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PARTICIPATORY SIMULATION TO SUPPORT TRANSACTIONAL CURRICULUM INQUIRY

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ABSTRACT

In this paper, we propose an approach to facilitate the identification of threshold concepts in undergraduate engineering curricula. The approach is based on the framework of transactional curriculum inquiry where educators work with a group of stakeholders (students, curriculum designers, industry practitioners) to identify threshold concepts. Our proposed approach involves developing a participatory simulation using agent-based modeling that will serve as a digital forum for the exploration of threshold concepts in engineering courses.

1 INTRODUCTION

In recent years, the engineering education community has come to recognize the value of threshold concepts and the important role that they play in both teaching and student learning (Male and Bennett 2015). Meyer and Land (2003) identify a threshold concept as a portal, a way of thinking about something in a "new and previously inaccessible way". They consider it a space between where a learner is and where that learner needs to be in order to make the transition from novice to experienced practitioner in a discipline. Threshold concepts align well with a student-focused approach to teaching and learning by providing instructors with the opportunity to reflect on what is taught, why it is taught, and how and when it is taught (Barradell 2013). However, the identification of threshold concepts in undergraduate engineering curricula has proven to be a difficult process.

One of the key problems with this process is that, despite threshold concepts being related to how disciplinary knowledge is learned by students, the role of identifying threshold concepts has predominantly been left to the disciplinary experts (*i.e.*, academics) who have long-since traversed the thresholds. To address this, Cousins (2008) advocated a "transactional curriculum inquiry" approach that recognizes that consultation amongst academics, students and educational developers is necessary. Barradell (2013) further extended this beyond the educational realm to include members of the professional community.

We propose using transactional curriculum inquiry to identify threshold concepts in the engineering curriculum. Our proposed approach is based on a form of consensus methodology (Waggoner et al. 2016) that utilizes participatory simulation developed using agent-based modeling. The model takes the form of a concept map (Novak 1984) that illustrates key concepts and their interrelationships and is intended to serve as a digital forum for stakeholder interaction where faculty and engineering professionals apply their knowledge of the discipline by identifying core concepts; students rely on their learning experience to identify troublesome concepts; and, educational developers apply their knowledge of the curriculum to identify linkages between concepts.

We begin with an introduction to the key areas addressed by our participatory simulation model: *i.e.*, threshold concepts, concept maps, and transactional curriculum inquiry. Next, we provide a overview of the modeling approach used for this study in Section 3, then describe the results of a modeling exercise in Section 4. We conclude with a discussion of our next steps and future goals for this work.

2 BACKGROUND

2.1 Threshold Concepts

In any discipline there are certain conceptual ideas that, when first encountered, are exceptionally hard for students to understand. However, once mastered, they have the capacity to change students' perception of the entire discipline. Some learners master these "threshold concepts" quite easily, while others struggle in a transitional state called liminality. With new knowledge to learn and misconceptions and misunderstandings to unlearn, this liminal state can involve disorientation and ambiguity as a learner moves between a state of knowing and not knowing.

Meyer and Land (2003) identify five key characteristics of a threshold concept: *i.e.*, a threshold concept is *transformative*, *irreversible*, *troublesome*, and can be *integrative* and *bounded*. Threshold concepts are considered as troublesome knowledge since they tend to require the learner to be able to suspend what is already known in order to fit the threshold concept into a new schema.

An example of a threshold concept in engineering is "measurment uncertainty", which requires an understanding that virtually every number used to describe the physical world is uncertain (Harrison and Serbanescu 2017). The International Organization of Legal Metrology (OIML) defines measurement uncertainty as "the parameter associated with the result of a measurement that characterizes the dispersion of the values that could be reasonably attributed to the measurand" (OIML 2007). The *troublesome knowledge* in this case relates to viewing measurement uncertainty as a *mistake* or *error* in measurement rather than a comprehensible and quantifiable result of the measurement process (Harrison and Serbanescu 2017). However, once mastered, this threshold concept is *transformative* in opening the door to understanding data analysis and uncertainty in a wide range of experimental courses in the engineering curriculum.

2.2 Concept Maps and Transactional Curriculum Inquiry

As noted previously, identifying threshold concepts in the curriculum has proven to be challenging. An often cited challenge relates to educators' understanding of the notion of threshold concepts: *e.g.*, as noted by Atherton et al. (2008), "the idea of a threshold concept is in itself a threshold concept". Although the term *threshold concept* is new and unfamiliar to many engineering educators, once grasped, it is generally understood from personal learning experience and observations of student learning. Arguably, the main challenge with identifying threshold concepts relates to educators' attempts to identify threshold concepts in isolation: *i.e.*, attempts to identify a threshold concept that they have long-since mastered and may consider as second nature.

