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Evidence of Learning Gains in Statics as a Result of Simulation-Based Instruction

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1. Introduction

At the University of Puerto Rico, Mayaguez (UPRM), the Engineering Statics course enrolls more than 500 students per year from Civil, Industrial, Mechanical and Chemical Engineering. Unfortunately, nearly 60% of the enrolled students earn a D, F, or W[1]. As a result, we are undertaking a series of initiatives to incorporate innovative and best practices into "critical" courses such as Statics.

In particular, we are conducting project sponsored by the NSF TUES Program in which we have developed new approaches and exercises for Statics that incorporate the use of simulation tools that expose students to engineering design. Use of simulation tools provides many benefits, enabling students (1) to solve problems that are both intensive (e.g., that require the solution of many equations), (2) to perform "experiments" (e.g., "what if" or sensitivity analysis), and (3) to attempt elementary design exercises[2]. As students engage in such activities, they also progress in their understanding of fundamentals such as Free Body Diagrams, sign conventions, and the necessity to check the reasonableness of a final answer. A detailed literature review of philosophies and attempts to incorporate simulation in the introductory mechanics courses in provided in Authors, 2012[3].

Our general concept of incorporating simulation in Statics (and other mechanics courses) is to provide a setting in which students can develop or run a model repeatedly to study system behavior. In Statics, we use the Excel spreadsheet as an accessible simulation platform that enables students to explore the behavior of a mechanical system. This is accomplished by providing students with a pre-programmed linear equation solver and other pre-programmed sheets that serve as black boxes to enable observation of output behavior as a function of input data. Although use of spreadsheets in Statics is well precedented[4], little research appears on how this changes student problem-solving behavior. Our goal is to demonstrate that exposure to simulation using well-programmed spreadsheets can lead to improvements in problem solving skills.

This project focuses on the cohort of Civil Engineering students. In particular, a culminating project about the design of a steel signpost to support a billboard makes use of professional design standards published by ASCE, AISC, and AASHTO. This project, along with other design-oriented projects, is continued in the subsequent course of Introductory Mechanics of Materials; student performance is tracked in this course and the further subsequent courses of Advanced Mechanics of Materials, and Structural Analysis[3].

Prior work by the authors[5] showed favorable attitudes among students who learned Statics in this manner. Of note here is that most students perceived the use of a simulation tool to be efficient. A fewer, but still significant number of students articulated that the use of simulation can aid in the design process by enabling changes of design parameters, though in language that is not as sophisticated, and often only when prompted to comment.

Since this prior work, we have conducted a series of 'think-aloud' interviews. Think-aloud interviews[6] are activities in which the interviewee is asked to perform a task or solve a problem in the presence of an interviewer. The interviewee is asked and prompted to verbalize his/her reasoning during the process.

To date, a total of 24 students who earned a grade of A, B, or C in Statics have been interviewed (with the approval of UPRM's Institutional Review Board). These students received a stipend of $25 for their participation. Of these 24 students, 10 were exposed to our spreadsheet based approach ("experimental group") and 14 received standard instruction without exposure to spreadsheet ("control group"). Each interview lasted approximately 60-90 minutes and engaged the students in two sets of questions. Each set was organized around a given system and tested both basic mechanics skills and the ability to use a simple prepared spreadsheet to act as a simulation tool for solving equations. Trained interviewers probed the students for explanations as needed, so as to ensure a relative uniformity of responses corresponding to key steps.

2. Description of Think-aloud Instrument

As is typical with many studies in engineering education research, ours includes a variety of subjective and objective measures, including student surveys, measures of performance data, and detailed think-aloud interviews that profile patterns of student thought. The subject of this paper is to provide details of the design, dissemination, and results of the think-aloud instrument. The results reported here consist of a preliminary aggregation of data that indicate student facility and preferred approaches in the interview problems. A detailed analysis of the transcribed interviews, indicating deeper cognitive responses, is forthcoming.

The think-aloud interview instrument is presented in the Appendix. It consists of two sets of five questions each. Set 1 is focused on the analysis of a beam supported by a hinge and a cable, with an external load applied. Set 2 is focused on the analysis of a truss with simple supports and given external loads. Within each set, the questions progress in procedural order and/or level of abstraction and complexity. After answering each question, and before proceeding to the next question, participants are shown a standard accepted answer. This process (1) enables participants to proceed to the next question even if they make a crucial error that would otherwise impede their progress, and (2) provides an opportunity for participants to offer a reflection on how their answers compared to the accepted answer.

