Concept Maps for Engineering Education: A Cognitively Motivated Tool Supporting Varied Assessment Functions

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***Abstract*—Assessment in the context of education is the process of characterizing what a student knows. The reasons to perform assessment are quite varied, ranging from a need to informally understand student learning progress in a course to a need to characterize student expertise in a subject. Finding an appropriate assessment tool is a central challenge in designing an assessment approach. The focus of this paper is on the use of concept maps for both course-level and program-level assessment in engineering education. Concept maps, which are node and arc representations of the relationships among concepts, provide one means to represent student knowledge. This paper presents background on concept maps and describes uses of concept maps at both the course and program level.**

***Index Terms*—Assessment, classroom assessment, concept maps, program assessment.**

I. Introduction

ASSESSMENT in the context of education refers to the process of characterizing what a student knows [1]. The reasons to perform assessment are quite varied. At the course level, the goal may be to explore what students are learning or to assign a grade. At the program level, the goal may be to explore students' conceptions of an overarching topic or to verify student mastery of a knowledge domain.

Finding an appropriate assessment tool is a central challenge in designing an assessment approach [2], [3]. The difficulty arises because of the diversity of learning objectives [4], the diversity in what counts as evidence of learning [1], the diversity of tools available [2], the varying resources available, and the varying assessment contexts.

One way to address these various assessment goals and challenges is through the use of concept maps, which are node and arc representations of the relationships among concepts. Concept maps represent a valuable assessment tool because they provide a means to capture and represent student knowledge and are particularly effective for representing the organization that students see among concepts. This paper presents background on concept maps and then describes six uses of concept maps for assessment, three at the course level and three at the program level. The aim is to illustrate the flexibility of concept maps in supporting assessment in engineering courses and programs.

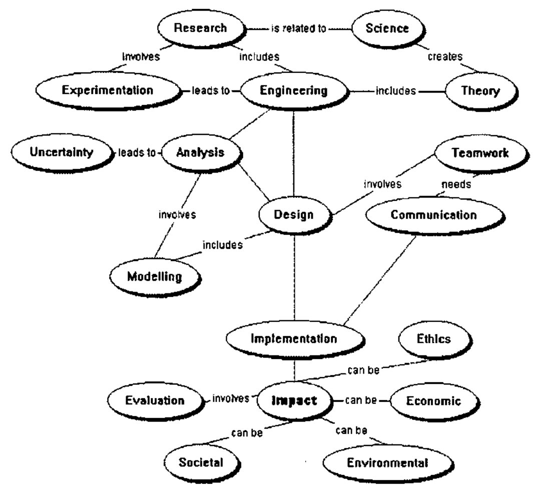

Fig. 1. Concept map for engineering.

II. Concept Maps

A concept map is a graphical node-arc representation of the relationships among a collection of concepts [5]. Fig. 1 represents an example concept map showing 18 important concepts in engineering and some relationships among these concepts. The nodes of the map contain the concepts, such as experimentation, research, and modeling. The links between the nodes capture the relationships among concepts. The labeling of the links provides information about the nature of the relationships. For example, labeling allows the creation of propositions such as "research is related to science" and "science creates theory."

Interest in concept maps stems from their relationship to memory and learning theory. A prominent element of semantic memory theory is that of associative networks of knowledge [6]. The central premise is that knowledge is stored in a network format where concepts are connected to each other. The more tightly interconnected the knowledge representation, the more likely it is that a person will recall information at the appropriate time. From the learning perspective, Ausebelian learning theory (or more generally, constructivist learning theory) posits that a learner attains new knowledge through a process of integrating new knowledge with existing knowledge [7]. In this case, a network representation can be used to show the integration of different concepts. These different theoretical bases for concept maps have resulted in different terms' being

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used to describe concept maps including semantic networks (e.g., [8]) and knowledge maps (e.g., [9]).

Concept maps have been used for a variety of educational purposes [10], [11]. Researchers have used concept maps as a means for displaying and communicating information (e.g., [12]–[14]) and as a tool to support the design of instructional materials [15]. Others have focused on concept map construction as an instructional activity [16]–[19]. Still others focus on the role of concept maps in assessment.

Using concept maps as part of an assessment approach requires consideration of two issues: 1) how the maps will be constructed and 2) how they will be interpreted. Perspectives on addressing these two related issues have resulted in two approaches. More detail on these approaches follows.

A. Approach 1: Student Generated Concepts

In this approach, the maps represent the collection of concepts and propositions a student identifies as related to a main topic. Concept maps are constructed either directly by the learner or indirectly by a researcher based on concepts and relationships described by the learner during interviews.

The interpretation of the map can involve both quantitative scoring and qualitative judgments on the appropriateness of the links. The interpretation involves scoring the map along a variety of dimensions such as 1) the number of concepts, 2) the number of links, 3) the number of cross links, 4) the number of hierarchy levels, and 5) the number of examples. These scoring dimensions represent characteristic features of knowledge such as breadth, depth, and connectedness. The dimensions also stem from the theoretical motivations for concept maps including the theoretical notions of subsumption, progressive differentiation, and integrative reconciliation [7]. In addition to scoring concept maps along these dimensions, the maps can be inspected for the number of valid and invalid propositions as well as the presence or absence of critical concepts and links based on input from an expert or referent source.