To address this difficulty, Cousins (2008) proposed broadening the conversation on threshold concepts to include the individuals who are encountering the troublesome knowledge (students) and those who understand the connections between the elements of the curriculum (curriculum designers). This idea was expanded by Barradell (2013) to include practitioners and was given the title "transactional curriculum inquiry": *i.e.*, a process of consultation amongst academics, students, curriculum designers, and practitioners on the curriculum.

To facilitate transactional curriculum inquiry, Barradell (2013) suggests using consensus methodology (Waggoner et al. 2016). For example, techniques such as Nominal Group Technique (NGT) and the Delphi Technique have proven to be useful means to explore the perspectives of various individuals.

Given that the conversations around threshold concepts involve the discussion of concepts encountered in the curriculum, we felt that a tool for visualizing concepts would be helpful with this process. One such tool is the *concept map*, which has proven to help undergraduate engineering students organize their knowledge and thereby see the "big picture" (Ellis et al. 2004). The concept map was proposed by Novak (1984) as a tool to represent knowledge held by a learner, and also structure knowledge in any subject domain. He defines a concept as a "perceived regularity or pattern in events or objects, or records, or records of events or objects, [that is] designated by a label" (Novak 1984) and develops a concept map by linking concepts by propositions. An example of one possible concept map for measurement uncertainty (based on the OIML definition) is shown in Figure 1. In the next section we propose using a participatory simulation model as a means to collaboratively develop concept maps in a classroom setting.

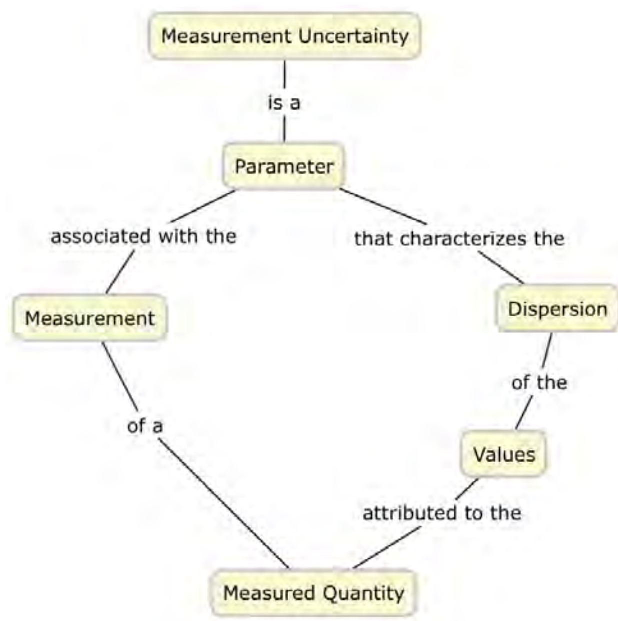

Figure 1: A concept map for "measurement uncertainty" generated using CmapTools (IHMC 2022).

2.3 The Participatory Simulation

To facilitate transactional curriculum inquiry, we developed a participatory simulation using agent-based modeling (ABM). The simulation allows instructors, students, curriculum designers, and professional engineers to interact with an undergraduate engineering curriculum to identify threshold concepts and understand their relationships within the curriculum. Effectively, the simulation serves as a tool to conduct consensus methodology research. Although other approaches such as nominal group process, consensus development panel, or Delphi technique could be used, we felt that a consensus approach that directly references concepts and allows student to collaborate on the development of a concept map would be better suited to our goal of identifying threshold concepts.

In recent years, there has been increasing interest in the use of ABM as a tool to understand the behavior of complex systems. This work has focused on the study of the dynamics of systems, such as organizations, whose behavior is the consequence of the interactions of many different independent agents such as individuals. ABM is a form of computational modeling whereby a phenomenon is modeled by software agents and their interactions (Wilensky and Rand 2015). Early work in this area focused on understanding natural phenomena such as ant foraging, termite nesting, bird flocking behavior, as well as the behavior of engineered systems such as freeways and computer networks (Resnick 1997). In the past two decades, interest has expanded to the study of social science systems (Epstein 2006).

ABM is also well-suited to participatory modeling and simulation. Learmonth and Plank (2015) define participatory simulation as "the combination of an underlying computer-based simulation model with human game players interacting directly with the simulation model". This approach has been used for a variety of applications that include agriculture and resource management (Becu et al. 2008), urban logistics (Singh et al. 2021), healthcare operations management (Raghothama et al. 2017), and workplace training (Gilligan et al. 2015). For this paper, we focus on student learning in higher education. As noted by Wilensky and Stroup (1999), in a teaching and learning context, students engaged in participatory simulations "act out the roles of individual system elements and then see how the behavior of the system as a whole can emerge from these individual behaviors".

For this project, we developed an ABM simulation that will allow instructors, students, curriculum designers, and practitioners to collaborate on developing concept maps of troublesome aspects of the curriculum. The ABM uses the Netlogo HubNet feature, which is an open client-server architecture that allows multiple users to control the behavior of individual objects in the simulation (Wilensky and Stroup 1999). In the next subsection, we describe how the stakeholders will interact with this model.