The questions are divided into two types. Questions 1a, 1b, 1d, 2a, 2b, and 2c test basic mechanics skills (henceforth referred to as "Basic Questions"). These questions pertain to drawing Free Body Diagrams and writing basic equilibrium equations, and ostensibly do not favor spreadsheet skill vs. hand calculation. Questions 1c, 1e, 2d, and 2e probe more advanced issues that are designed to favor spreadsheet skill (henceforth referred to as "Advanced Questions"). For example, Question 1e poses a conceptual question to determine the effect on the reactions due to a change in the angle of the supporting cable. This is difficult for the novice to answer without insight into which equations specifically target the posed results; however, even in the absence of such insight, the question is tractable by simulation, i.e., by changing the cable angle in the appropriate spreadsheet cell several times. Likewise, Question 2d asks students to imagine solving for all of the unknown member forces of a truss, a problem that would be daunting to do by hand, and which is presumably an unfamiliar task to students who have not had some type of simulation or computer based instruction.

A laptop with a pre-programmed spreadsheet, capable of solving linear systems of equations, was provided to the students as a resource. Students were given the option to solve equations by entering coefficients into the designated area, but they were not required to use it. In fact, participant choice to use the spreadsheet is an important indicator of the influence of the spreadsheet-based instruction.

Trained assistants gave the interviews, which were both audio and video recorded. Before starting the interview, we explained the instructions to the participants and gave them a practice problem to familiarize them with the procedure, including with how to use the spreadsheet. After the interviews, participant performance was tabulated, including detailed transcription of their verbal comments.

3. Results and Discussion

The preliminary results of the think-aloud interviews were tabulated as “Yes” or “No” to indicate the essential (favorable or unfavorable) responses to each question. The results are summarized in Tables 1 and 2.

Table 1. Students answering favorably to Questions in Set 1.
Advanced Questions are denoted with an asterisk (*).

Question	**Experimental Group (N = 10)**	**Control Group (N = 14)**
1a. Draw Free Body Diagram of beam correctly?	7/10 (70%)	8/14 (57%)
1b. Write equilibrium equations correctly?	5/10 (50%)	13/14 (93%)
1c*. Solve equations for reactions and tension correctly?	7/10 (70%)	12/14 (86%)
1c*. Use spreadsheet?	7/10 (70%)	1/14 (7%)
1d. Transfer numerical values onto Free Body Diagam?	9/10 (90%)	11/14 (79%)
1e*. Determine change (increase or decrease) in reactions and cable tension with respect to change in cable angle?	8/10 (80%)	7/14 (50%)
1e*. Use spreadsheet?	6/9 (67%)	3/13 (23%)

Table 2. Students answering favorably to Questions in Set 2.

Question	Experimental Group (N = 10)	Control Group (N = 14)
2a. Draw Free Body Diagram suitable to determine reactions (entire structure)?	5/10 (50%)	9/14 (64%)
2b. Draw Free Body Diagram suitable to solve for members FG and LG (joint G)?	9/10 (90%)	12/14 (86%)
2c. Draw Free Body Diagram suitable to solve for members KL, EL, and EF (section)?	5/10 (50%)	11/14 (79%)
2d*. Suggest method to solve for all members forces and reactions?	8/9 (89%)	9/14 (64%)
2d*. Suggest spreadsheet or compatible procedure?	6/8 (75%)	3/14 (21%)
2e*. Is zero weight assumption for members of a truss valid?	4/8 (50%)	6/13 (46%)

Considering first the Basic Questions, the results are mixed. However of note is that for qQuestions 1b, 2a, and 2c, students in the control group generally outperformed the students in the experimental group. This raises the troubling possibility that students in the experimental group may not be missing some of the fundamentals, possibly due to being distracted by use of the spreadsheet as a technique. This question will be examined further in the detailed analysis of the interview transcripts. We note that common errors were (i) forgetting to write the moment balance equation in Question 1b and (ii) drawing the joints at the reaction points rather than the entire structure in Question 2a. These errors match common errors made in general instruction as observed by the authors over many years.