Novak and Gowin were early users of concept maps [5]. In the late 1970's, they were interested in demonstrating that young science students could understand complex scientific concepts. To this end, they collected many hours of interview data from students and wanted to represent the student understanding present in the interviews. The concept map provided a means of showing the connections the students had made among the concepts being studied. This initial work led to over a decade of research on science learning, including a longitudinal study [20]. Other examples of this approach include the work by Beyerbach where researchers had student teachers iteratively create a concept map of the topic “effective teaching” in order to understand the teacher's final perspective on the topic as well as the evolution of their perspective [21].

Recent research on concept maps created with student-generated concepts has focused on determining the validity of concept maps as an assessment tool. One validation study focused on demonstrating that concept map scores show an increase after instruction [22]. This study found that concept map scores captured effects of instruction even when standardized tests did not. Another study explored the dependence of the different dimensions used to characterize a single map in order to determine whether individual scoring dimensions should be combined into a single overall metric or treated as a vector of individual scores [23]. They found scores on many of the dimensions to be independent and thus more powerful when treated as a set of individual scores rather than combined quantitatively into a single overall metric.

A strength of the student-generated concepts approach is that emphasis is placed on understanding how a specific student understands a particular domain. The approach can capture individual differences as either concepts or links that are or are not included. However, while the concept maps resulting from this approach can be insightful, they can also be large, complicated, and difficult to interpret. It can be difficult to provide a final judgment about a student's knowledge.

Another concept map assessment approach provides a remedy to this. The assessment involves a quantitative comparison between two concept maps—the student's map and the expert's map.

B. Approach 2: Externally Generated Concepts

In this approach, a student's knowledge about the relationships among a set of *predefined* concepts is captured in a concept map. In some studies, students directly construct the map; in others, the map is created based on the mathematical Pathfinder algorithm using student judgments of the relatedness of pairs of concepts [13].

Interpretation of the map is based on the premise that learning in a domain is a process of acquiring the expert-like organization of a set of domain relevant concepts. Research on semantic memory, specifically associative theories of memory, indicates that experts have a specific type of organization of concepts. Following from this result, the interpretation of a map is performed by determining the similarity between a student's map and a referent map. The referent map might be one constructed by an expert based on his/her own knowledge or one constructed to represent key knowledge in a textbook. The measure of similarity between the two maps is an assessment of the student's knowledge. Goldsmith explored this issue by comparing several similarity metrics and identifying the ones that led to the best results [24]. In this approach, the labels of links are typically ignored.

Examples of this use of concept maps in assessment exist in the domains of statistics [25], aviation [26], global atmospheric change [27], and teacher knowledge [28]. Some of this work is motivated by a desire to understand what the subjects do and do not know. For example, Hoz *et al.* were interested in characterizing teacher pedagogical and domain knowledge in biology and geography [28]. Other work has focused on validating this approach by comparing concept map results with results of other accepted assessment methodologies [29].

C. Uses in Engineering Education

The previous discussion focused on an abstract description of concept maps as assessment tools. This description suggests that concept maps can be a valuable assessment tool. The goal of this paper is to demonstrate that concept maps can be a valuable tool for addressing assessment issues arising in engineering

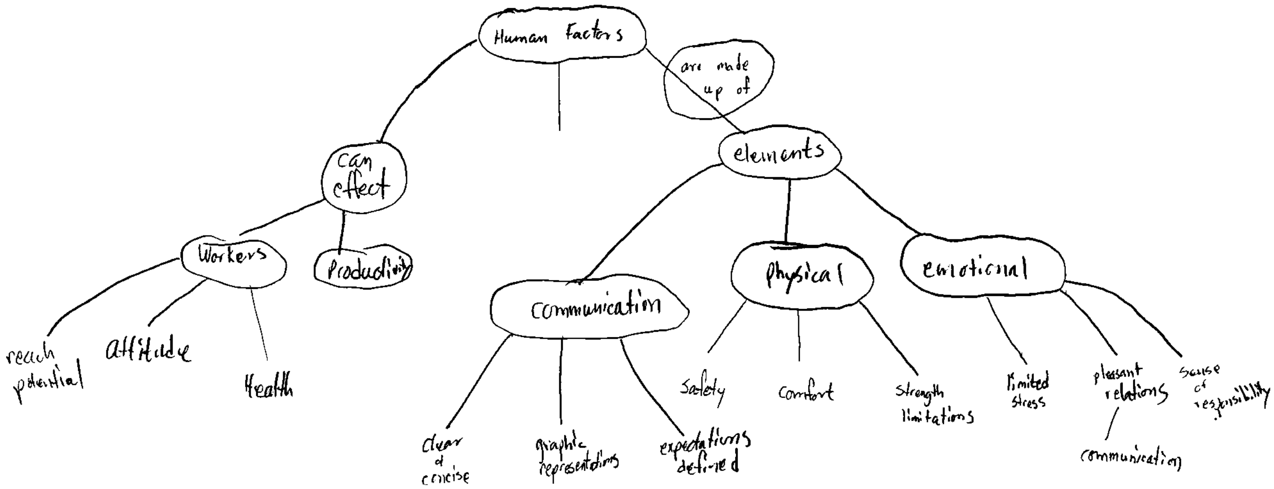

Fig. 2. Initial human factors concept map.

education. The remainder of this paper focuses on uses of concept maps to address specific assessment scenarios arising in engineering education. Specifically, this paper provides six examples of concept map use to address assessment needs in engineering education—three that address course-level assessment and three that address program-level assessment.

