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Work in Progress: Quantification of Problem-Complexity and Problem-Solving Skills with Directed Networks in a Sophomore Course in Mechanics of Materials

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Work-in-progress: Quantification of problem-complexity and problem-solving skills with directed networks in a sophomore course in Mechanics of Materials

Abstract

Assessing learners' problem-solving skills, such as in a sophomore course in Mechanics of Materials (MoM), is critical to course and program accreditation related assessments. Assessments in a MoM course typically involve problems structured as a sequence of steps, each of which transforms data in a directed fashion toward numerical solutions, analysis inferences, or design decisions. Designing assessments to measure learners' competency is another crucial and essential part of instructional design. From an instructional design perspective, there are challenges in quantifying the complexity of problems, while from the learners' perspective, the difficulty experienced is not easily quantifiable. In this work-in-progress (WIP) paper, we will demonstrate the feasibility and utility of a quantifiable directed network representation of the sequence of steps in engineering problems in a MoM course. The network representation visually and numerically captures two aspects of problem-solving: concept knowledge and process knowledge. We report quantification of the complexity of an example problem and learners' problem-solving competency by computing metrics for the directed network representations. Future work will focus on assessing the evolution of learners' problem-solving competency, utility of the directed network representations in designing course assessments, supporting program assessment and accreditation, and its application in measuring learner's metacognition.

Introduction

In this WIP paper we describe a method of assessment of problem-solving skills that may be extended to assist with the process of assessment planning and quantification for accreditation of undergraduate degree programs in engineering. Accreditation of undergraduate degree programs in engineering, such as by ABET, currently requires programs to demonstrate students' ability to "*identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics"*[1]. Traditional assessment data can lack reliable granularity [2] to measure problem-solving skills. Reliable granularity is the reliability (or agreement) of assessment across instructors while quantifying problem-solving processes with accurate granularity. We propose a new method using directed graphs to quantify the complexity of engineering problems and students' problem-solving skills.

We propose and define a network representation technique that combines concept knowledge and process knowledge into a measurable monolithic visualization object [3]. Knowledge may be visualized using hierarchical maps with a positive impact on student learning and stored as an object [4] - [5]. Our network representation technique is based on the use of directed graphs or digraphs. A digraph is a set of vertices or nodes connected by edges. For example, Figure 1 illustrates a directed graph with five nodes 1, 2, 3, 4, and 5 connected by edges or arrows which connect nodes 1 to 2, 2 to 4, 4 to 3, 3 to 1, and 1 to 5, thus describing a relationship that binds the nodes in the shown order.

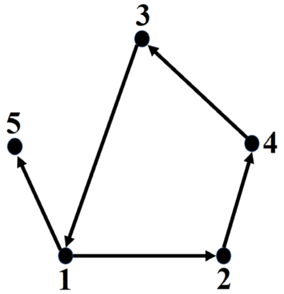

Figure 1: Schematic illustration of a digraph.

Directed graphs are used in social network [6] and linguistics representation [7] - [8], network of biological systems [9], and relationships between concepts and sequential entities. A directed graph is quantifiable through graph measures such as *degree centrality* (the individual node scores that represent the number of edges that enter or exit it), *eigenvector centrality* (a rank of a node based on its visitation frequency), and *closeness centrality* (how close one node is to another). We use digraphs as a representation framework for the sequence of steps necessary to solve problems in a sophomore-level course in MoM from a bachelor's degree program in mechanical engineering. In our approach, different cognitive levels (preliminarily identified using Bloom's taxonomy) are treated as nodes and connected using edges to create digraphs, and we limit ourselves to degree centrality as a quantitative measure of importance of a step. It is possible to use combinations of centrality measures, but for this WIP paper, we focus on interpretability and simplicity of "degree centrality."

Our network representation focuses on the structural visualization of the solution space and the number of branches at each step or node of the solution. We focus on data and data transformation objects, with decision objects to be included in the future. In a typical MoM problem, data objects are geometric properties, material properties, and load conditions. Data transformation objects are the equations that operate on the data objects. For example, the normal stress equation takes a normal force and cross section area to produce normal stress.

Our directed network-based approach may be applied towards the assessment of problem-based learning, to assess a systems-thinking approach, or to augment Bloom's taxonomy, which relies on rule-based identification of cognitive levels such as knowledge, comprehension, application, analysis, synthesis, and evaluation. Furthermore, the network-based tool we propose may facilitate developing quantitatively insightful assessment tools at various required-course levels to collect data on and, as a result, provide evidence of students' achievement of ABET's Student Outcome-1[1].