For the Advanced Questions, the results indicate that the students in the experimental group generally outperformed the students in the control group, at least as exhibited by their greater facility and willingness to use the spreadsheet (or simulation-related reasoning) to answer advanced level questions. In Question 1c, for example, although students in both cohorts were able to solve the equilibrium equations correctly, students in the experimental group chose to use the spreadsheet much more frequently. In Question 1e, students in the experimental group outperformed students in the control group in getting the correct answer, and not surprisingly, they used the spreadsheet to perform the required sensitivity analysis. It should be noted, however, that students in both groups had difficulty explaining the results in words, regardless of the correctness of their final answer or their approach. Similarly, in Question 2d, students in the experimental group were much more likely to attempt an answer and to articulate a correct method to determine all reactions and member forces in the truss. The results of this problem indicate that the spreadsheet enables students to approach problems of greater complexity than are normally amenable to hand calculation.

4. Conclusions

The overall results of this study are mixed. On the one hand, the results of the Basic Questions indicate that the use of the spreadsheet based instruction did not increase student performance, and in some cases, possibly distracted students from developing basic skills. These results do not support the authors' hypothesis that spreadsheet-based instruction would improve conventional skills. The reason for this belief is that the spreadsheet requires a more regimented framework for problem solving (that is, students cannot skip steps or fudge answers as easily) that would be expected to improve students' overall problem solving ability.

On the other hand, students who received the spreadsheet based instruction were generally more willing and able to approach problems of greater complexity and difficulty. This is encouraging, because despite the shortcomings in the basic questions – shortcomings that can be presumably overcome – the spreadsheet possibly offers a vehicle to accelerate the development of advanced level problem solving skills. The results of Questions 1e and 2d particularly underscore this point.

Although speculative, we propose a possible framework that might explain how the use of simulation can help students advance in solving more complex problems, even though they still not might attain the complete conceptual understanding of an expert. As depicted in Figure 1, an expert might be able to completely conceptualize a procedure that can capture the behavior of a system. A novice, on the other hand, using only hand calculation to solve a problem, is unlikely to see any broader system behavior. However, equipped with the simulation tool, even a novice can run several examples to see how the system behavior changes with changes in various parameters, even if they are still unable to give a clear (qualitative or verbal) explanation.

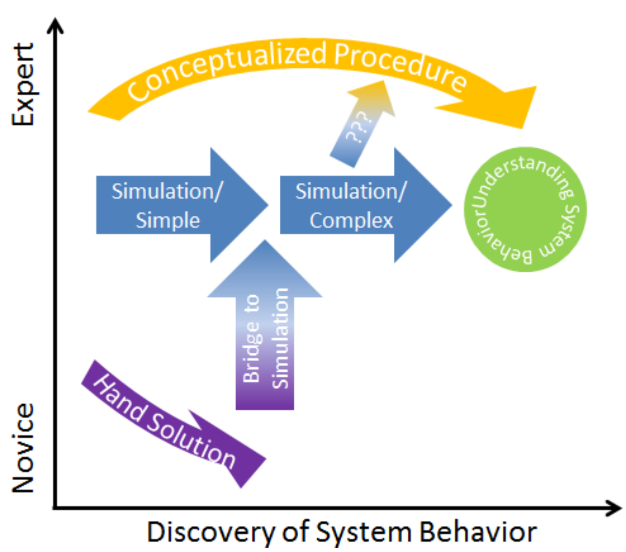

Figure 1. Schematic Showing that Simulation "Bridges the Gap" between Expert and Novice.

This framework is exemplified by the results of Question 1e. Students were unable to convincingly explain the effect of increasing the cable angle without using the spreadsheet. Using the spreadsheet, they were able to correctly identify this behavior. However, they were unable to provide correct explanations, such as to see the "right" equations that would enable them to confirm the results. This higher level of critical thinking represents an ill-structured aspect of problem solving. We plan to test this framework as we continue to collect further data.

Further analysis is necessary to determine if the use of the spreadsheet and other simulation tools have overall long term benefits. The authors are in the process of investigating these questions be observing the performance of the experimental and control students in subsequent courses. With further reflection, the authors also intend to address the need to improve students' understanding of fundamental concepts in Free Body Diagrams in response to the shortcomings observed in this study.