III. Concept Maps for Course-Level Assessment

Course-level assessment refers to assessment of the knowing and learning associated with specific courses. The purposes of such assessment include quickly gauging students' understanding, assigning a grade, or exploring what students perceive themselves to be learning.

A. Classroom Assessment: Quickly Gauging Understanding

Concept map construction and interpretation can be used as a form of classroom assessment. The goal of classroom assessment is to quickly explore what students are understanding at a particular moment [3].

The use of concept maps in a semester-long introductory human factors course at the University of Pittsburgh illustrates how concept maps can be used for classroom assessment. As an engineering subject, "human factors" refers to the body of knowledge used to understand issues and make decisions concerning a human's role in a socio-technical system. Typically, students enter a human factors class with some level of prior understanding of the subject matter based on their experience with existing technologies. The terms *human* and *factor* are readily understood, and this adds to a student's prior understanding of the field. A course in human factors typically introduces students to new concepts and theories such as physiology, memory theory, and reaction time laws. As such a course progresses, students are expected to develop a more theoretically sophisticated vocabulary. In addition, students are expected to develop a more complex understanding of the interconnections among the concepts.

Concept maps were used as a classroom assessment tool in order to explore the incoming conceptions and to verify progress in the development of both technically sophisticated vocabulary and interconnections among the terms. Specifically, concept maps were used during the first week of the term to assess incoming knowledge and then again during the ninth week of the term to monitor the effectiveness of the instruction. At each point, students were told to form impromptu teams of four. The students were to individually think of concepts. The group then created a map, adding additional concepts as necessary. The maps were interpreted informally during class. This use of concept maps for assessment is consistent with Approach 1 described previously. Figs. 2 and 3 provide examples of the concept maps that resulted from this activity.

The map in Fig. 2 is an example of an initial concept map. It demonstrates that the students have a prior understanding about human factors. Specifically, the map suggests that the students can identify the contexts of human factors work and general dimensions of a human factors analysis such as strength limitations and safety. A survey of all the maps produced in the class suggests that the students, as a class, bring an awareness of a variety of human factors concepts. This suggests that while the students may not have extensive prior knowledge as individuals, as a class they have an extensive body of knowledge.

At the same time, the initial maps show significant room for improvement. The maps are almost exclusively hierarchical with no cross-links. This suggests that even among the concepts the students bring into the course, there may not be awareness of interconnections. Further, terminology in the maps is limited almost exclusively to everyday language rather than sophisticated, domain-relevant terminology. For example, students may introduce memory issues but not include concepts such as working memory, long-term memory, or memory limitations.

Fig. 3 is an example of a map generated nine weeks into the term. It is illustrative of the types of maps generated across the class. In general, these maps include more concepts and more links. The appearance of cross-links in the maps suggests that the students are starting to see interconnections. Moreover, the maps contain much more sophisticated domain-relevant terminology distributed across an increased number of levels of detail.

These features of the maps confirm that students are indeed making progress in developing an integrated understanding of

