Assessing Student Learning of Systems Thinking Concepts in an Online Education Module

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Abstract - **Institutions of higher education are vast interconnected networks of departments, programs, majors, and courses, whose complexity is only increased by the rapid growth and availability of technology-based learning in recent years. In today's data-driven world, it is critical for college students in all academic disciplines to understand the basic concepts of "systems thinking" and how systems thinking strategies can be applied to nearly any problem they encounter in their careers. While making this information available to students online is an easy way to disseminate the content within the complex network of higher education, the decision to do so may be at the expense of students' understanding of the material. Therefore, this paper aims to assess the effectiveness of an online module in introducing systems thinking concepts to both engineers and non-engineers. To conduct the study, a gap analysis was performed among existing online education platforms, resulting in the selection of Thinkific as the most effective massive open online course (MOOC) platform through which to disseminate our online module content. Thinkific has open access and allows for interactive participation through the Internet. A short online module was developed and validated in Thinkific using human design principles and user testing. Upon completion of the module design, groups of students in the College of Arts and Sciences (CLAS) and in the School of Engineering and Applied Science (SEAS) at the University of Virginia completed a pre-test, the online module, and a post-test. The qualitative and quantitative results of the pre- and post-tests were analyzed to determine the effectiveness of the module and to learn how understanding varies by intended major. Through this analysis, two findings were elicited: online learning increases learning and understanding concerning key systems thinking concepts, and this learning and understanding is not significantly different between CLAS and SEAS participants. These results inform educators about the degree of emphasis that should be placed on continued development and scalability of online learning programs to enhance understanding of systems thinking concepts. More broadly, this study contributes to the growing body of literature which seeks to understand the impact of technology on the spread of information not only within the field of higher education, but within other large systems as well.**

Keywords—online learning, systems thinking, metrics, objectives

INTRODUCTION

As technology rapidly becomes more developed and widespread, learning continues to expand from traditional lectures in a classroom to virtual learning experiences through online education. Online education flourished quickly; in just twenty years since the first large-scale online education trials, the percentage of all American college students enrolled in at least one online course has grown from 0% to 30% [1],[2]. The growing availability of lightweight, lightning-fast laptops, tablets, and smartphones encouraged the development of hundreds of online learning platforms that enable users to learn about anything, anywhere. Popular websites and accompanying apps such as Coursera, EdX, Google Classroom, and Khan Academy are just a few platforms that provide flexible learning environments for both students and teachers. Over 6.7 million students now enroll in online courses each year, and 69% of academic leaders say online learning is critical to their long-term strategy [3]. Benefits of online learning include that "...the learner has their own responsibility in learning, and realizes their own pace of learning according to their own style, which takes place in the context of a full co-operation and an opportunity for continuous self-evaluation" [4]. Experts who oppose online-based learning claim that students in online courses are less likely to engage with course material than those in face-to-face courses and are therefore more inclined to do worse on examinations [5]. Despite this worry, web-based education presents an opportunity to teach course material to a large, diverse population without adhering to traditional time, location, and spatial constraints. If executed carefully, online education can be a successful channel through which to disseminate information to large groups of people with ease.

Systems Thinking

One topic that lends itself to online instruction is systems thinking. While systems thinking has historically proven itself to be an integral tool for systems engineers, when understood properly it can also be beneficial for a wide range of different individuals, organizations, and even nations. These groups are often faced with complex challenges which require them to make informed decisions. For example, an individual may be attempting to choose which car to purchase, an organization might be deciding which manufacturer to use in the development of a new product, and a nation could be choosing how to allocate funding. Most decisions are made on the basis of attempting to solve a problem or reach a goal, and systems thinking begins with formulating well-conceived objectives and metrics that track how well those objectives are achieved. Objective formulation and the metrics that define their success are critical components of the systems approach. With metrics existing in all aspects of an individual's life, from speed limits to taxes, most people, regardless of whether or not they are engineers, need to understand the process and meaning behind the development of objectives for problem solving.

Objective Statement

After examining the importance and effectiveness of systems thinking, as well as the potential of using technology for online education, the goal of our research is to develop and validate an approach to disseminating the ideas of systems thinking to a large group of people through an online platform.

