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A Framework for an Engineering Reasoning Test and Preliminary Results.

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The work reported here describes the development and initial testing of a framework to help assess the broad understanding of technology by individuals who are not specifically educated as engineers. It is generally accepted that technology is essential to our current lifestyles and well-being, and the importance of engineering to economic prosperity is commonly acknowledged. However limited work has been done determine the extent to which undergraduates possess a general understanding of the principles, products, and processes of technology. A challenge in developing assessments of engineering and technological literacy is the diverse audiences seen as beneficiaries of such knowledge. The need exists for greater understanding of engineering and technology by diverse groups such as the general public; liberal arts undergraduates; managers in technologically-based industries; other professionals such as lawyers, policy makers, and public servants; and even those trained as engineers. Each of these groups is seen as benefiting from different aspects of technological and engineering literacy leading to difficulty in developing broadly applicable assessment methods. To address this dilemma, the current work developed a framework based on the underlying nature of technological systems and, using this framework, developed an initial engineering reasoning assessment. The framework starts with the concept of function and extends through the design process and technological evolution. Major ideas include the following: technological systems are created to achieve a function that is accomplished through physical form. Technological systems transform materials, energy, and information. Function is provided by components combined into systems. Components utilize physical phenomena which can be modeled using mathematics. Systems employ diverse interacting phenomena. Component functions transfer across systems. Systems can become components in other systems and systems are sociotechnical. System design creates component ensembles with emergent properties. Technological system domains are groups of systems related by a set of shared component types and underlying physical principles. Technological systems evolve often by a process of substitution at the component and subsystem level. This framework is not dependent of any one specific type of technology and can be used to address higher order thinking rather than simple recall of specific facts or repetition of rote procedures. A set of pilot questions has been developed and tested with a range of students across multiple institutions. Some of the initial testing at the current stage of development is reported. The work reported here seeks to demonstrate the potential feasibility of establishing assessment methods that can be used with students who are not majoring in one of the STEM disciplines.

Introduction

It is widely recognized that our standard of living, economy, and way of life are dependent on the use of technology created by engineers. However, the National Academy of Engineering (NAE) has drawn attention to the paradox that while most people acknowledge their dependence upon technology, few have even rudimentary understanding of the underlying principles at work or the nature of engineering [1]. The NAE has long advocated that all citizens should possess an understanding of technology, how it is developed, how it works, how it affects society, and how society determines the path of technological developments.

The NAE has made an effort to characterize engineering and technological literacy as an ability to understand the broader technological world. They further define technology as any modification made to the natural world to meet a human need or want. In this way technology includes physical products as well as processes and knowledge needed to develop and apply these products. In a similar way the various facilities and varied expertise needed in the design, manufacture, operation, and maintenance of technological systems and devices also constitute part of our technological infrastructure.

In a 2006 study reported in *Tech Tally* [2], the NAE Committee on Assessing Technological Literacy attempted to survey the available methods for measuring technological and engineering literacy. The committee determined that no suitable methods existed to measure the broader understanding of technology among the general population. The report concluded: "Thus far, no studies have addressed general engineering concepts, such as systems, boundaries, constraints, trade-offs, goal setting, estimation..." In addition it was noted that: "Not a single study investigates what the general public understands about these concepts, much less how they come to understand them." No well-established and broadly applicable method exists for assessing the understanding of our technological world by the majority of citizens who are not STEM professionals.

Assessing Engineering Literacy

The work reported here is attempting to develop a means of assessing the general understanding of modern technological systems by people who have not received specific training about these systems as part of a job or career. Learning outcomes have been widely studied for those obtaining accredited engineering degrees under the current ABET accreditation criteria. This project reported here addresses primarily undergraduate students in US colleges and universities. The goal is to create an assessment method suitable for use by faculty teaching general education courses on engineering and technological topics.