From a students' perspective, creating a network diagram will allow students to recognize standard pieces that exist across problem-solving domains, lending to the two dimensions of metacognition: the "*procedural knowledge of being able to solve problems in a known environment*" and "*strategic competence of the ability to navigate new problem-solving environments*" [10]. However, an application of our technique from students' perspective is outside the scope of this WIP paper. This approach can also create a framework for computational thinking [11]. From instructional design, curricula, and program assessment perspectives, this approach standardizes the communication structure of problem-solving, thereby allowing quick assessment at scale. From both learners' and instructional designers' perspective, it allows instructors to create balanced course assessments, such as summative exams, with a fine granularity, calibrate examination complexity, and allows students to objectively assess their problem-solving quality [12] - [13].

This WIP paper answers the following research questions (RQs): “Can digraph representation of student problem solving create a quantifiable metric to group student’s problem-solving competence?” and “Can digraph representation of examination problems lead to a quantifiable metric to score the problems’ complexity?”

Method

We demonstrate the method of our digraph approach of visualization and quantification of problem complexity and students’ problem-solving ability through the following exam problem from a sophomore-level MoM course, in which fifteen students were enrolled.

Problem statement: A simply supported beam of length L has a uniformly distributed load of 4 kN/m applied. It has a hollow cross section shown in Figure 2. Compute length L to cause a maximum normal stress of 16 MPa and the maximum shearing stress developed for this length.

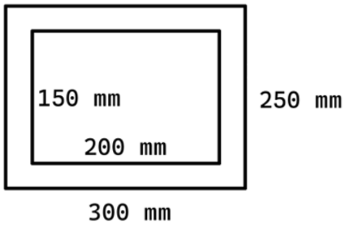

Figure 2: Hollow beam cross-section for the example MoM problem (not drawn to scale).

The solution requires the following steps: Computing reaction forces, Constructing a Shear Force Diagram (SFD), Constructing a Bending Moment Diagram (BMD), Computing the Bending Moment, Applying the Flexure Formula to derive an expression for the Normal Stress, Computing the Length of the beam from the expression for the Normal Stress, Computing the Shear Stress from the confluence of: geometric properties (Moment of Inertia, thickness of the beam, and first moment of area of the relevant section) and Shear Force (from the SFD).

We used the Graph[] function [14] in Wolfram Mathematica to create a directed graph from the aforementioned sequence of steps involved in the correct solution, and the solution from three sample students. The nodes in the directed graph represent the steps identified in the correct solution, while the edges represent the flow of the solution from one step to another. The degree centrality score of such a directed graph was computed by invoking the DegreeCentrality[] function [15].

Preliminary Results and Discussions

Figure 3a shows the correct step-by-step solution to the example problem considered via a digraph with nodes sized by degree centrality. Branches in the digraph suggest that certain calculation processes are independent of the other. The topography of nodal arrangement in this and subsequent digraphs, which does not affect degree centrality, is “*spring-electric embedding*". Other arrangements, for example “*circular*”, are possible and may be controlled by the user. Currently, we define problem complexity as total degree centrality of the digraph, that is, the sum of the number of vertices that enter or exit each node. The number of vertices that enter or exit each node in the correct solution is shown in Figure 3a. Based on this, we quantify the complexity of the example problem as 26. We could choose to use other network centrality measures and an investigation into their suitability will be conducted in the future. The horizontal shear equation computation node is the most "central" to the computation, with a degree centrality of 5.