METHODOLOGY

Online Platform Selection

The first step in developing the online learning module was to identify and evaluate learning platform alternatives for presenting information online. The following criteria were established to determine which of thousands of existing online learning platforms would best align with our project objectives:

- *Criteria 1:* Content should be asynchronous so students can view content at their own pace.
- *Criteria 2:* Students can respond to and interact with content through discussions, surveys, quizzes, etc.
- *Criteria 3:* Teachers or course administrators can access and export student responses.
- *Criteria 4:* Content should be free for students or participants to access.
- *Criteria 5:* Students should be able to track their progress while taking a course.
- *Criteria 6:* Tools for teachers or course administrators to develop content are clear and intuitive.

These criteria are not universal for evaluating effective online learning platforms, but represent the characteristics that are most relevant for the proposed online module's purposes. Gap analyses performed on over 15 potential platforms determined how well each technology satisfied the specified criteria. In the gap analysis, qualitative descriptions of features of each technology that would or would not work well for the purposes of the project were provided. Platforms were also given a quantitative ranking on an ordinal scale between 1 and 3 for each criterion, with 1 meaning the platform does not meet the criteria at all and 3 meaning the platform satisfies the criteria perfectly. A summary of these rankings for the 4 most highly-ranked platforms is provided in Table I.

While none of the platforms satisfied all of the outlined specifications perfectly, Platform C most closely met the designated criteria and was thus selected as the tool through which the learning module would be developed. Platform C is a MOOC platform known as Thinkific which allows teachers and course creators to develop content that can be organized into digestible chapters and lessons, integrates various forms of multimedia, customize class websites and course requirements, and more.

TABLE I.
ASSESSMENT OF ONLINE PLATFORMS AGAINST SPECIFIED CRITERIA

Platform	**Criteria**						**Total**
	1	***2***	***3***	***4***	***5***	***6***	
A	2	3	3	1	2	2	13
B	1	3	1	3	2	2	12
C	3	3	3	3	3	2	17
D	3	1	2	3	2	3	14

Table I. When scored on an ordinal scale from 1-3 against six criteria, Platform C has the highest score.

Module Development

After reviewing studies of best practices in online learning conducted by the U.S. Department of Education, we determined that our module should have the following properties:

Holds User Attention: Participants should be able to complete the module in one sitting without losing interest.

Understandable: Any participant with a high school diploma should be able to comprehend and internalize the module content, regardless of further specialized education or training.

Meaningful: Participants should gain knowledge through the module that has clear applications to their lives.

To satisfy the first property, we first applied research showing that the average student attention span for an online course is no more than 25 minutes. This informed our decision that the module should be designed to be completed within that time frame [6]. We narrowed the extensive field of systems engineering to focus on two fundamental topics that could be taught in that time, *objectives* and *metrics*. These topics proved to be strong candidates for the module because they satisfy the second and third properties: they can be easily simplified to remove any technical prerequisite knowledge and they have wide application to a variety of technical and nontechnical fields. To further satisfy the third property, a final section of the module that provides examples of objectives and metrics applied to real-world problems was included.

An initial module, "Introduction to Systems Thinking", was developed in Thinkific based on these considerations. In the objectives section, participants are taught about the seven steps of objective development, the proper way to write objectives, and how to create objectives trees. In the metrics section, participants are taught about the importance of developing strong metrics and the five characteristics all strong metrics must have. In the examples section, participants are exposed to the following three scenarios in which objectives and metrics are used to guide the problem-solver toward optimizing the situation at hand: (1) using GPA as a metric to understand student performance; (2) developing objectives and metrics to reduce solid waste at UVA; and (3) creating a universal metric to measure a nation's wellbeing. These applications introduce participants to key themes in objective and metric development, such as the importance of choosing metrics carefully based on the problem trying to be solved and the difficulty of selecting a single metric that satisfies the values of all stakeholders involved.

Primary usability evaluations were conducted following initial module creation, during which test users noted areas of excessive wordiness, confusions in phrasing, and inconsistencies in overall design. Appropriate changes were made to the module to reflect this feedback. We completed a second iteration of usability evaluations to arrive at our final module design.

Experimental Design

To test the project objective, an experiment was designed that employed paired data as well as permitted the comparison of two groups of students to determine whether or not choice of academic school makes a difference in learning. The following two null hypotheses were proposed for the experiment: (1) the online module is not effective in increasing an individual's knowledge and understanding of objectives and metrics, and (2) there is no difference between CLAS and SEAS participants' increase of knowledge and understanding of objectives and metrics after completing the online module.