Determination of the engineering literacy of the general population encounters several specific challenges. Engineering consists of multiple subdisciplines such as civil, chemical, electrical, and mechanical engineering, each with a particular domain of technological systems addressed and underlying principles utilized. The technological systems which are the products of engineering include a wide array of diverse elements ranging from incomprehensibly small integrated circuits to enormous infrastructure in the form of elegant suspension bridges and an expansive highway system. The number of potential specific facts to include in an engineering literacy test is large. Compounding this difficulty is the evolution of technological systems over time. A set of facts describing the technological devices prevalent in everyday life today is likely to be different in one, two, or five years.

Ideally an engineering literacy assessment need not be based on specific technological systems which may be soon outdated. Similarly, a dependency on a particular prerequisite experience, such as a highly specific series of science or mathematics material should be avoided. As a test intended primarily for undergraduates in US colleges and universities, questions should utilize basic high school-level reading and mathematics training rather than assume competence in more specialized college-level subjects. Engineering literacy should not be linked to specific knowledge particular to one of the engineering subdisciplines such as mechanical, chemical, or electrical engineering.

Brief Review of Related Assessments

Some existing approaches to generalized assessment exist that informed the present work in developing an assessment for engineering literacy. This section reviews some well-known assessments and points out how these assessments of different types of abilities were used to inform the present attempt to construct an engineering literacy assessment.

Some type of concept inventory may initially appear as an appealing principle for an engineering literacy test. A widely-recognized example of this assessment approach is the Force Concept Inventory as developed by Hestenes, Wells, Swackhammer, and others [3]. Concept inventories avoid questions that can be answered by application of rote learning. The tests are in multiple-choice format and possible answers to each question typically include distractor options that are based on commonly held misconceptions related to the particular principle addressed by the test question.

While a concept inventory approach to determining engineering literacy may seem appealing, concept inventories are not well-suited as general literacy assessments. Concept inventories are targeted at a very specific and well-defined set of concepts rather than ranging widely across a discipline. For example, the Force Concept Inventory addresses only the concept of force in Newtonian mechanics. It is very successful in this endeavor but other aspects of physics such as energy, electromagnetic radiation, and principles of quantum mechanics are not addressed. Because they address well-defined and long-standing static concepts in established areas of science, changing the test over time is not an option. This generally static unchanging nature of foundational science concepts stands in contrast to the dynamic and rapidly changing nature of the technology developed by engineers.

Other approaches to assessment are better-suited to inform an effort to probe the engineering abilities of non-engineers and the general public. Examples include the ACT Science Reasoning Test [4], Law School Admissions Test (LSAT) [5], the Critical Thinking Assessment Test (CAT) [6] and the Miller Analogies Test (MAT) [7]. Each of these tests seeks to assess a particular set of abilities and each test does so without assuming specific prior knowledge of particular facts. The basic factual information needed is included in the question statements. These tests assess the ability to carry out particular types of thinking processes based on the facts presented.

The ACT Science Reasoning Test presents the test taker with statements that contain data, observations, summaries of experiments, or hypothesis. Some of the information may be mutually inconsistent. Questions address the ability to engage in scientific inquiry and include assessing assumptions, drawing conclusions from data, evaluating concepts, and generating models consistent with given information [4]. The ACT Science Test is concerned with scientific inquiry and reasoning rather than recall of particular facts learned prior to the test. Since the test is focused on science reasoning, the questions are not dependent on any one field of science. Subject matter for questions can be drawn from any field of science such as: astronomy, biology, botany, chemistry, geology, meteorology, physics, and zoology.

The Law School Admissions Test (LSAT) measures a variety of abilities considered relevant to the practice of law. No prior legal training is assumed. The factual information needed to engage in higher level cognitive tasks accompanies each question. The test aims to assess the ability to understand the structure of relationships, draw logical conclusions and the ability to evaluate arguments. Also assessed is the ability to read complex lengthy materials [5].