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3.1 Modeling Approach

For this research, each stakeholder interacts with the same model, but from a different perspective. The general approach is based on Novak's steps for building concept maps (Novak 1984):

1. Identify a focus question that addresses the problem, issues, or knowledge domain to map, and identify 10-20 concepts that are pertinent to the question.
2. Rank order the concepts. The broadest and most inclusive idea is at the top of the map. Sub-concepts are placed under broader concepts.
3. Cluster the concepts by grouping sub-concepts under general concepts.
4. Link the concepts by lines. Label the lines with one or a few linking words.

Figure 2 illustrates a participatory simulation implementation of this process. The instructor (interface shown on the right of Figure 2) interacts with the model through the HubNet server, and starts the process by creating the focus question and the initial concepts. Students (interfaces shown on the left of Figure 2) interact with the model through the HubNet client. Each individual student sees a representation of the concept map as it develops, and has the ability to interact with elements of the model. For example, by moving concepts to different locations on their interface, students influence the rank order and clustering of concepts; by adding links and propositions, students influence the overall structure of the final concept map.

The instructor steps students through the process of developing the concept map as shown in Figure 2, and encourages discussion on the concept map as it develops. The simulation uses the input from the student clients to build a *consensus concept map* that is displayed on the instructor (server) view. More specifically, the position of the concepts in individual student maps serve as weightings for the final position of the concepts in the consensus concept map. As well, concepts that show considerable disagreement with respect to rank order or clustering are highlighted in the instructor concept map, providing further opportunity for discussion.

The curriculum designers and the members of the professional community are not shown in Figure 2 as it is anticipated that the process described above will be a classroom activity involving the instructor and students. Input from curriculum designers and members of the professional community would be requested at different points of the exercise. For example, they may be involved at an earlier stage to assist the instructor with the framing of the focus question and identifying the initial concepts. As well, they will be asked to provide their reflections on the final concept map.

For example, curriculum designers will consider the mapping of curriculum content. This will help to identify the transformative and troublesome aspects of the curriculum as well as how various topics in the curriculum integrate with each other. Members of the professional community will be given the opportunity

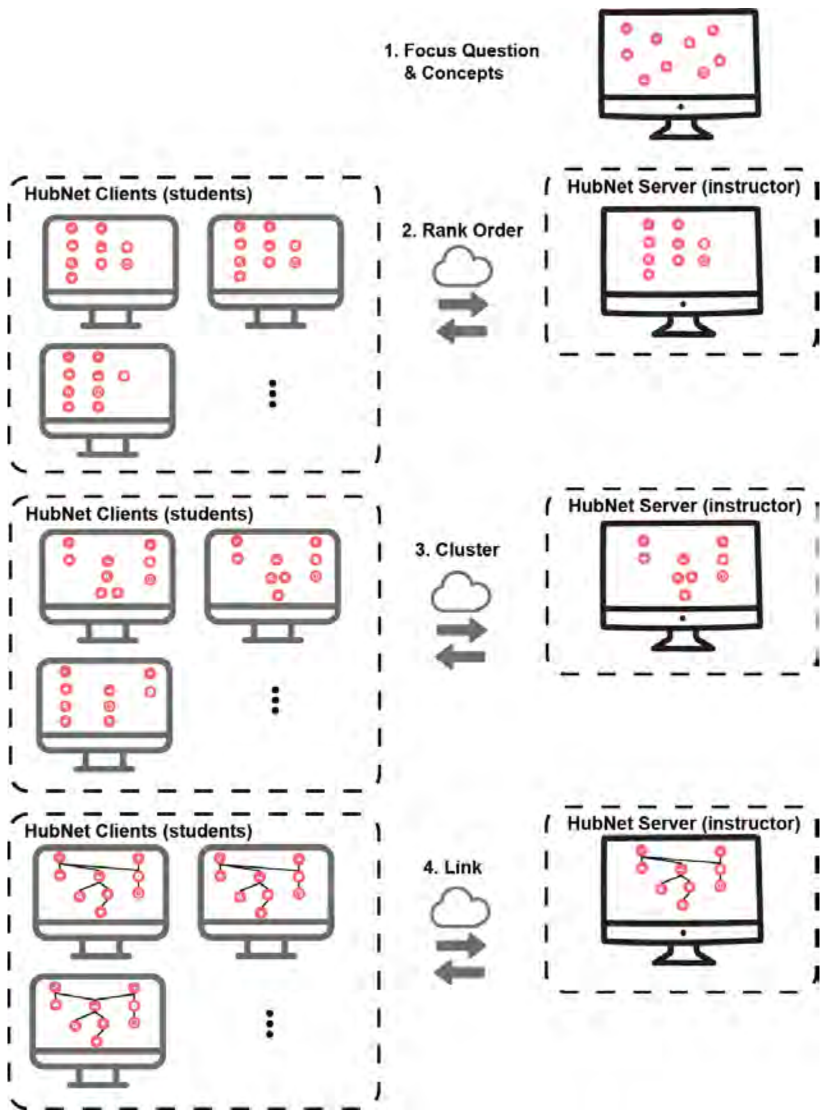

Figure 2: Using participatory simulation for transactional curriculum inquiry.

to identify concepts that practicing engineers struggle with. Like the input by students and instructors, this will help identify and refine troublesome and transformative aspects of the curriculum; however, the professional viewpoint should also provide contextualization, and in particular, the bounded aspects of the learning process.