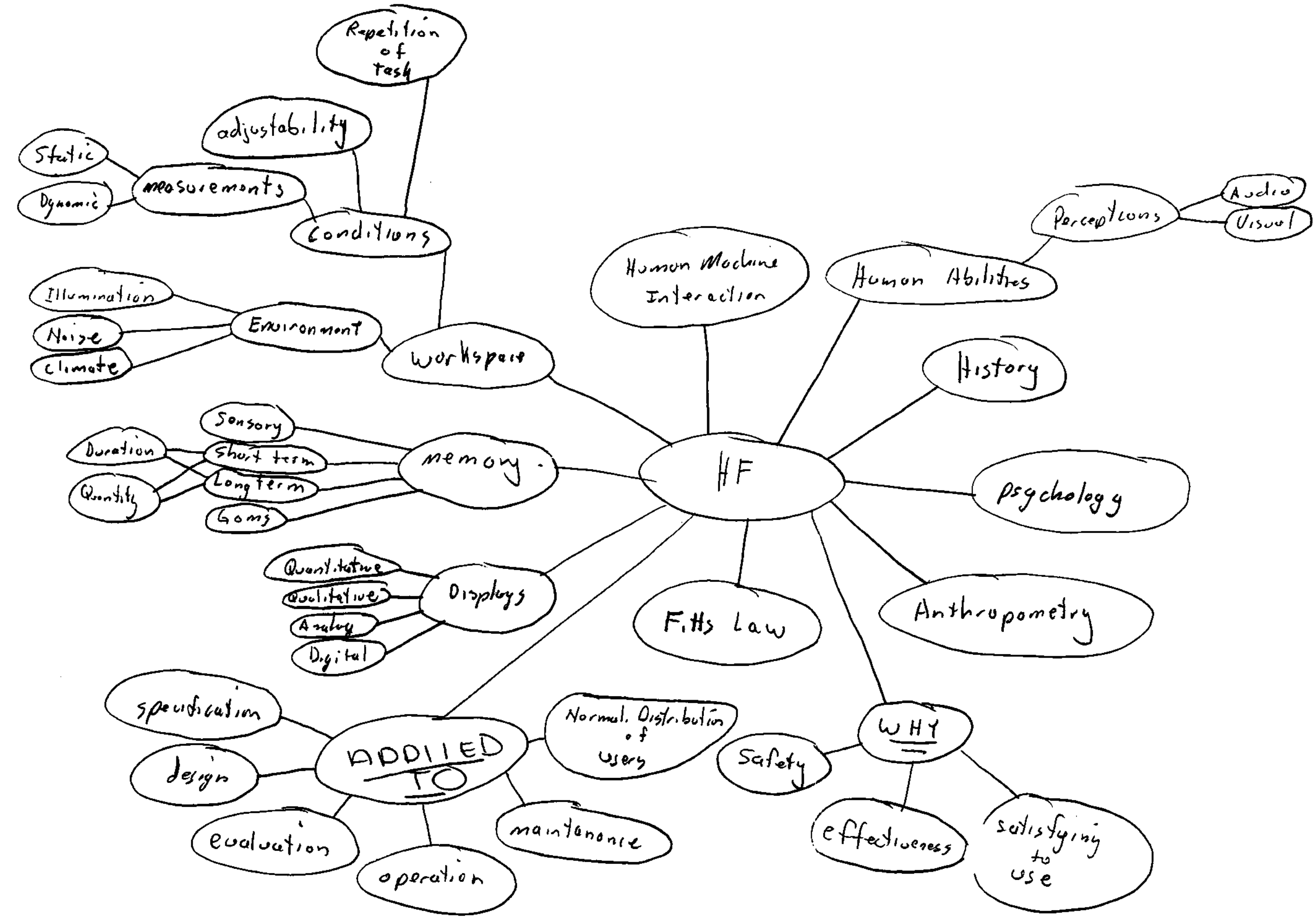

Fig. 3. Midterm human factors concept map.

human factors. At the same time, some features of the maps suggest additional room for improvement. With the expansion of the number of concepts, some of the maps (including the one in Fig. 3) had come to contain between eight and ten concepts connected directly to the central concept of “human factors.” An important next step in understanding might be for students to explore the relationships among these concepts at the highest level. The goal would be to see if there are ways to further organize these concepts into a smaller number of categories that might be interjected into the concept map between the main concept of human factors and these more specific concepts.

These examples illustrate many of the strengths of the use of concept maps for classroom assessment. Because concept maps are easy to explain to students, the training and the construction of the maps can occur at the same time. Concept maps can represent any amount of knowledge that students want to represent. Concept map construction can play a role in helping students see what they bring to the class. It can also help students make connections between class concepts and prior concepts. These maps can reinforce knowledge integration goals by providing students with an activity that promotes this goal. Also, by taking class time to promote integration, the instructor can emphasize the importance of integration. Concept maps can be used to promote discussion, particularly when the maps are placed onto overhead transparencies and the students discuss them. Finally, the maps can provide guidance on where students need additional instruction.

B. Grading Motivated Assessment: Concept Maps as a Final Exam

Concept map construction used as the basis for a graded final examination emphasizes and rewards the identification of concepts and the identification of hierarchical and cross connections between concepts. Such an emphasis may be particularly appropriate in an introductory class where the intention is for students to acquire an overarching understanding of the subject matter. In such cases, concept map construction is appropriate for a final exam because the map can be constructed to represent and integrate topics from the entire term.

The human factors course described in the previous example is an instance of an introductory course and is a context where concept map construction has been used for a final exam. Such an introductory course in human factors is often the extent of human factors treatment in an engineering curriculum. While some students may take follow-up courses in physiology, biomechanics, cognitive science, or other related subject matter, many other students may spend the rest of their professional lives relying on the foundational knowledge they acquire in the introductory course. Thus, using concept map construction as a final exam is a way to promote student development of an overarching subject-matter understanding.

Below is the concept map final exam assignment given to students during one semester. During that semester, the concept map final exam was one of several assessment mechanisms. These other learning and assessment mechanisms, including laboratory work and a design project, encouraged a detailed focus on specific class topics. The use of concept maps provided a means to complement these other assessment opportunities and to emphasize the diversity of concepts related to human factors and the interconnectedness of these concepts.