The Critical Thinking Assessment Test (CAT) is designed to assess a broad range of skills seen as the components of critical thinking. The test includes a variety of tasking including: separating factual information from inferences, understanding the limitations of correlational data, evaluating evidence and identifying inappropriate conclusions, identify alternative interpretations for data or observations, identifying new information that might support or contradict a hypothesis, separating relevant from irrelevant information and integrating information to solve problems [6]. The test describes specific scenarios and problem situations to which the test taker applies critical thinking skills to answer questions. The test does not assume any specific prior factual knowledge and the question content is drawn from a wide range of real-world situations.

The Miller Analogies Test (MAT) is a high-level mental ability test requiring the solution of problems stated as analogies [7]. The test is designed to assess analytical thinking. The test content is drawn from various academic subjects. No specific prior training in any one particular academic discipline is assumed. Positive correlations have been shown between MAT scores and subsequent success in graduate programs in academic disciplines [7].

The ACT Science Reasoning Test, the Law School Admissions Test (LSAT), the Critical Thinking Assessment Test (CAT) and the Miller Analogies Test (MAT) were taken as models for developing an Engineering Reasoning test. The term “Engineering Reasoning” was adopted as more appropriate than “engineering” or “technological literacy.” Like science reasoning, engineering reasoning points to a specific set of skills and abilities used across a particular subject matter domain. Engineering reasoning avoids many of the ambiguities and misinterpretations that have accompanied the term technological literacy.

To proceed in this process requires identification of the characteristics of engineering that are not restricted to any one particular discipline of engineering. Similarly the LSAT is based on aspects of the practice of law in general rather than specific subdisciplines such as business law, constitutional law, or criminal law. Similarly, the ACT Science Test identifies scientific inquiry skills that are common to the biological and physical sciences. By following the example of the ACT Science test, it will be possible to draw test material from across the spectrum of engineering products. This content can be continually updated as new technologies are developed just as the ACT Science Test is able to update test content with new scientific developments.

Framework for Engineering Reasoning

A framework was developed to serve as a platform upon which an engineering reasoning test could be based [8,9]. In developing this framework several key characteristics were desired.

First, the framework should be independent of any particular field of engineering and capable of being applied to any of the engineering subdisciplines such as mechanical, chemical, or electrical engineering. It was desired that the main features of the framework would be somewhat unique to engineering. In other words, the framework would establish engineering as a field of activity related to, but distinctly different from, science, mathematics, or business. The role of science and mathematics should be included but should not dominate the framework. The system nature of engineering products should be evident. The framework should show the role of the engineering design process but also include existing devices and processes that have already been developed. The framework should include the sociotechnical nature of engineering.

The main themes which serve as a framework for the engineering of technology are summarized below. A more detailed explanation of the framework itself is available in our prior work [8]:

1. Technology created for a function accomplished through form.
People create technology to satisfy needs and solve problems. Function provides problem solutions or satisfaction of need. Form describes the characteristics and physical properties of a particular object. The function of an object is determined by the form or physical characteristics of that object. A form may be able to accomplish multiple different functions.

2. Technological systems transform materials, energy, and information.
Technological devices can be viewed as systems that convert available inputs into desired outputs. In general terms, inputs and outputs take the form of materials, energy, or information.

3. Function is provided by components combined into systems.
Systems are created by networks of components that combine to produce the overall function of the system. Components are sometimes clustered into intermediate-level groups or subassemblies. Component function can include control of system behavior.

4. Components utilize physical phenomena.
Components used to create technological systems are based on the application of physical effects and phenomena. For example an electric motor utilizes the phenomenon of electromagnetism. The behavior of components is often described in mathematical form to facilitate system design by utilizing the predictive capabilities of mathematics.

5. Systems employ diverse interacting phenomena.
Nearly all technological systems use a wide variety of physical phenomena. For example a typical type of automobile employs combustion, electromagnetism, friction, hydraulics, and heat transfer in the course of operation. In a technological system, components employing different phenomena must interact by exchanging the same type of material, energy, or information flow.

6. Component functions transfer across systems.
A component that is used in one system can be employed in a different system. The component may be providing the same subfunction within two different systems that have different overall function. For example an electric motor can be used in a vacuum cleaner or a power drill. Components can be varied to emphasize particular characteristics or scaled around the same core functionality and underlying principle. For example the electric motor can be modified to suit the

requirements of devices as different in end use as a domestic washing machine and a window fan.