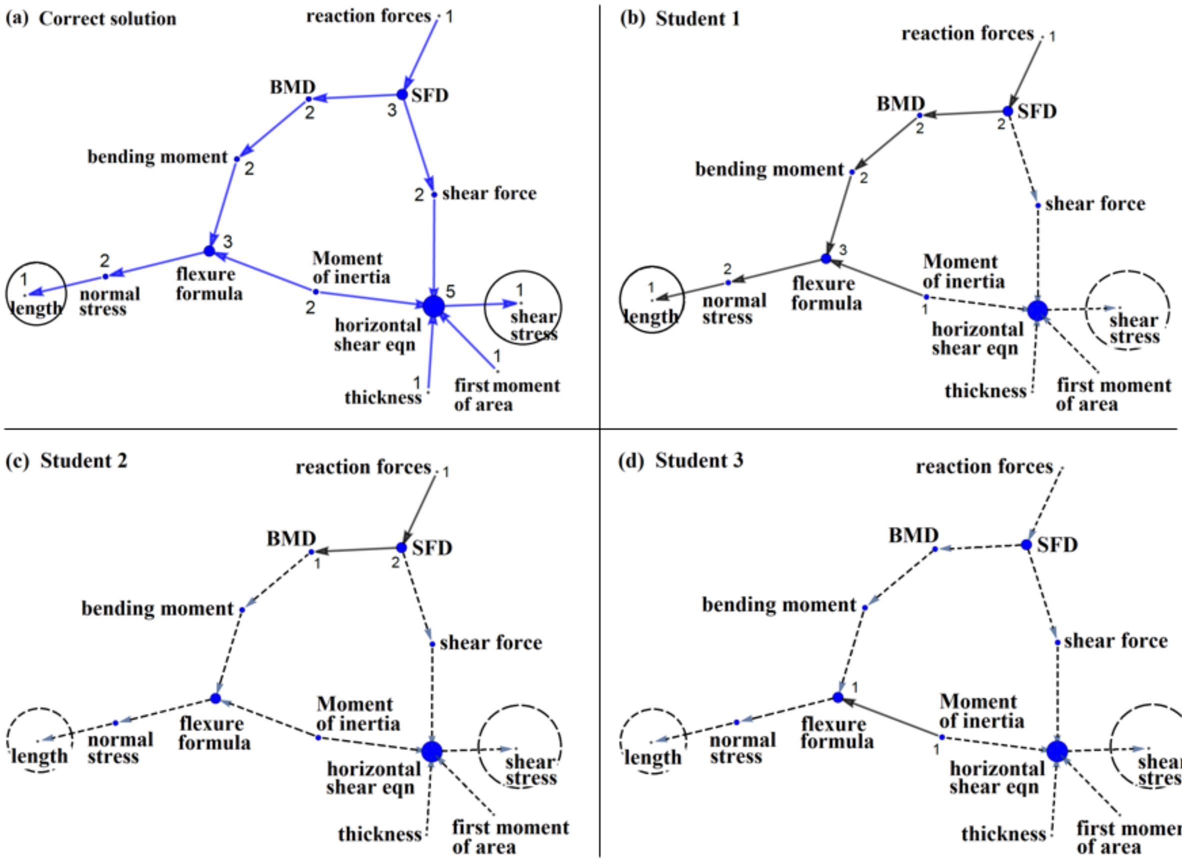

Figure 3a-d: (a) Digraph of the correct solution. Steps to the two-part correct solution start at the "*reaction forces*" node. Solid circles show target nodes for achieving the two-part solution to the problem. (b) Student 1's solution with solid and dotted circles showing parts of the solution achieved and unachieved, respectively. (c-d) Student 2's and 3's solutions, respectively, with dotted circles showing both parts of the solution unachieved.

Figures 3b-d show digraph representation of the step-by-step solutions provided by three sample students 1, 2, and 3. Of the enrolled students, three students had the correct solution, six students were like "student 1," and three students each were like student 2 and student 3. Solid edges in these digraphs signify the sequence of steps that were performed accurately by students. Dashed edges show students missed those steps. Missed steps lead to a reduction in the realized degree centrality. Next, we compute each student's problem-solving ability or competency score, relative to the correct solution, by calculating the ratio of the total degree centrality achieved by the student to the total degree centrality of the correct solution, which is a problem complexity score of 26 in this case. The quantitative measures of student problem-solving competency are normalized to a maximum value of "1". Table 1 summarizes degree centrality and problem-solving ability or competency score for each student.

Table 1: Degree centrality and competency score of students.

Student #	Degree Centrality	Competency Score
1	14	0.54
2	4	0.15
3	2	0.08

Future Work

In the future, our digraph framework will provide a standardized, unbiased visual representation of problem-solving that can be used for assessment and longitudinal studies. It will allow a focus on continuous improvement and learning, rather than subjective grades. Figure 4 shows a synthetically generated histogram for a possible multi-year longitudinal study of student performance. This figure represents how a longitudinal study would bin student competency scores into "n" bins, which may be arbitrarily quantiled. From a program perspective, a change in the membership per bin that exceeds an established threshold could be a lagging indicator of the required review of a course. Future work might also lead to applying our approach to other applicable engineering courses.

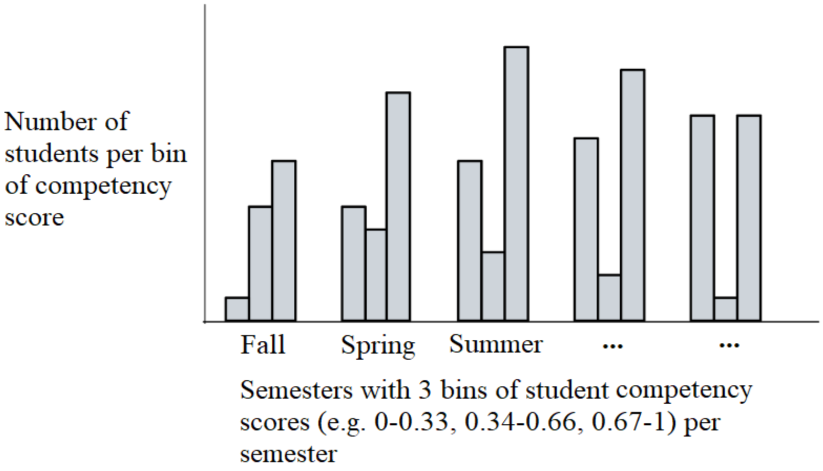

Figure 4: A fictitious histogram for visualizing longitudinal study of students' performance.

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