3.2 The Agent-based Simulation Model

A preliminary version of the model was developed in Netlogo 6.2.2 with the HubNet extension. In this section we illustrate the model interfaces using the measurement uncertainty example described in the previous section. The model contains two kinds of of entities: concept agents and link agents. Concept agents represent individual concepts in the map (*e.g.*, "parameter" in Figure 1) and have attributes associated with their x-y position in the map and their relationships to other concepts. The link agents represent the hierarchical relationships between concept agents and include the "proposition" attribute.

As noted, the process begins with identifying a focus question and a list of concepts. For example, in a classroom setting the class would be asked to discuss the concept question, and based on the discussion, a list of concepts would be developed.

The focus question and the list of concepts serve as the starting point for developing the concept map. At the beginning of the exercise, the instructor initializes the simulation model with this information. Students are then asked to connect to the server where they see the concept question at the top of their view, and the list of concepts in alphabetical order. They are then asked to complete the rank ordering and clustering steps by dragging the concepts to the appropriate levels and horizontal positions respectively. Figure 3 shows an example of a student interface with these steps completed.

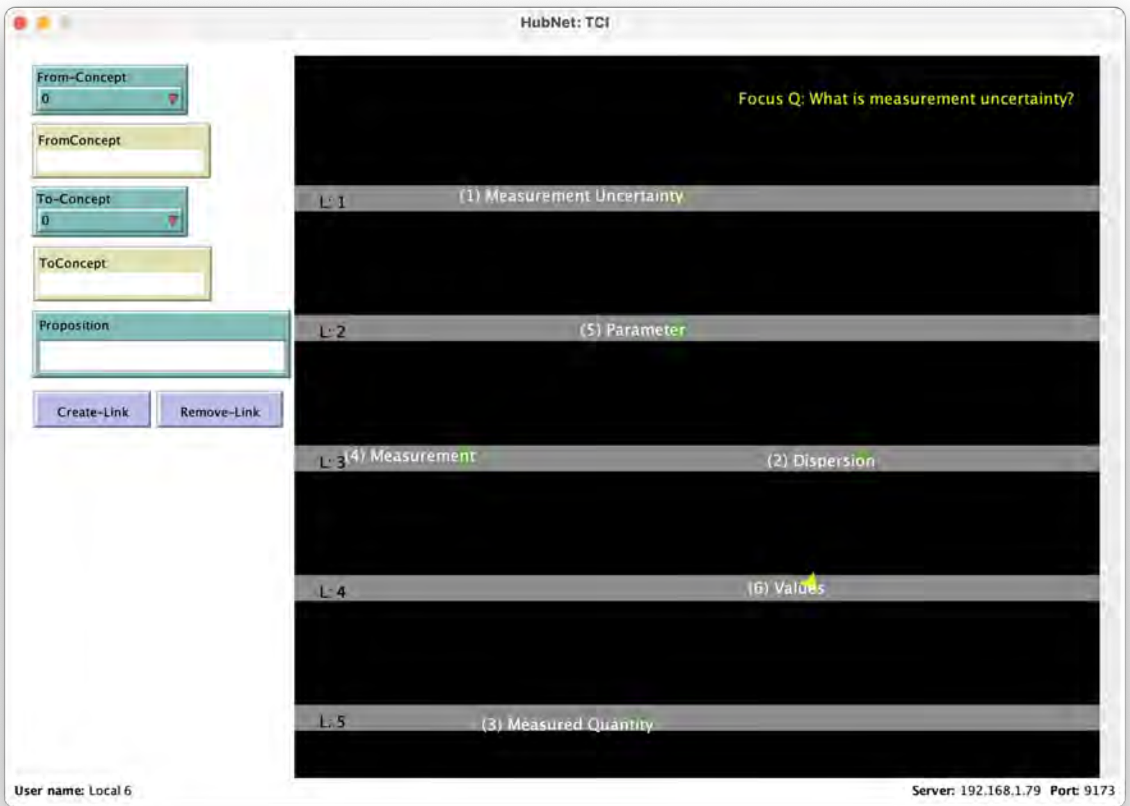

Figure 3: An example of a student (client) concept after leveling and clustering.