7. Systems become components and systems are sociotechnical.
A particular technological system can become a component in different system. The distinction between a system and a component is not absolute. Technological systems are influenced by social and cultural interactions and are therefore sociotechnical in nature. For example the internal combustion engine can be considered as a system itself or as a component in the system of an automobile. Some of the design features of an internal combustion engine are influenced by the reciprocal relationship that exists between the automobile and social and cultural values.

8. System design creates component ensembles with emergent properties.
Technological systems are created through a process that utilizes both form and function representations of the system. The process involves compromise or optimization within various constraints. Design entails creating an overall structure of individual elements or components to achieve system goals. Component parameters are varied to obtain desired performance requirements. The assembly of components into a system provides function and utility that exceeds that of an ordinary grouping of the components.

9. Technological system domains are groups of related systems.
Through the engineering design process, groups or domains of related technological systems are created around a set of core underlying principles and components. Systems within a domain typically share common principles applied to different overall functions. Small home appliances are an example of a domain. This would include products such as a coffee maker, dishwasher, hair dryer, blender, and toaster. Nearly all home appliances are based on an electric motor, an electric heater, or both an electric heater and motor. Home appliances share a considerable degree of components in common that may be scaled to suit the needs of specific applications.

10. Technological systems evolve.
Technological systems progress over time. A common means for advancement is change in particular components. An example would be the substitution of jet engines for propeller propulsion in aircraft. Systems also change through the merging of individual components into combined elements. Integrated circuits are an example of this type of development. Technological systems also evolve by adding features and functions to enhance existing capabilities. The evolution of the smart phone is an example of evolution that includes a proliferation of additional functions.

Preliminary Test Questions

A preliminary version of some test questions have been developed. The purpose was to investigate if questions could be derived from the framework and posed in a way that did not require specific prior knowledge of the particular technology. Factual information needed to engage in a specific aspect of engineering reasoning is included in the question. The questions were intended to be analogous to the types of questions on the ACT Science Reasoning Test, The LSAT, or the Critical Thinking Assessment Test.

An initial test of seven questions was developed. A full copy of the test is available to educators by contacting the authors. A brief overview of each question is given below.

Question 1: Hybrid Car System Configuration Design.
This question is based on the principle that function in technological system is provided by components which contribute subfunctions to the overall system. This is framework item 3 above. The question describes major components of a hybrid car including the battery, fuel tank, internal combustion engine, electric motor and generator. The function of each component is described. An operating mode is described and a correct systems-level diagram must be selected from a number of options. Incorrect answers include options with incorrect directions of energy flow. The question measures the ability to correctly interconnect components to achieve a more complex system that accomplishes a function which none of the components can achieve individually. By providing a description of a set of components, the question goes beyond requiring simple factual recall of the components involved.

Question 2: Refrigerator Evaporator Principle Recognition
The question addresses the recognition that components employed in technological systems utilize physical phenomena. This is item 4 in the framework. The question describes the operation of the four major components in a vapor-compression refrigerator. Then the physical phenomenon of phase change from liquid to a gas is stated and the test taker is asked to identify in which component this physical phenomena is found. By providing the background information about the function of the major refrigerator components, the question is able to address the ability to transfer understanding of the basic phenomenon onto a particular application in this system.

Question 3: Refrigerator Condenser Form Characteristics.
This question concerns understanding of the relationship between the form and function of a component in a technological system. Specifically, major form features such as physical dimensions and shape are determined in part by the function carried out by that component. This is contained within framework item 1. The function of the refrigerator condenser is described and the physical principles utilized in the condenser are outlined. The test taker is asked to determine which of the physical attributes of the condenser are influenced by the underlying phenomena at work in this component. The question is intended to address the ability of the test taker to associate form with function.

