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Computerized Algorithmic Approaches for Evaluating Systems Thinking of Both Engineers and Non-Engineers

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Computerized Algorithmic Approaches for Evaluating Systems Thinking of Both Engineers and Non-Engineers

This work in progress paper reports on the study of the potential of automated assessments to improve the systems thinking abilities of both engineering and non-engineering students. The computer-based approaches compare any node-and-link diagram of a system created by a student to an expert-generated diagram and produce a similarity rating. The ability to describe a technological system in the form of a diagram is an important element of engineering literacy. Creating a diagram that shows how system inputs are transformed into outputs by a network of interconnected components is also one characteristic of systems-level thinking. Systems-level thinking is critical for engineers and non-engineers as most modern engineered products are technological systems. Systems thinking includes the ability to adopt a holistic, integrative, synthesis perspective, identify system elements and their interactions, and recognize dynamic characteristics. Currently, systems thinking is time-consuming for instructors to assess manually. This work reports on the use of automated assessment. The study was conducted with introduction to engineering students and students in a technological literacy course for non-engineers. In the class activities, students are asked to create system diagrams of common appliances. Evaluation by an instructor was compared with automated assessment using both the Similarity Flooding and Graph Edit Distance algorithmic methods. The automated assessment compares favorably with the by-hand evaluation of student diagrams by the instructor and further improvements are anticipated. Automated instructional aids will become increasingly important in higher education. Systems thinking is a portion of engineering available to anyone without the mathematics prerequisites. Reducing the time and effort needed by instructors in the evaluation of systems thinking has the potential to increase both technological literacy and systems thinking ability of engineers and non-engineers.

Importance of System-thinking Skills

Systems thinking is a critical skill for a majority of the STEM workforce as well as essential to a scientific and technologically literate population. A system is a group of interconnected and interacting elements forming a complex whole serving a common purpose. While various definitions of systems thinking exist, systems thinking generally refers to an ability to comprehend the system holistically, identify its major elements and appreciate how these elements interact to determine overall system behavior. An integrative, synthesis perspective characterizes systems thinking, in contrast to an isolationist reductionist approach.

Engineers create technological systems. From this perspective many of the products designed by engineers are systems. Everything ranging from household appliances, medical devices, structures, agricultural machinery, robots, chemical processes, satellites, integrated circuits, automobiles, highways, and computer networks is a group of interconnected elements serving a common purpose.

The Importance of Systems Thinking for Non-Engineering Students

There is a need for both engineers and non-engineers to have a broad understanding of the nature of technological systems and the products of the engineering disciplines. Systems thinking is conceptual and doesn't rely on higher-level mathematics knowledge explicitly. It is one of the most accessible aspects of engineering for non-engineers. Non-engineers can learn the basics of how things work.

Definition of Systems Thinking

The applicability of systems thinking across many different fields has led to many variations of definitions of system thinking (some representative examples include [1-5]). While sharing an essential emphasis on the foundational importance of identifying elements and relationships between those elements, varying definitions reflect the vocabulary and priorities of different disciplines. Recent comprehensive definitions aimed at engineering applications include Stave and Hopper [6], Froyd et al. [7], Behl and Ferreira [8], and Camelia and Ferris [9]. In this work, the definition of systems thinking advanced by Arnold and Wade [10] is used. This definition is focused on engineering applications, is comprehensive in largely subsuming many previous models, and is formulated in a manner consistent with the assessment of constituent skills.

Major features of the systems thinking definition include:

1. System boundary: Recognition of the concept of a system of interest, identification of the objective of the system, identification of the system boundary.
2. System structure and interrelationships: Understanding the components of a system of interest, the processes within the system, and the inter-linking of components or processes to each other to make integrated wholes.
3. Changes over time (dynamic characteristics): Displaying an awareness of transformations of components or processes within the system of interest that may change over time. Identification of feedback loops and control processes.
4. Multiple perspectives and hierarchies: Demonstrating the ability to observe the system of interest from different levels of the system hierarchy and multiple points of view.