To facilitate the rank ordering and clustering steps, the instructor creates a grid that represents the possible number of levels for the concept map (grey bars in Figure 3); as well, the instructor may choose to place the top-level concept (*i.e.*, *Measurement Uncertainty* for our example) at the top of the concept list.

While each student works on her/his individual concept map, the instructor can monitor the overall consensus concept map in the server view (Figure 4). The centre view shows the consensus concept map: *i.e.*, each concept agent (represented by a colored triangle) is positioned based on the mean position of the student (client) concept agents and is colored based on the degree of consensus (*i.e.*, red represents low consensus - green represents full consensus). Plots are also provided on the right side of the instructor interface showing how consensus for each concept evolves over time. Time is represented in the model in real-time (seconds): *i.e.*, the plots provide a record of the time it takes students to construct their respective concept maps.

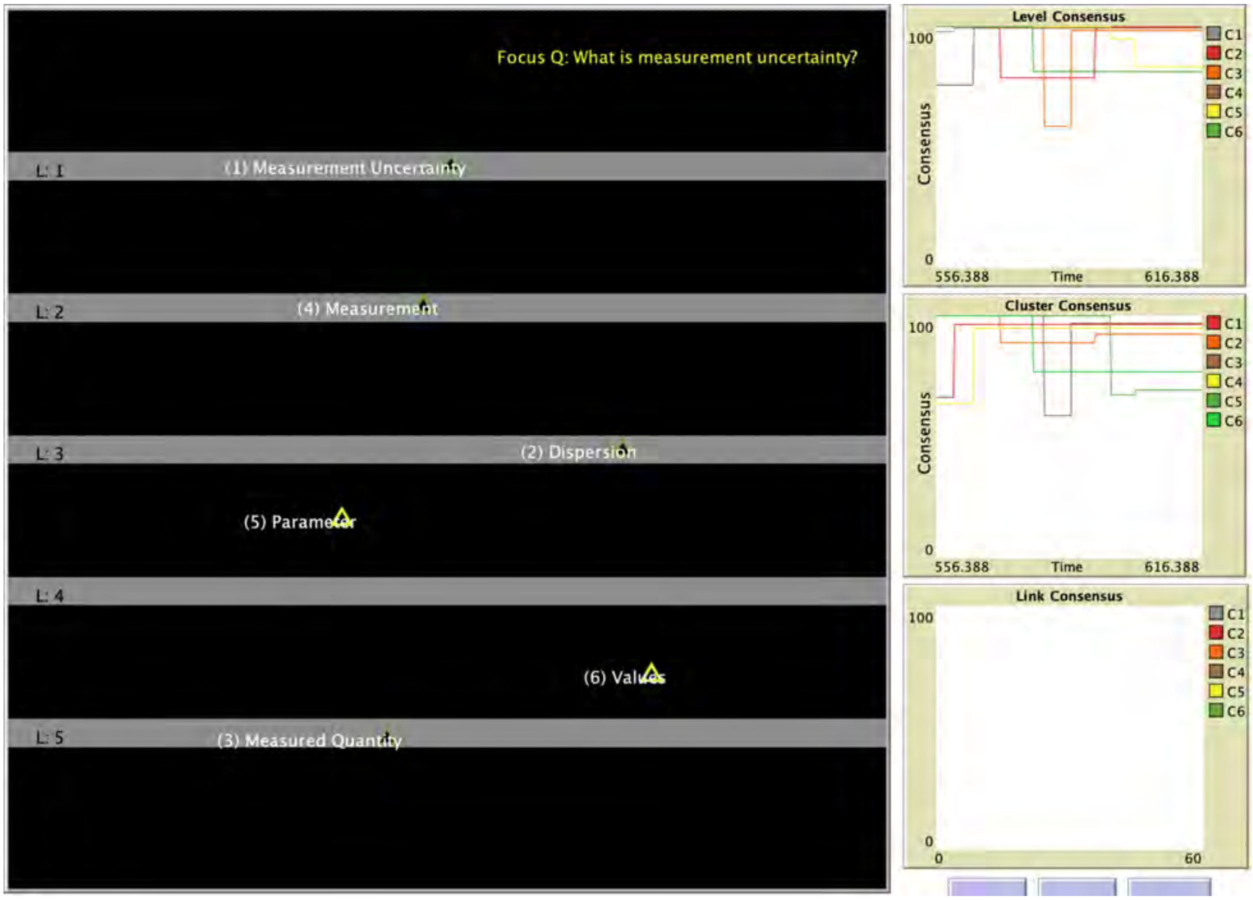

Figure 4: An example of the *consensus concept map* in the instructor (server) view.

The model also provides students with direct feedback on the consensus concept map as they complete the leveling and clustering steps. This is illustrated in Figure 3 by the color and orientation of the concept agents. More specifically, the model provides feedback to the students on the proximity and relative position of the consensus concepts (Figure 4) by coloring (red to green for distant to close respectively) and pointing direction of the student concepts respectively.