Question 4: Electric Heater Selection
This question involves the use of a mathematical formula to help select an appropriate component for a system. Framework item 4 notes that engineering relies on mathematical models as an aid to the design process. The question asks the student to select an appropriate electrical heater based on calculation of the power requirement. The basic equation relating power, voltage, and current is provided. The question is challenging because the test taker must perform the calculation correctly and then select an appropriate heater from an array of choices in an excerpt from an actual product catalog. In addition, none of the heaters in the catalog is an exact match to the calculated value, so the test taker must also decide if the appropriate choice is higher or lower than the calculated value. The catalog excerpt also contains a variety of information that is irrelevant to this particular design question and should be ignored.

Question 5: Generalizing Hairdryer Inputs and Outputs
Technological systems transform energy, materials, and information. This is noted in framework item 2. This question addresses the ability to envision the most general statement of what transformations take place in a particular technological system. The test taker is asked to identify the most general description of the inputs and outputs of a hairdryer. The question does not assume any prior knowledge about the physical principles employed in a hairdryer.

Question 6: Recognizing Closely Related Appliances.
The question asks the respondent to identify which devices are most similar based on the underlying structure of the internal system. The question concerns the idea, represented by framework item 9, that technological domains exist around systems related by common underlying principles. Engineering experts can recognize when technological systems are similar based on the types of components and subsystems used rather than external appearances. Diagrams are given for common appliances consisting of: coffeemaker, toaster, coffee grinder, microwave oven, and a blender. The student is given several pairs of devices and asked to select for which choice the two devices are most closely related by internal structure and type of components used. By presenting diagrams of each device the question is able to address the ability to analyze diagrams looking for similar relationships rather than any memorized facts about appliances.

Question 7: Automobile Exhaust System Drawing and Schematic Diagram
Engineering relies on a variety of representations of physical systems. An important underlying ability is the recognition of the correspondence between representations of form, such as drawings and CAD solid models, and representations of functions such as schematic diagrams. This idea is an aspect of framework item 8. In the question, a physically accurate drawing of an automobile exhaust system is presented and the correct schematic representation must be selected from a choice of several possible options. By providing the diagram and schematics the question focuses on the ability to transfer between form and function representations rather than preexisting knowledge of the automobile. Incorrect options include schematic diagrams with the components out of order, incomplete diagrams, and options with incorrect component interactions.

Results to Date

A snapshot of the current state of development and testing the assessment is presented in this section. A goal is to convey presently available results at this initial stage of the project.

Results are available from preliminary trial testing with students in three different institutions. Figure 1 shows the results from this trial. A total of 131 students took the test. Of these, 42 were from Hope College. These were non-engineering students enrolled in a course called “Science and Technology of Everyday Life”. The course satisfies a general education laboratory course requirement for non-STEM majors. All of these students are majoring in a discipline that is not a field of science, engineering, technology, or mathematics. There were 59 students from Iowa State University. These non-engineering students were enrolled a course entitled “From Thought to Thing.” This course fulfills a distribution requirement for non-STEM students at Iowa State

University. The preliminary results also include 30 students from Mission College. Mission College is a two-year college. These 30 students were enrolled in Introduction to Engineering. Although the Introduction to Engineering course is the first course in the pre-engineering sequence Mission College, most of the students in the course have limited background and exposure to engineering and are taking the class to explore the option of pursuing an engineering degree.

For each of the test classes, the questions on the test were not specifically taught or discussed in class ahead of time. Students were not given any advance notice or opportunity to study. This was to ensure that this preliminary test would reflect the student's own thought processes rather than memorized procedures.

As can be seen in Figure 1, the results followed a bell-shaped curve. The mean score was 4.0/7 with a standard deviation of 1.4/7. The median score was also 4.0/7. The fact that the mean and median are identical is not surprising given the relatively Gaussian shape of the score distribution.

These preliminary results are an indication that the type of questions on the test are at an approximately correct overall level of difficulty to create a well-distributed outcome of scores. The expected score for random guessing is 1.2/7. The average score of 4.0/7 indicates that the test takers engaged in deliberate thinking about the questions when selecting answers. Similarly, the distribution is not clustered around low or high scores which would indicate that the test is either too easy or too difficult for most of the test-takers.