To determine whether or not there is sufficient evidence to reject these hypotheses, 24 first-year undergraduates at the University of Virginia, 12 from CLAS and 12 from SEAS, were recruited to complete the module. A five-question test was administered to each participant both before and after the participant completed the module. Each question 1 through 5 asks participants to demonstrate knowledge of the same learning objective in both the pre- and post-test, listed here:

- *Question 1:* What do you think is the biggest challenge systems engineers face when developing objectives?
- *Question 2:* Write two sub-objectives for the following objective based on the scenario provided.
- *Question 3:* Create a metric for objective provided.
- *Question 4:* A metric is a measurement of success toward reaching a specified goal. List as many characteristics of a good metric as you can.
- *Question 5:* What is systems thinking and why is it important?

Upon module completion, participant responses to the pre- and post-test questions were deidentified. A rubric was used to score each question with a 0, 1, or 2 to represent whether the question had been answered at a naive, apprentice, or competent level, respectively. The change in an individual's scores from the pre-test to the post-test allowed us to measure increases in knowledge and understanding of objectives and metrics.

Results and Discussion

The two metrics used to measure the success of students are the total scores calculated by adding up individual scores from each question on the pre-test and on the post-test. Since the objective of the experiment is to discover if scores on the pre-test and post-test are different, the total scores provide a holistic metric to measure the overall progress of a student's learning. In addition, an understanding of the data distribution is needed to determine what statistical tests are valid to use, and to discover any limitations that are present in the data. The frequency distributions of the pre- and post-test scores shown in Fig. 1 indicate that the data does not completely follow a normal distribution.

FIGURE I.
DATA DISTRIBUTION OF PRE-TEST AND POST-TEST SCORES

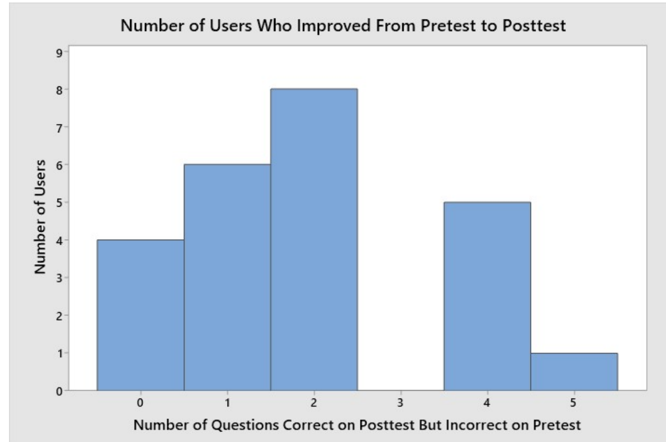

Fig. I. The frequency distributions of the pre- and post-test scores show that the data does not follow a normal distribution.

Thus, there is greater interest in using non-parametric tests to ensure greater validity of the results without making assumptions regarding the distribution. Non-parametric tests like the Wilcoxon signed-rank test and the Mann-Whitney tests make no assumptions about the distribution of the data [7]. As the Wilcoxon signed-rank test is used for paired samples, this test is useful for Hypothesis I to test whether the difference in pre-test and post-test scores indicate an increase in understanding at a 5% significance level. The Mann-Whitney test is useful for Hypothesis II to test whether two independent samples of CLAS and SEAS students differ in their learning and understanding of the module content at a 5% significance level.

Hypothesis I

H0: the online module is not effective in increasing an individual's knowledge and understanding of objectives and metrics.

Using the metric of total score as our response variable, the analysis shows that online learning does increase learning and understanding. The median score of all users being tested on the pre-test is 3 out of 10 possible total points, whereas the median score of all users being tested on the post-test immediately following the module is 6.5 out of 10 possible total points.

Using this data, a Wilcoxon signed-rank test is conducted on the paired distributions of the pre- and post-test scores to test if the difference between the scores is significant at a 5% significance level. The test elicits a p-value of 0.00008, rejecting the null hypothesis and suggesting that students did in fact learn from the online module given regardless of their background as SEAS or CLAS students.

Additionally, the histogram in Fig. II shows that users benefited from the online module because the frequency of students getting no questions correct is far less than the frequency of students getting at least one question correct.