The final step in the concept mapping process involves linking the concepts by lines and entering labels that describe the nature of the linkage (*i.e.*, propositions). The drop-down menus and *Proposition* text box on the left of the client interface (shown in Figure 3) are provided to allow students to create these link agents. An example of a completed student map is shown in Figure 5. As students work on this final stage of the concept mapping exercise, the instructor can monitor the evolution of the consensus concept map on the server interface as shown in Figure 6. Links are shown using a similar coloring scheme as noted previously, a *Link Consensus* plot (upper right) shows how consensus evolves over time, and a *Propositions* output (lower right) is provided to analyze student propositions.

4 SIMULATION RESULTS AND EVALUATION

To test the simulation model, we ran the concept mapping exercise in a classroom setting with a focus group of six students. This small group size allowed us to interact with individual students as they worked on the

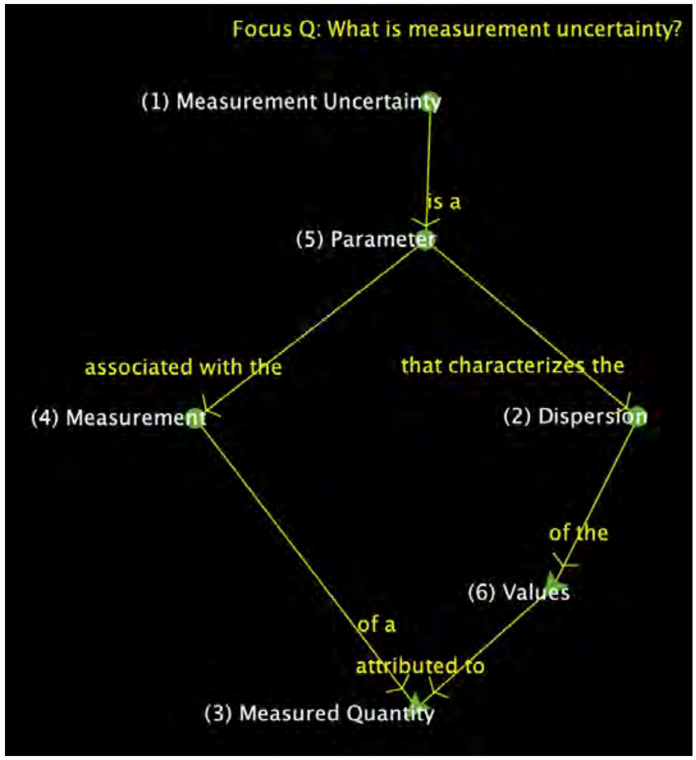

Figure 5: An example of a completed student concept map for measurement uncertainty.

model and thereby obtain direct feedback on the concept mapping exercise. We also used the opportunity to collect data on the consensus concept map as it developed over time.

4.1 General Feedback on the Participatory Simulation

Although the focus group encountered no difficulties using and understanding the model, we ran into difficulties with overall structuring of the exercise. More specifically, the exercise was performed outside of a regular class with a group of students from a variety of backgrounds. As a result, the group did not have lectures, exercises, or reading materials on the topic prior to the exercise. Instead, the focus question was provided to the group the day before the exercise and a proposed list of concepts was provided the day of the exercise.

This led to more disagreement on the list of concepts than would be expected in a regular classroom environment where students are more likely to be "on the same page" with the topic. As a result, some students felt that different terms should be used for the concepts (*e.g.*, "measurand" instead of "measured quantity") or that the list should be shortened or expanded (*e.g.*, add "error" to the concept list). These discussions would certainly be encouraged in a regular classroom environment, but would be resolved prior to running the participatory simulation exercise so that a common, agreed upon list of concepts could then serve as a starting point for the construction of the concept map.

Despite this, we were able to test the participatory simulation model with the group and found that it was well-suited for the concept mapping process described in Section 3.1. Students were able to follow each of the steps and use the client interface to build their individual concept map.

4.2 Analyzing the Consensus Concept Map

The participatory simulation model includes a number of metrics that allow the instructor to collect time-based data on the concept map as students work through the steps described in Section 3.1. These metrics