> *The objective of creating the concept map is to evaluate your overall understanding of the topic of Human Factors. I would like you to construct a concept map that represents your perception of the most important concepts discussed for each general topic we covered in class, and how these concepts are linked together.*
>
> *Please see the previous handout for examples of concept maps. They do not need to be generated on the computer—they may be hand-written, as long as they are neat and easy to read. If you would like, you can also hand in a couple of paragraphs to guide my reading of the concept map.*
>
> *Please turn them in to me by the time of our final, which is Wednesday, December 11 at 10:00 am. You may also turn them in any time before this date.*

The students receiving this assignment had previously constructed concept maps as a classroom assessment activity; therefore no additional concept map training was required. The students worked individually and created the maps via a variety of means ranging from paper and pencil to computer-aided design systems. The maps were scored along several dimensions, including:

- the comprehensiveness of the included concepts;
- the level of detail in the map (operationalized through number of hierarchical levels);
- the complexity of the links.

To complete the grading, each of the dimensions was scored on a scale from zero to five. The dimensions were not weighted equally.

The maps submitted by the students were quite diverse. Some of these maps resembled the maps created by students during the Week 9 classroom assessment activity described in the previous section. Such maps received low scores on the comprehensiveness, level of detail, and complexity scoring dimensions.

Fig. 4 represents a map receiving a high grade. The map clearly shows a large number of concepts, a large number of connections between concepts (links), and an extensive hierarchy among the concepts showing that the student can differentiate among the levels of detail in describing the elements of the course. The presence of a large number of meaningful cross links contributed to a high rating for link complexity. The cross links appear primarily within clusters of concepts in the mid levels and lower levels of the map. However, there are also cross-links at higher levels. For example, safety is depicted as a concept connecting to all other first level concepts, suggesting that the student sees safety as a critical component of human factors.

The map in Fig. 4 also stands out because of the creativity and human factors theory embedded in its design. This creativity is embodied in the imagery that the student uses to help to communicate the meaning. For example, the concept "allocate function" is connected to the concepts of "human" and "machine." "Machine" is shown in a precisely drawn rectangle suggestive of the precise ways in which machines execute instructions. "Human," however, is drawn in an ill-defined oblong shape suggestive of the flexibility with which humans can adapt to different situations.

While it is not obvious in the black-and-white reproduction, color was used in the original. All topics related to workplace design (upper right corner of the map) were shown in green while topics related to information input and output (upper left corner of the map) were shown in blue. Overall, the student used eight colors to facilitate the interpretation of the map. In addition, the term "color" in color coding (connected to "displays," which in turn was connected to "human factors") was written with each letter in a different color.

Overall, the set of submitted maps was quite diverse. Of the six dimensions used to grade the map, three were particularly useful in differentiating the students—the comprehensiveness of human factors concepts, the level of detail, and the complexity of the links. Fig. 5 shows the distribution of the scores as assigned to the 38 students enrolled in the class. The distribution of scores assigned for concept comprehensiveness shows most of the students receiving high ratings. This suggests that by the end of the course, the students as a whole seemed aware of the concepts that they had learned. The distribution of scores for the level of detail shows more students receiving middle-level scores. This suggests differences in the abilities of the students to describe concepts at various levels of detail. Finally, the distribution of scores for link complexity shows the greatest variation. This suggests that a key to distinguishing among the students who learned a lot and those who were less successful may be the ability to see complex connections among the various topics covered in the class.

This experience suggests how concept map construction can be a viable alternative to a traditional final exam. Using the grading procedure previously described, the amount of time to grade the maps was comparable to the time to grade a traditional exam. The students seemed to readily understand the task, even if they were not all equally enthusiastic about doing it. Finally, the dimensions used to assign grades resulted in a distribution of grades consistent with expectations.

C. *An Exploratory Tool: Characterizing Learning in a Novel Class Format*

Another area in which concept maps can be used is in an exploratory assessment of what students perceive themselves to be learning in a course, apart from the stated and/or implicit expectations. This type of information is particularly important for classes with novel formats and ill defined learning objectives, such as product dissection courses and undergraduate research