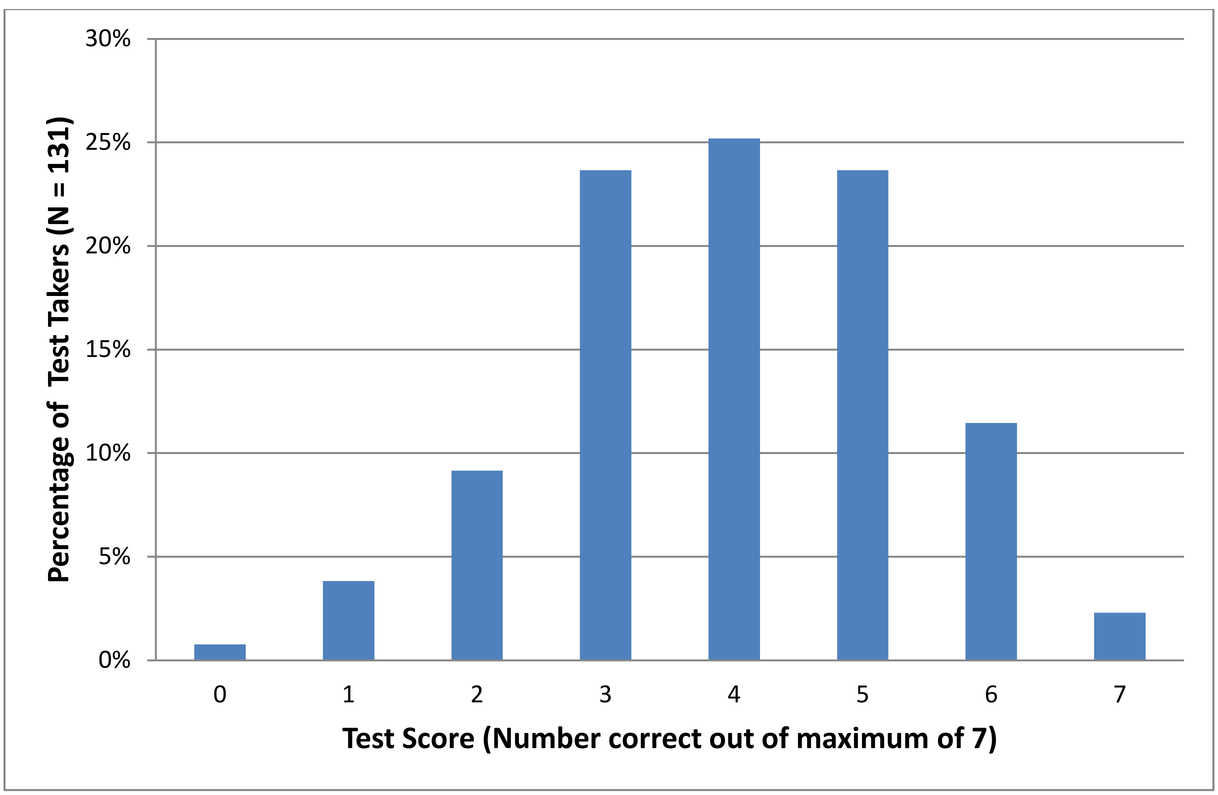

Figure 1: Distribution of Scores from Preliminary Use of Engineering Reasoning Test.

A complete engineering reasoning test requires validation to ensure that outcomes are meaningful. Validation will occupy a major part of future phases of this work. However, some early data are available that are presented in Figure 2. The intent of this data is not to assert validation for the current engineering reasoning questions, but rather to illustrate that a more detailed validation is warranted given currently available results.