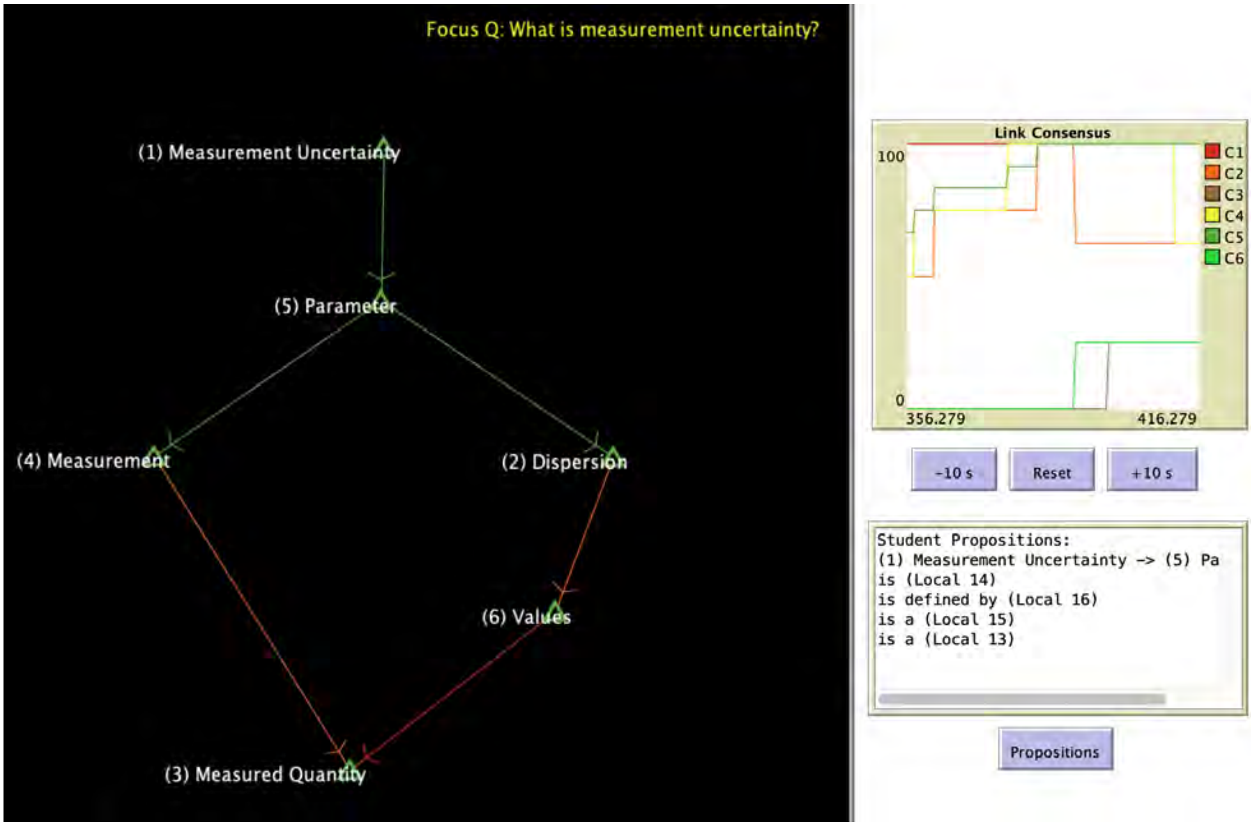

Figure 6: An example of a consensus concept map during the linking step.

are displayed both in real-time in the simulation interfaces (*i.e.*, using colors, concept positions, and plots), and are collected for external analysis at the completion of the exercise.

4.2.1 Level Consensus and Cluster Consensus

Level Consensus, LC_i, is determined by calculating the standard deviation in vertical position of student concepts i for all students j (*i.e.*, $(\sigma_y)_i \, \forall j$) relative to the maximum standard deviation in position for the world view, $max(\sigma_y)$:

$$LC_i = \frac{max(\sigma_y) - [(\sigma_y)_i \, \forall j]}{max(\sigma_y)} \times 100\%. \qquad (1)$$

The maximum standard deviation is a constant that is based on the size of the world view (area with black background in the interfaces). In this case, the world view is a 30×30 patch square, resulting in $max(\sigma_x) = max(\sigma_y) = 21.21$. Cluster Consensus, CC_i, is calculated in the same manner as equation (1) using the horizontal standard deviation, σ_x.

4.2.2 Link Consensus

For Link Consensus, we view the concept maps as directed graphs where concepts are represented by vertices, V, and links are represented by edges, E. The Link Consensus, IC_i, of concept i is

$$IC_i = \frac{\sum_{j=1}^{n} (e_i)_j}{n(e_i)_c} \times 100\% \qquad (2)$$

where n is the number of students, $(e_i)_j$ is the number of edges (links) with a start or end point at v_i (concept i) for student j, and $(e_i)_c$ is the number of edges (links) with a start or end point at v_i in the consensus map. The numerator in equation (2) is the edge multiplicity of the consensus concept map for links to/from concept i, while the denominator is the edge multiplicity of the consensus concept map for links to/from concept i if all students created the same links.

4.2.3 Concept Map Score

Finally, we use the scoring method proposed by Novak (1984) to calculate a concept map score, *CM*, for each student. This is a quantitative and structural metric that is based on the criteria proposed by Waggoner et al. (2016): *i.e.*,

1. Proposition: Are propositions included? *1 point for each*
2. Hierarchy: Does the map show hierarchy? *5 points for each level of hierarchy*
3. Cross Links: Do cross links connect one level of hierarchy to another? *10 points each*

4.2.4 Level Consensus Results

An example of the Level Consensus results for the measurement uncertainty exercise is shown in Figure 7. In this case, students reach consensus on the first step of the concept mapping exercise relatively quickly.