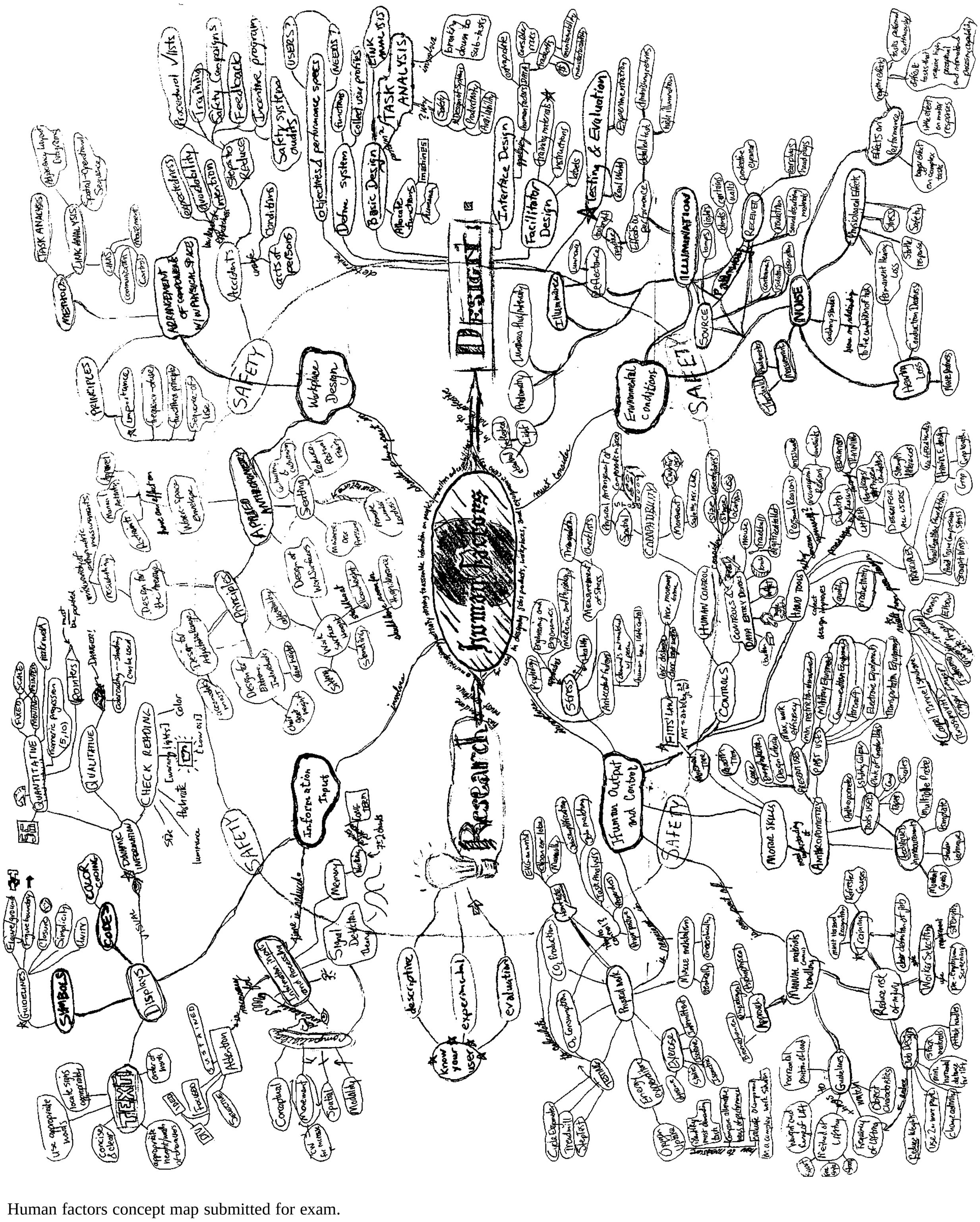

Fig. 4. Human factors concept map submitted for exam.

experiences. Knowing what students are actually learning is important for judging the appropriateness of existing learning objectives or deciding how to modify instruction.

Concept maps provide a means to explore what students are actually learning. The concept map construction process provides an open-ended means for students to communicate what they see as important concepts and their perceptions of the relationships among these concepts. The results of the analyses of the data can have implications for refining learning objectives, for refining instructional strategies, for identifying appropriate assessment tools, and for understanding how the learning objectives are being realized by the students.

Concept maps are currently being used to explore student learning in a sophomore-level product dissection course at the University of Washington. As part of an exploration of what students are actually learning in this course, students were asked to construct concept maps on the general topic of product dissection. The analysis of the data is currently under way. Initial

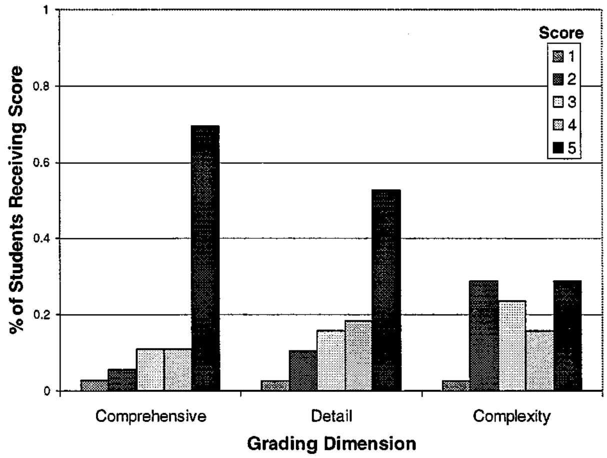

Fig. 5. Distribution of scores along three dimensions of concept map grading.

observations are that students are learning about a wider variety of topics than is represented in the current learning objectives but also that students are having difficulty organizing these concepts in a meaningful and integrated manner. These results suggest that the instructional activities are successful in helping students see a large picture of engineering. At the same time, the results suggest that the instructors may need to consider providing the students with more support in understanding how to integrate these diverse topics in order to make sense of them.