Node and link diagrams are an intuitive means to develop a visual depiction of the elements of a system and their interactions. Some educators and researchers have used the term concept map to describe visual depictions of systems. A problem with this terminology is the nature of concept maps is more general and open-ended than node-and-link diagrams of technological system. To avoid confusion with the more general, non-specific nature of concept maps, the term system diagram is used in this work to refer to a visual representation of the hardware component elements and interconnections of a technological system.

It is possible to demonstrate the major features of the Arnold and Wade systems thinking definition through diagrams. System diagrams depict the boundary between the system and its external environment. Components of the system and their interrelations are central features of a node and link diagram. Feedback loops and control processes can be indicated on a diagram. The level of system hierarchy under consideration is readily discerned from a system diagram.

Figure 1 is an example of a system diagram created by a student. Having studied the refrigerator, students were asked to design a water fountain with cooled water, a similar but different system. Her system diagram demonstrates knowledge of actual existing hardware components and their interactions in a functioning system. The use of this approach makes it possible to introduce systems thinking that does not require extensive mathematical prerequisites.

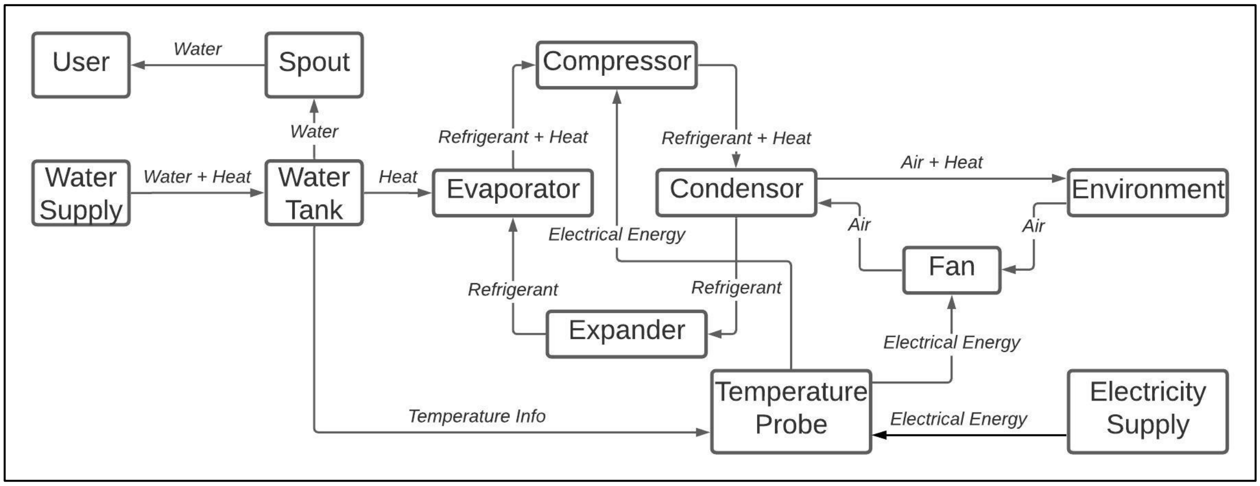

Figure 1: Student-Created a System Design for a Water Fountain.

Evaluating Systems Thinking

To address the importance of systems thinking in STEM and especially engineering, some instructors have introduced features of systems thinking into STEM courses. However, the assessment of systems thinking abilities has proved challenging. One common mode of direct assessment is comparing student diagrams of a system to experts' diagrams. Comparison of a student's system diagram to an expert's diagram of the same system is especially relevant in engineering. Technological system elements are actual physical components and assemblies. Recognizing the role and interactions of specific physical components helps to distinguish expert from novice understanding of technology.

Several studies Assaraf [11] Plate [12], and Brandstädter [13] assessed systems thinking by comparing student-generated system diagrams to diagrams created by experts. In all of these studies, the comparisons were done manually. Huang et al. [14] assessed systems thinking by asking students to prepare written descriptions of systems and compared these to expert descriptions. Gilbert et al. [15] employed diagrams and written descriptions. Studies found that, in most cases, student systems thinking performance does improve with practice. While a common approach for direct assessment is comparing student diagrams to expert diagrams, evaluation has been done manually.