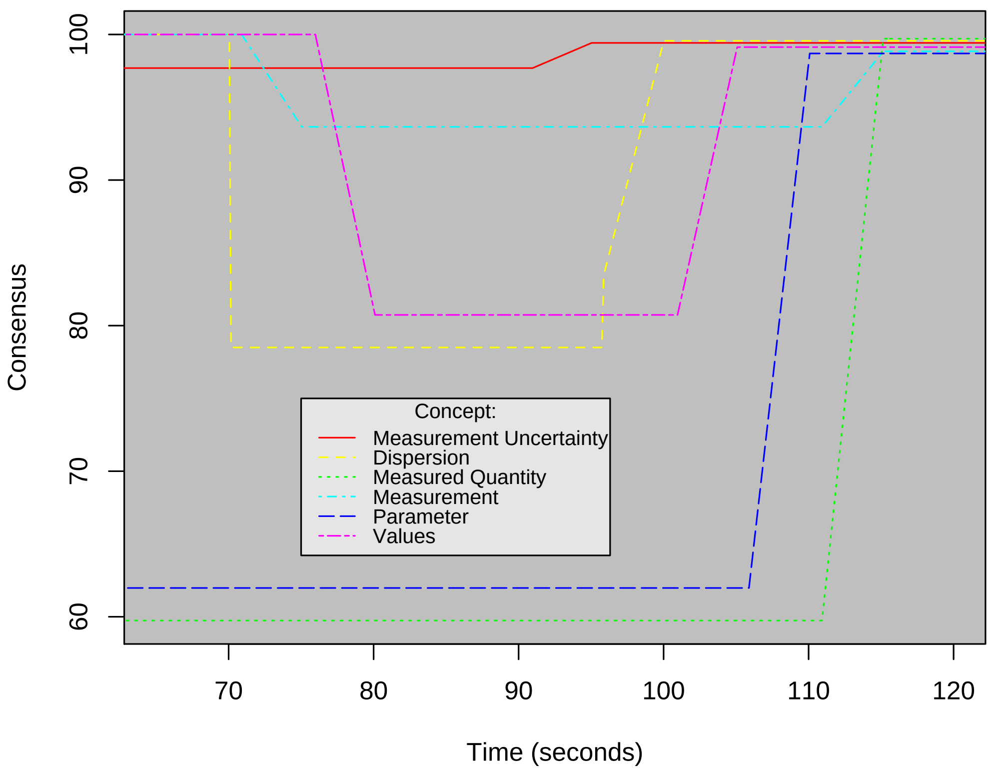

Figure 7: Level consensus results for the measurement uncertainty exercise.

In a regular classroom setting with larger numbers of students and the concept mapping exercise aligned with the course topics, we would expect to see similar results; however, we anticipate that more troublesome concepts would take longer to reach consensus. For example, recognizing the importance of the sub-concept "parameter" is key to understanding "what is measurement uncertainty". Misunderstandings around measurement uncertainty being an error or mistake in measurement rather than a parameter associated with any measurement would lead to the class taking longer to reach consensus on this and other sub-concepts (*e.g.*,"measurement").

These differences will serve as clues to where students struggle with specific aspects of the curriculum. Our intention is that, the identification of this *troublesome knowledge* will assist in identifying threshold concepts in the engineering curriculum.

5 CONCLUDING REMARKS

The overall goal of our work in this area is to develop an open-source software tool that can be used by various stakeholders to collaboratively identify threshold concepts in undergraduate engineering curricula. Although our focus is on engineering programs, it seems reasonable that this model could be widely applicable across a range of disciplines.

Our hope is that the tool will not only lead to the identification of threshold concepts, but also to a greater understanding of the concept of threshold concepts amongst stakeholders. From the perspective of the academia (instructors, curriculum designers), this should lead to improvement in the delivery of undergraduate engineering programs as well as support for accreditation reporting. For example, a better understanding of the threshold concepts in a particular course should assist instructors with providing appropriate scaffolding while students are *en route* through a given threshold portal. From the perspective of students, we hope that by interacting with the ABM, they will gain a better sense of their place within the discipline, and also recognize the emotional aspects associated with learning (*i.e.*, that the learning journey involves periods of "being stuck" for all students). Finally, from the perspective of the professional community, we hope that their involvement with this process will help establish stronger connections with our "end users" and will provide them with a sense of shared responsibility in the education of future engineers.

Ultimately, the identification of threshold concepts will help instructors and curriculum designers to improve both the curriculum and the teaching and learning approaches in undergraduate engineering programs. More specifically, threshold concepts will provide information on where students struggle, and where improvements to teaching and learning are required.

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