FIGURE II.
DISTRIBUTION OF USERS WHO IMPROVED FROM PRE-TEST TO POST-TEST

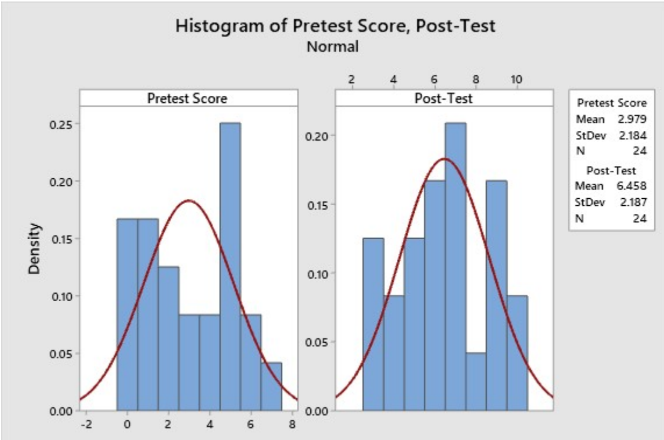

Fig. II. The frequency distributions show that more users improved by getting at least one question correct on the posttest that they didn't get correct on the pretest.

Hypothesis II

H0: there is no difference between CLAS and SEAS participants' increase of knowledge and understanding of objectives and metrics after completing the online module.

To test the second hypothesis that there is no difference between CLAS and SEAS participants' increase of knowledge and understanding after taking the online module, three statistical tests are completed. Details of each test are shown in Table II.

TABLE II.
MANN-WHITNEY TEST RESULTS

	Test 1	**Test 2**	**Test 3**
Data Compared	Median pre-test scores	Median post-test scores	Median differences in pre- and post-test scores
CLAS Median	2	6.5	4
SEAS Median	5	6.5	3
p-value	0.047	0.381	0.601

Table II. This table displays the results of three Mann-Whitney tests conducted to determine if the difference in scores between samples of CLAS students and SEAS students is significant at a 5% significance level.

The first statistical test is used to discover if there is a difference in pre-test scores between CLAS and SEAS students. The median pre-test scores for SEAS students is 3 points higher than that of college students. The Mann-Whitney test further proves that this difference is significant at the 5% significance level.

The Mann-Whitney test is repeated on post-test scores to evaluate whether there is a significant difference between average post-test scores for CLAS and SEAS students. Results show that SEAS and CLAS students have the same median score on the post test. At a significance level of 5%, it can be concluded that SEAS students' performances on the post-test is not statistically different from CLAS students' performance.

Furthermore, the relative growth in understanding for these two groups of students is similar. The third Mann-Whitney test conducted on the differences in test scores for SEAS students versus CLAS students proves that the null hypothesis that there is no difference in learning cannot be rejected at the 5% significance level. As shown in Fig. III, the distribution of growth in scores is the same for these sample groups.

FIGURE III.
DISTRIBUTION OF THE DIFFERENCE BETWEEN PRE- AND POST-TEST SCORES BY SCHOOL TYPE

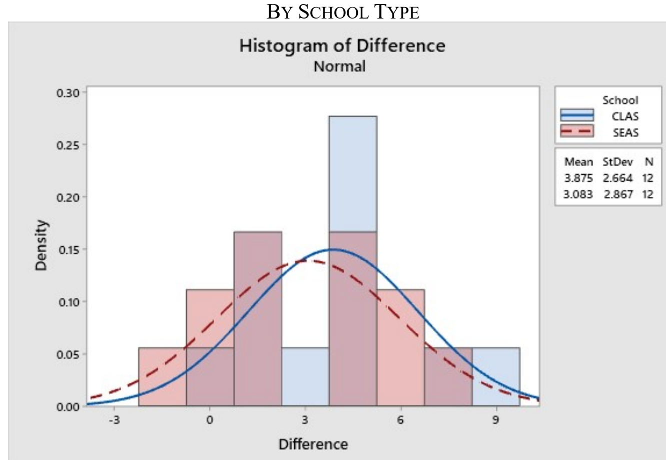

Fig. III. The distribution of the difference of scores is not significantly different between SEAS and CLAS students.

Thus, even though SEAS students have greater prior knowledge before completing the online module, the median post-test scores show that CLAS students' knowledge converges to SEAS students' knowledge after completing the module. However, when directly testing the difference in pre- and post-test scores, the increase in understanding and learning from the online module is relatively similar, as statistical tests did not show a significant difference.

Based on the average scores for individual post-test questions shown in Table III, it is clear that both CLAS and SEAS students perform, on average, most poorly on Question 2. As this was a scenario-based question, the low score could be attributed to unfamiliar or poorly-worded scenarios. This lack of clarity is an example of one disadvantage of online learning - there is no opportunity for interaction with the instructor. It also, however, could be attributed to a lack of understanding of a particular concept by both SEAS and CLAS students.