The Potential of Computerized Assessment

An important factor in limiting the teaching of systems thinking in engineering and technological literacy courses is certainly the challenge of time-consuming by-hand instructor evaluation of student diagrams. Computer-based learning approaches have the potential to replace labor-intensive instructor evaluation and revolutionize the teaching and learning of systems thinking abilities in engineering and other STEM disciplines.

Algorithmic Computer-Based Approaches to Assessment

Computer-based algorithmic approaches to diagram assessment can be utilized by considering a system diagram to be a type of node and link (or node and edge) graph. Further, these nodes and links are both labeled and directed. One measure of directed graph similarity is the graph edit distance (GED) approach [16,17]. The GED between two directed graphs is defined as the number of "edits" required to change one of the graphs into the other. Here, an "edit" is defined as the addition or deletion of an edge, the relabeling of one node or edge, or the addition or deletion of a disconnected node. While the basic concept of the GED approach is clear, a limitation of the GED method is the exponentially increasing computation time needed as the number of nodes and edges increases.

An implementation of the graph edit distance comparison method was created using Python-based code that can input diagrams created in Lucidchart (lucidchart.com) and determine the GED between two diagrams. A similarity rating is then determined from the GED using the normalization described by Bai et al [18]. A comparison was then made between the GED evaluation and the similarity rating determined by the course instructor. Results are summarized in Figure 2 for a sample of student water fountain diagrams. Both the instructor and the algorithmic rating were based on a 0 to 100 point scale. A 100 represents perfect agreement between the expert and student diagram. Results show a reasonable trend in the agreement between GED calculation and instructor rating however the level of correspondence is moderate at best over the range of student diagrams tested.

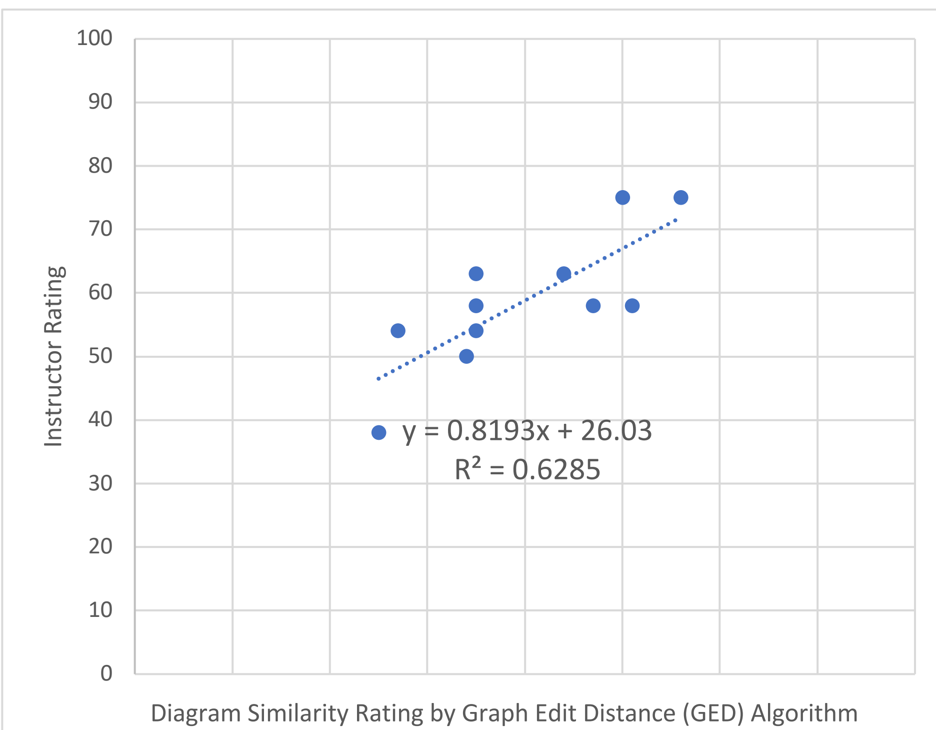

Figure 2: Comparison of Ratings of Similarity between Student and Expert System Diagrams Performed by the Instructor and the GED Algorithmic Approach.