Figure 2 shows the correlation between student scores on an existing set of activities in the Hope College course and scores on the engineering reasoning test. In the existing activities non-engineering students are asked to complete two exercises that are primarily systems analysis questions. In the first activity, non-engineers are asked to analyze an actual automobile problem and report on the systems involved, root causes, and steps needed to address the problem. In the second exercise non-engineers are asked to study a home appliance not already studied in the course and describe the system, the major components, principles utilized, and then use a decision matrix to select from several purchase options based on their own weighted criteria. Average scores on the system analysis assignments are plotted against engineering reasoning test scores.

Although there is considerable noise in the currently available data, a moderate correlation was found between engineering reasoning and system analysis assignment results. Students with high scores of 6 or 7 on the engineering assessment tended to have high scores of 90-95 (out of 100) on the system analysis assignments. Students scoring lower on the assessment, in the 3 to 4 range, tended to have scores of 70-80 (out of 100) on the system analysis assignments. The error bars for the data point on the extreme right are too small to appear legibly primarily due to the relatively small number of students who obtained a perfect score of 7 on the engineering reasoning test also obtained near perfect scores on the system analysis assignments. Other scatter in the data might be attributable to the fact that the system analysis scores in this case included factors not directly attributed to the engineering ability of the student (for example, points taken off for late assignments). Such extraneous factors will be addressed in future validation testing.

A subset of the students taking the test were also asked to report their self-assessment of the extent to which they felt “technologically literate.” The students were asked to rate themselves on a scale of 0 to 10 with the lower score indicating a lower degree of technological literacy. This self-reported technological literacy rating was then compared to the students’ result from the engineering reasoning test. Interestingly, self-reported technological literacy appeared to have very little correlation with engineering reasoning test score. These results are summarized in Figure 3.

The lack of correlation between self-reported technological literacy and engineering reasoning test score is an interesting result that requires additional study. One reason for this result may be lack of alignment between what non-engineering students perceive as technological literacy and the subject matter of the test. This might explain those students who rated themselves high in technological literacy but scored low on the engineering reasoning test.

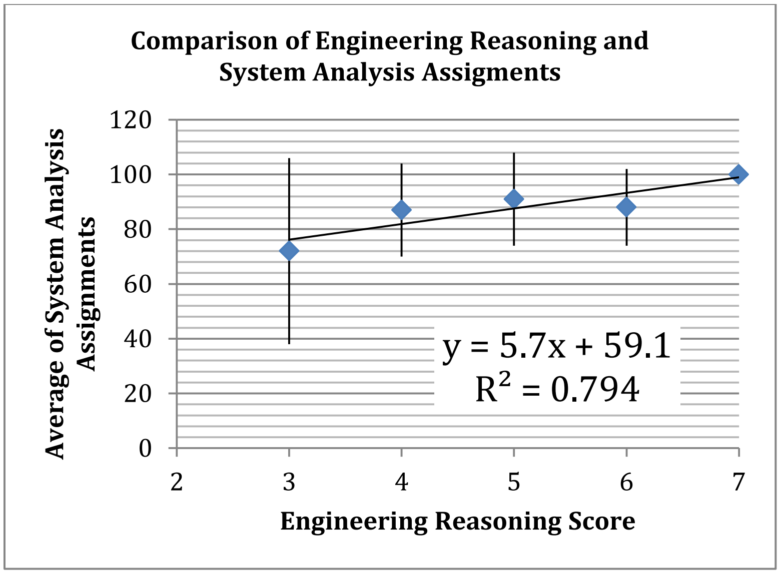

Figure 2: Comparison of Engineering Reasoning Test Scores to System Analysis Assignment Results for a Subset of Test Takers.