TABLE III.
AVERAGE POST-TEST SCORE PER QUESTION FOR EACH SCHOOL TYPE

School Type	**Average Q1 Score**	**Average Q2 Score**	**Average Q3 Score**	**Average Q4 Score**	**Average Q5 Score**
CLAS	1.08	0.83	1.33	1.38	1.38
SEAS	1.67	1.00	1.75	1.17	1.33

Table III. The table displays the average score out of 2 points per posttest question for each school type. The values highlighted in red showcase the lowest point value for each school type, and the values highlighted in green showcase the highest point value(s) for each school type.

SEAS participants, on average, respond more accurately on Question 3, which pertains to the topic of creating a metric. However, CLAS students receive higher scores on Questions 4 and 5, and also outperform SEAS students on these questions.

Questions 4 and 5 are different in nature, as Question 4 pertains to the characteristics of metrics and Question 5 pertains to the challenges of systems thinking. It is possible that SEAS students perform better on Question 3 because it is more design based than experimental, whereas CLAS students perform better on the conceptual portions of the test. However, these hypotheses require further analysis to determine a plausible explanation for these differences.

Our results show that our online module does increase learning and understanding of systems thinking. On the other hand, the amount of learning and understanding students receive from the model does not significantly differ based on participants' academic discipline.

Limitations

First, despite following a rubric, the open-ended nature of the test questions left responses open to interpretation by the research team scoring the test. Thus, inherent biases of individuals on the research team may have led to differences in quiz scores. To mitigate this risk, two people scored each question, but variation in the scoring was still present. In addition, students' inability to clarify their responses for graders to understand may have led to differences in grading.

One of the more important limitations is the small sample size that was used. Experimental results from 24 students may not accurately represent the entire population of SEAS and CLAS students at UVA. However, due to time constraints as well as limitations in accessing a larger student population due to the onset of COVID-19 in the spring of 2020, a larger sample was unattainable. Furthermore, participants were all students from the University of Virginia whose similar educational experiences may have skewed results. Performing this experiment on students across different universities would introduce greater randomness into the experiment.

Another concern is the academic classification of the two groups as SEAS vs CLAS students. There are many college students who pursue science, technology, engineering, and mathematics (STEM) majors, like computer science, biology, chemistry, physics, etc. These students may have been introduced to systems thinking in their studies or may have critical thinking skills that align more closely with SEAS students than other CLAS students.

FURTHER STEPS

In response to the pre-test question "What is systems thinking and why is it important?", one first-year CLAS student responded "I don't know". After completing the online module, the student's answer to the same question was "Systems thinking is important because it is a holistic approach to solving a problem. It leaves no stones unturned, and creating objectives entices creative thinking. All the goals are clearly defined and so are the methods of measuring their efficacy. As the system changes, the objectives and metrics can adjust as well". This answer is one of many that highlight the effectiveness of the online module in increasing participant knowledge about the critical thinking concepts that are fundamental to not only systems engineering, but to a wide range of problems faced in a variety of careers as well. While this research has developed a foundation for increasing student accessibility to fundamental systems engineering concepts through online learning, there remain several areas for improvement. Future steps include incorporating more engaging features into the learning module such as discussions, audio/visual components, and interactive activities. Additionally, the module should be promoted as a valuable resource for all undergraduate students so that a larger number of students take advantage of understanding fundamental systems thinking concepts. We hope that this module can be further developed to be used as a tool by the UVA Engineering Systems and Environment department to introduce undeclared engineers to systems engineering to help them decide if they would like to declare the program as their major.

CONCLUSION

In an effort to increase the knowledge and understanding of systems thinking to a population outside of the systems engineering community and to harness the rapid advancement of available online learning technologies, the online module "Introduction to Systems Thinking" was developed on Thinkific. The module introduced students to the fundamental concepts of objectives and metrics and provided real-world applications of these concepts to various fields of study. Two null hypotheses about the module were tested: (1) the online module is not effective in increasing an individual's knowledge and understanding of objectives and metrics, and (2) there is no difference between CLAS and SEAS participants' increase of knowledge and understanding of objectives and metrics after completing the online module. To test these hypotheses, 12 first-year CLAS students and 12 first-year SEAS students were asked to complete the module and answer pre- and post-test questions that assessed their learning. Analysis of these answers show that the online module does significantly increase understanding of systems engineering concepts for both CLAS and SEAS students, and that the degree to which understanding increased does not significantly differ by school.

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