Acknowledgement

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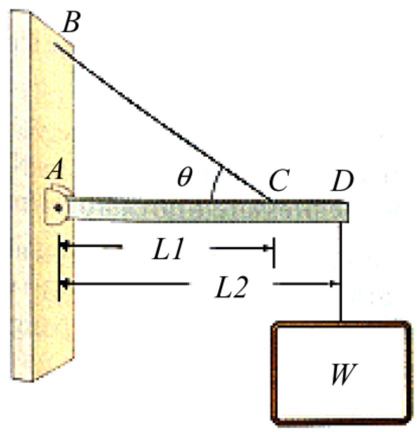
Appendix. Description of Think Aloud Interview Instrument

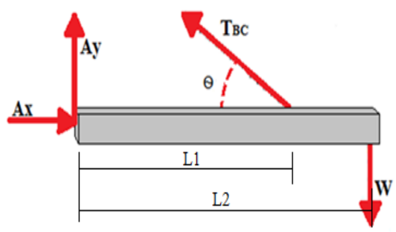
The following is a condensed version of the interview instrument. An asterisk (*) indicates problems of the Advanced type.

Set 1. A beam ACD supports a weight W at point D; cable BC supports the beam at point C. Assume that the weight of the beam is small compared to the weight W.



1a. Draw a Free Body Diagram of the beam.

1a Continued. The standard accepted Free Body Diagram of the beam is given. Examine this diagram carefully. Explain how and why your answer is similar or different. Do you wish to make any changes to your original answer?



1b. Using this Free Body Diagram, write all of the equations of static equilibrium.

1b Continued. One set of correct equations of equilibrium for the beam is given. Carefully examine these equations. Explain how and why your equations are similar or different. Do you want to make any changes to your original answers?

$$\sum F_x:\ A_x - T\cos\theta = 0$$
$$\sum F_y:\ A_y + T\sin\theta - W = 0$$
$$\sum M_{/A}:\ (T\sin\theta)(L1) - (W)(L2) = 0$$

***1c.** Using the values L1 = 15 in, L2 = 24 in, Theta = 30°, W = 100 lbs, solve these equations using any method that you like. You may use any combination of the following methods to do what you think is most efficient or effective: (1) Handwritten notes and calculations, (2) A hand calculator, (3) the spreadsheet provided.

L1 =	15	IN	W =	100	LBS
L2 =	24	IN	Theta =	30	DEG
			Theta =	0.52	RAD
	Ax	Ay	T	data	
Sum Fx	**1.00**	**0.00**	**-0.87**	**0.00**	LBS
Sum Fy	**0.00**	**1.00**	**0.50**	**100.00**	LBS
Sum M/A	**0.00**	**0.00**	**7.50**	**2400.00**	LBS-IN
		Ax	**=**	**277.13**	LBS
		Ay	**=**	**-60.00**	LBS
		T	**=**	**320.00**	LBS

Figure A1. Excerpt of Spreadsheet Interface for Question 1c.

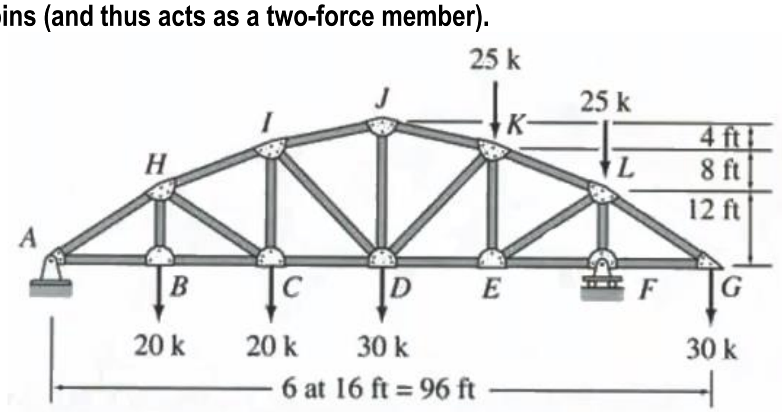
1d. The accepted answers are as follows: Ax = 277.13 lbs, Ay = -60.00 lbs, and T = 320.00 lbs. On the following diagram, re-draw the forces using their numerical values (shown above) instead of the symbols.