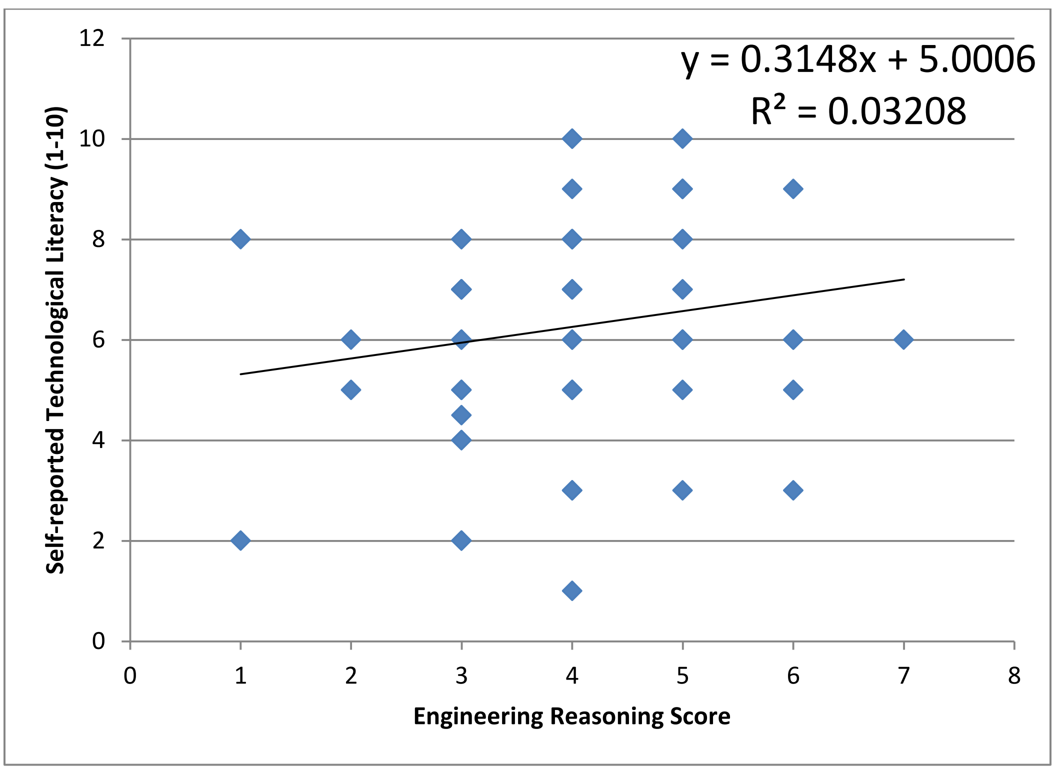

Figure 3: Self-Reported Ability vs Reasoning Test Score.

Another possible explanation for lack of correlation may be that the student's self-reported technological literacy is based only a narrow interpretation of the concept of technological literacy. In this case a few of the test items might align with the students' perception of technological literacy. The remainder of the test may be assessing abilities that the non-engineering students did not associate with their concept of being technologically literate. These results are not anomalous, Sarfaraz and Shraibati have noted the challenges of aligning an engineering course for non-engineers with the expectations of non-STEM students [10].

Work is currently being done to develop a more detailed understanding of what the non-engineers believe constitutes technological literacy in comparison with the framework of items developed for the engineering reasoning test. A survey is being conducted of non-engineering student to develop a more precise understanding of the type of knowledge and abilities that non-engineers associate with being technologically literate.

Conclusions and Future Work

The ultimate long-term goal of this project is the creation of an engineering reasoning test that could be widely used in a manner similar to how the ACT Science Reasoning Test, The Critical Thinking Assessment Test, and the Miller Analogies Test are used today. Such an assessment could be used to show gains achieved by non-engineering students in general education "engineering literacy" and "technological literacy" classes.

The current work has shown useful preliminary results in developing an engineering reasoning test that is applicable for use with individuals who are not specifically trained in any of the engineering disciplines. An approach was followed based on other tests of general ability such as the ACT Science Reasoning Test, The Law School Admission Test, The Critical Thinking Assessment Test, and the Miller Analogies Test. These tests focus on thinking skills rather than recall of facts by providing data and other background information within the body of the test question. Preliminary work indicates that questions based on this approach produce reasonable results when used by undergraduate non-engineering students. Future work intends to increase the number of pilot test questions and proceed to other phases of establishing validity of this intended test of engineering reasoning. The relationship between a non-engineers self-reported sense of technological literacy and test score will also benefit from more thorough and detailed investigation.

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