IV. Concept Maps for Program-Level Assessment

The previous examples illustrate uses of concept maps for addressing course-level assessment issues—monitoring progress, assigning grades, and exploring students' perceptions of learning in a course. However, there is another level of assessment that engineering schools must address—assessment at the program level. Program-level assessment refers to assessment directed at understanding the overall knowledge of a group of students. The following sections demonstrate how concept maps have been used to explore three program-level assessment issues—characterizing a student's level of expertise in a domain, identifying what students know about their discipline, and exploring students' conceptions of engineering.

A. Assessing Overall Domain Expertise: An Example in Statistics

There are instances where it is important to assess a student's general level of expertise in a subject area apart from specific classes. For example, one might be interested in characterizing expertise in a domain, such as statistics, or a skill, such as design or modeling. This type of assessment is useful in a range of situations, from verifying that students have the prerequisite knowledge required to enter a class to determining if students have achieved the ABET-mandated learning outcomes necessary to graduate from their engineering program. Concept map assessment can be used to characterize expertise for these purposes.

At the Georgia Institute of Technology, concept map assessment has been used to characterize the level of statistics expertise of students in the industrial engineering department. Expertise in statistics implies many things, including an ability to carry out statistical procedures and an ability to model real-world scenarios in statistical language. One dimension of statistics expertise is the presence of an understanding of the key elements of statistics and their relationships. For example, an expert may see variability as a pivotal concept in statistics, while a novice may perceive the concept as being peripheral.

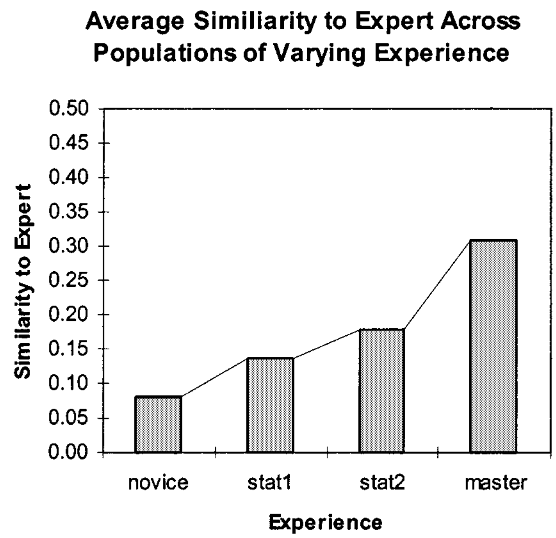

Fig. 6. Similarity of population groups (based on experience) to the expert.

The procedure for the assessment followed Approach 2 described earlier (external generation of concepts). First, a faculty member in the statistics division of the industrial engineering department (hereafter known as the expert) was asked to identify a set of 25 statistics concepts associated with differing levels of statistics knowledge. Next, concept maps were generated for the students and the expert based on ratings of relatedness between pairs of these concepts. The interpretation of the students' maps was based on the similarity of the generated concept map to the expert's concept map. To facilitate the collection of subject data, a Web-based tool was designed specifically to complete this type of concept map assessment [29].

Eighteen student subjects participated in the study. These subjects were representative of four populations defined by level of prior statistics instruction, including 1) no previous experience, 2) completion of undergraduate Statistics I, 3) completion of undergraduate Statistics II, and 4) advanced instruction at the master's level. The graph in Fig. 6 represents the average similarity of students to the expert within each of these populations. The factor of experience was significant in explaining the differences among similarity values ($p < 0.0001$). This result validates the similarity measure as a means of capturing overall expertise in statistics. The pilot study demonstrated the feasibility of completing this form of concept map assessment with a Web-based tool.

B. Exploring Students' Conceptions of Their Discipline: What Is Industrial Engineering?

At the program level, it is important not only to quantitatively assess expertise in a domain but also to explore students' understanding of broad topics that encompass several elements of the

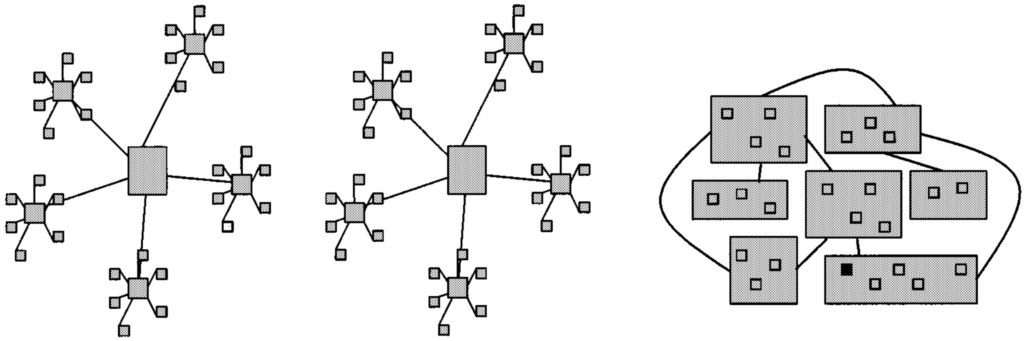

Fig. 7. Schematic representations of concept map structure in industrial engineering.

engineering curriculum and/or extend beyond the engineering curriculum. For example, one may be interested in students' conceptions of their discipline, such as their conceptions of industrial engineering or civil engineering. Concept maps may be an appropriate tool for exploring such an issue because their open-endedness will not constrain student responses, they are capable of capturing divergent issues, and they are capable of representing unique elements that students see as important.

