000). Concept maps for engineering education: A cognitively motivated tool supporting varied assessment functions. IEEE Transactions on Education, 43(2), 164-173.
18. Edmondson, K. M. (2000). Assessing science understanding through concept maps. In J.J. Mintzes and J. H. Wandersee (Eds.), Assessing science understanding: A human constructivist view. San Diego, CA, US: Academic Press, Inc. (pp. 15-40).
19. Ruiz-Primo, M. A., Schultz, S. E., Li, M., & Shavelson, R. J. (2001). Comparison of the reliability and validity scores from two concept-mapping techniques. Journal of Research in Science Teaching, 38(2), 260-278.
20. Ruiz-Primo, M. A., & Shavelson, R. J. (1996). Problems and issues in the use of concept maps in science assessment. Journal of Research in Science Teaching, 33(6), 569-600.
21. McClure, J. R., & Bell, P. E. (1990). Effects of an environmental education-related STS approach instruction on cognitive structures of preservice science teachers. University Park: Pennsylvania State University, College of Education. (ERIC Document Reproduction Service No. ED 341 582).
22. Roth, W., & Roychoudhury, A. (1993). The social construction of scientific concepts or the concept map as conscription device and tool for social thinking in high school science. Science Education, 76(5), 531-557.

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