Paper ID #14629

Scaffolding Engineering Students to Be the Problem Solvers We Want Them to Be

Dr. Renee M. Clark, University of Pittsburgh

Dr. Renee Clark has 23 years of experience as an engineer and analyst. She currently serves as the Director of Assessment for the University of Pittsburgh's Swanson School of Engineering and its Engineering Education Research Center (EERC), where her research focuses on assessment and evaluation of engineering education research projects and initiatives. She has most recently worked for Walgreens as a Sr. Data Analyst and General Motors/Delphi Automotive as a Sr. Applications Programmer and Manufacturing Quality Engineer. She received her PhD in Industrial Engineering from the University of Pittsburgh and her MS in Mechanical Engineering from Case Western while working for Delphi. She completed her postdoctoral studies in engineering education at the University of Pittsburgh. Dr. Clark has published articles in the Journal of Engineering Education, Advances in Engineering Education, and Risk Analysis.

Arash Mahboobin, University of Pittsburgh

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Abstract

In addition to communicating theoretical knowledge, successful engineering education programs equip prospective engineers with the strategies and methods to solve practical problems encountered in the work place. In contrast to many of the limited-scope problems in textbooks, practical problems are open-ended, loosely structured, and complex. Engineering programs have long recognized the need to convey both theoretical and practical knowledge by supplementing textbooks and lectures with laboratory experiences and integrated design projects; however, many of the teaching methods employed in the traditional lecture hall are carried over to the lab environment.

In the fall 2014, we observed student difficulty in solving open-ended problems, leading to low achievement outcomes with junior-level bioengineering signals and systems design projects. To drive and improve the development of problem solving skills in our laboratory environment, a three element approach was used that included problem based learning (PBL), flipped instruction, and cognitive apprenticeship. Together, these three elements composed our scaffolding approach, in which a student is supported during the early stages of skill acquisition, and as the skill level increases, support is scaled back. Our hypothesis was that this scaffolding approach, as described in the PBL literature, would lead to enhanced achievement in the fall 2015 on these open-ended laboratory projects.

The signals and systems projects required students to design input signals to test and analyze unknown systems using MATLAB programming. The problem based instructional approach for the fall 2015 term began with a series of assignments guiding the students in decomposing the problem into components; this allowed the problem itself to become central to skill development. The flipped instructional environment challenged students to prepare for lab sessions by reviewing programming examples and completing online assessments to gain early feedback before going to the lab sessions. The lab sessions were then reserved for collaborative, hands-on programming practice with peers and just-in-time instructor questioning and monitoring.

Students were encouraged to submit periodic progress reports (i.e. design reviews) for instructor feedback and guidance that included their decision justifications. The students, rather than passively taking in information from the instructor, became actively involved in the apprenticeship. As part of this transformed role, the students were encouraged to reflect on changes in their problem solving approaches in the final progress report. The students' reflective responses were then qualitatively analyzed for insight into their problem solving processes. A statistical comparison of the project scores was also done to assess improvement. The instructor's assessment of the students' use of his feedback and their problem solving approaches was gathered via semi-structured interview and included as part of the overall evaluation.

1. Introduction

Engineering education must prepare students to practice engineering through approaches such as instructional laboratories.[1] Practice in the laboratory often involves activities such as collecting, analyzing, and interpreting data; building and testing systems; and (in general) solving open-ended problems to gain practical experience. Our goal with this research project within a laboratory setting was to improve students' open-ended problem solving skills, motivated by the instructor's observations during the previous semester. Unfortunately, he had observed difficulty, low achievement levels, and even panic in solving open-ended problems.

Our laboratory is part of a junior-level bioengineering course in biological signals and systems. The course introduces students to the fundamental theory and methods for analyzing and designing linear time-invariant (LTI) systems, and for representing biological systems by LTI models. Furthermore, the course provides students with the understanding necessary to properly acquire biological signals for subsequent analysis using digital signal processing techniques. To fulfill the laboratory requirements for the course, students completed three team-based projects, or *virtual* laboratories, in which they conducted experiments using MATLAB to analyze unknown systems, both biological and non-biological, through the use of time- and frequency-domain analysis techniques.