At the University of Washington, concept maps have been used to explore students' conceptions of industrial engineering. In the spring of 1999, students enrolled in a capstone design course constructed concept maps of industrial engineering. The activity was framed as an opportunity to create a tool for use during their senior design experience. The students worked in teams to construct concept maps. The nine teams produced a total of nine maps.

Insight can be gained by exploring both the structure and the content of the maps. The maps submitted by the students have quite different structures. Fig. 7 suggests three prototypical structures that collectively capture the general structures of the nine submitted maps—strict hierarchy, interconnected hierarchy, and decentralized. Maps organized according to a strict hierarchy have a central concept with all other concepts radiating from the central concept in a strictly hierarchical manner. Other maps can be described as an interconnected hierarchy. Such maps have an overall hierarchical structure with a clear central concept but also have cross-links between concepts at various levels of the hierarchy and in various branches of the hierarchy. These cross-links represent an integration of concepts. The remaining maps are best described as decentralized. These maps contain no clear central concept, making them difficult to interpret. However, they also contain a set of highly interconnected concepts.

In comparing these structures, the two types of hierarchies seem easier to interpret because the creators clearly depict the focus of the map via the central concept. The central concepts in the hierarchical maps include the following: "successful in senior design," "practical applications in engineering," "effective IE group," and "how to become a successful IE." Concerning the level of interconnectivity, the decentralized network and the interconnected hierarchy suggest a more expert-like representation because of the interconnections seen among the concepts.

The maps submitted by the students also differ in the content represented by the concepts. Some student teams included primarily course labels, such as IE 342. In one such map, which includes course labels and titles exclusively, the students demonstrated an understanding of the building up of the curriculum by differentiating courses more central to industrial engineering, such as a course on manufacturing design and a course on quality control, from courses focused on underlying contributing knowledge, such as a course on statistics.

Other teams went beyond course elements to identify and integrate concepts that are more implicit in the curriculum. For example, one map, an interconnected hierarchy map whose central concept was "practical applications in engineering," has a branch entitled "How to think like an engineer." The students who created the map related the concept of "thinking like an engineer" to concepts that cut across many classes including "modeling," "creativity," and "being flexible with changing ideas."

These results suggest the different ways in which students are building an understanding of their discipline. The results also suggest that one of the potential areas for facilitation includes helping students identify the abstract concepts present in many classes and helping them identify connections among topics included both explicitly and implicitly in the curriculum.

C. *Exploring Students' Conceptions of Their Profession: What Is Engineering?*

The results of research in professions other than engineering suggest that it is important to understand how students view their profession in general because their professional practice depends on their conceptions of the profession. For example, what do students see as the role of ethics in engineering? What do students see as the relationship between science and engineering? How do students understand science?

At the Center for Engineering Learning and Teaching at the University of Washington, the overarching issue of students' conceptions of engineering is being explored through two tasks—an open-ended Approach 1 concept mapping task and a constrained Approach 2 concept mapping task. In the first approach, students are asked to construct concept maps of engineering. The resulting concept maps are analyzed by looking for the presence or absence of concepts (e.g., ethics) and relationships (e.g., science and engineering). In the second approach, students are asked to construct a concept map with a constrained set of 18 concepts critical to engineering. These concepts are shown in Fig. 1. These concept maps will be analyzed by comparing them to a concept map constructed by an expert. To date, 39 civil engineering seniors have completed the second task, and 110 pre-engineering freshmen have completed the first task. Assessing students' high-level conceptions of engineering in these two ways has the potential to become an important part of understanding students' development into professional engineering practitioners.

V. Concluding Remarks

This paper has provided examples of how concept maps can be used for both course-level assessment and program-level assessment. These examples have included work already completed as well as work in progress. These example uses of concept maps clearly demonstrate how concept maps can serve a variety of assessment functions ranging from everyday grading to the exploration of high-level student conceptual structures.

Clearly, concept maps are not a perfect assessment solution. They can require extensive time to interpret and can still remain ambiguous. Additionally, demonstrating through a concept map that students understand the relationships among concepts does not guarantee that the student will be able to use the concepts to support design or other authentic engineering activities. At the same time, concept maps are a flexible tool. They focus attention on an important aspect of knowing—the relationship among concepts. Both approaches have been widely studied and demonstrated as valuable.

A further strength of concept maps is their value beyond their role in assessment. Researchers have used concept map representations to communicate information (e.g., [12]–[14]) and as tools to support the design of instructional materials [15]. Others have focused on the construction of concept maps as an instructional activity [16]–[19].

In conclusion, concept maps represent an innovative way to assess, and gain insight, into student learning about the relationships among concepts. This paper has discussed the cognitive psychology origins of concept mapping and two approaches for conducting assessment with concept maps, and has demonstrated how these may be carried out in engineering education. Concept maps should be seen as a valuable component of an assessment toolbox.

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