Another approach to evaluating diagram similarity is the similarity flooding (SF) method. SF is a process for matching elements of data schemas and an algorithm for matching nodes and edges of labeled directed graphs [19]. The SF algorithm first creates an initial map between graphs by matching strings on text labels. An initial level of similarity is thus determined between the objects. Starting from the initial map, the algorithm then adjusts these similarities based on adjacencies. Two nodes or edges are determined to be similar this should increase the likelihood that adjacent objects are similar to each other. This process iterates until a fixed point is reached where the process stabilizes. The final results provides a estimate of the extent of matching between the two directed graphs. Unlike GED, SF does not result in exponentially increasing computation time as the number of nodes increases.

Results from the SF implementation are summarized in Figure 3. For the range of student diagrams tested, the similarity flooding algorithm method shows a reasonable agreement with the trends in the instructor ratings. Overall agreement with similarity flooding is comparable to that achieved using the graph edit distance approach. While similarity flooding computes ratings faster than the GED algorithm other limitations were encountered. We found that similarity flooding tends to give high ratings when the student diagram is a subset of the expert diagram, indicating a limited ability to discriminate against extraneous nodes. Thus, if a student diagram contains most of the expert diagram, a high score can result regardless of the number of excess non-matching nodes included. In this case students might learn that they can obtain high scores by creating "everything but the kitchen sink" diagrams.

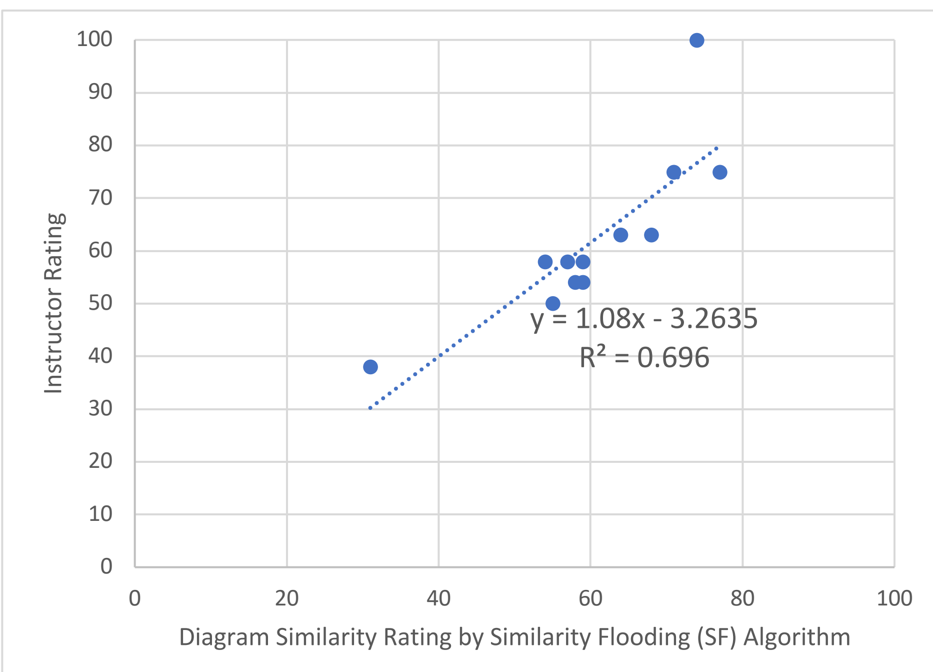

Figure 3: Comparison of Ratings of Similarity between Student and Expert System Diagrams Performed by the Instructor and the Similarity Flooding Approach.

Conclusions and Future Work

These work-in-progress results indicate some guarded optimism about the potential use of software-based assessment of systems thinking. The initial study shows that two different approaches to algorithmic evaluation display trends comparable to by-hand assessment by an instructor. Given that the software used in this work utilized unmodified versions of the basic algorithms, it might be expected that agreement will improve as the algorithms are modified to better detect features most prevalent in diagrams of technological systems. Additional testing is planned with both engineering students enrolled in an introduction to engineering and non-engineers in a general education engineering literacy course.

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