***1e.** Suppose that you are an engineer who is designing this structure and you need to know how the angle of the cable affects the values of the cable tension and the reactions at A. Use or modify your previous procedure to investigate the following question: As the angle of the cable increases …

The magnitude of T	Increases / Remains constant / Decreases
The magnitude of Ax	Increases / Remains constant / Decreases
The magnitude of Ay	Increases / Remains constant / Decreases

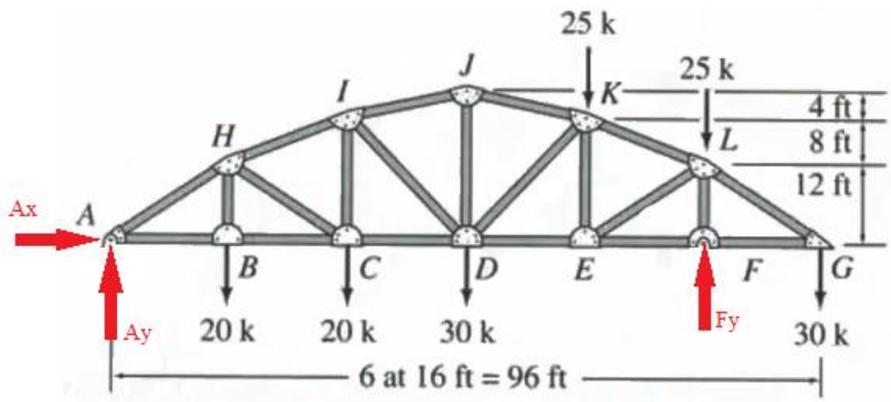
Explain why you think these results make sense and/or whether any answers surprise you.

Set 2. Consider the truss structure shown. Assume that it is an ideal truss – that is, each member is weightless and connected by pins (and thus acts as a two-force member).



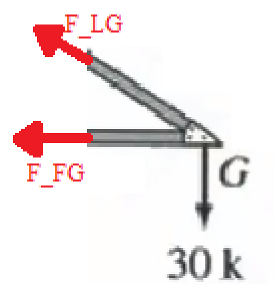
2a. Draw a Free Body Diagram or Diagrams that allow you to solve for the reactions at A and F.

2a Continued. The standard accepted Free Body Diagram of the truss is given Carefully examine this diagram. Explain how and why your diagram is similar or different. Do you want to make any changes to your original answer?



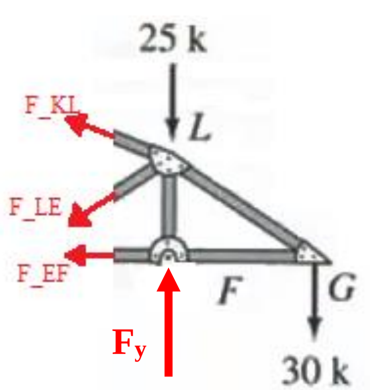
2b. Consider again the same truss structure … Is it possible to solve for the forces in members FG and LG *quickly*? If so, draw a Free Body Diagram that will allow you to do this.

2b Continued. The standard accepted Free Body Diagram of the appropriate joint is given. Carefully examine this diagram. Explain how and why your diagram is similar or different. Do you want to make any changes to your original answer?



2c. Consider again the same truss structure … Draw a Free Body Diagram that shows the internal forces in members KL, EL, and EF.

2c Continued. The standard accepted Free Body Diagram of the appropriate section is given. Carefully examine this diagram. Explain how and why your diagram is similar or different. Do you want to make any changes to your original answer?



***2d.** Consider again the same truss structure … Now suppose that you were asked to determine all of the reactions and the internal forces carried by each member. **Explain how you would go about doing this**. Can you propose a procedure or show a sample of a calculation that you would do? If not, can you explain why you would have difficulty accomplishing this task?

***2e.** The internal member forces in this truss are as follows:

AH = 65 Kips (C),	AB = 52 Kips (T),	HB = 20 Kips (T),	HI = 52 Kips (C),
HC = 7 Kips (C),	BC = 52 Kips (T),	IJ = 39 Kips (C),	ID = 14 Kips (C),
IC = 24 Kips (T),	CD = 46 Kips (T),	JD = 19 Kips (T),	JK = 39 Kips (C),
DK = 27 Kips (T),	DE = 20 Kips (T),	KE = 45 Kips (C),	KL = 23 Kips (C),
LE = 76 Kips (T),	EF = 40 Kips (C),	LF = 111 Kips (C),	LG = 50 Kips (T),
FG = 40 Kips (C).			

Based on these values, do you think that the assumption that this structure behaves as an ideal truss is valid? Hint: Assume that each member is made of steel and weighs 23 lbs/ft.