As expected, engineering students must be prepared during their undergraduate careers to solve "real world" practical problems.[2] Engineering educators have specifically called for a greater focus on open-ended problem solving in engineering curriculums.[3-4] Workplace, or "real world," problems tend to be open-ended, ill-structured, and complex, containing multiple solutions and solution paths that often require justification.[2]

One approach that has been used to better prepare engineering students to solve real world problems, including in laboratory settings, is problem-based learning (PBL).[2,5,6,7,8,9] Our signals and systems laboratory contained elements of a problem-based-learning classroom. In this environment, students solve open-ended problems in a student-centered environment, in which their acquisition of knowledge is self-directed and driven by and centered on the problem to be solved.[10] Instructors provide support versus disseminate knowledge, in part by probing students' understanding. Thus, according to PBL principles, learning is anchored in an authentic problem to solve.[11]

Our signals and systems laboratory also contained elements of a flipped classroom to better simulate "real world" practical learning. The flipped classroom is another pedagogy that not only promotes active learning in class but also enables just-in-time monitoring and support by the instructional team. With the flipped classroom, students arrive prepared to actively work by having watched video lectures or read materials beforehand to obtain the foundational knowledge.[12] Class time is then used for higher-engagement activities, such as problem solving, with the instructor present for monitoring and support.[13]

As discussed in the literature on problem-based learning (PBL) environments, support, or scaffolding, of students is necessary in their learning to solve complex problems, and it may entail multiple instructional components.[11] In short, scaffolding consists of the supports that the instructor provides to the student in performing an activity or solving a problem, taking the form of items such as apprenticeship-like guidance or just-in-time assistance during problem solving.[14] Scaffolding is also a means to increase students' higher-order thinking skills.[15] With scaffolding, the teacher assists with parts of the task that the student cannot yet handle. It is designed to be offered temporarily to relieve some of the cognitive load while students gain the necessary skills.[14,16] Our research hypothesis was that a scaffolded problem solving approach, as described and suggested in the problem based learning literature, would lead to enhanced performance in the fall 2015 on our open-ended laboratory projects.

2. Literature Review

The need to scaffold engineering students in their problem-based reasoning was described previously for a biomedical engineering program.[17] In this program, *cognitive apprenticeships* were used to scaffold students. The term *cognitive apprenticeship* refers to the learning of cognitive and metacognitive skills for problem solving through the guidance of an expert, possibly in a PBL or flipped classroom environment.[14] The support or help of an expert, as in a traditional trades-based apprenticeship, is one aspect of scaffolding. Without such support, novice problem solvers may follow incorrect approaches and experience frustration.[17] Controlling student frustration has been identified as one of the mechanisms of scaffolding.[15,18]

Cognitive apprenticeships also encourage the development of self-monitoring and metacognitive skills. They often encourage reflection on the differences between expert and novice performance in order to promote incremental adjustments in the student's performance.[14] An example of such a reflection is students' postmortems of their own problem solving processes, which can help students gain access to and control of their problem solving processes.[14]

Having students study worked examples that decompose complex problems into smaller elements is another means to support their problem solving.[11,16] Such examples emphasize the conceptual structure of the problem and thereby enhance students' understanding of the problem and their ability to solve it. Indicating the important problem elements has been identified as a scaffolding mechanism.[15] This has previously been referred to as "reduction in the degrees of freedom," whereby the size of the task is reduced to allow the learner to accomplish the component skills that he/she can handle.[18] Problem solving is a complex skill that involves a synthesis of individual skills, and students must become proficient in the component skills to master the complex skill.[16]

Questioning students is critical for guiding their reasoning as well. Questions can be inserted at multiple points in the learning process, such as during self-directed instruction with web-based, flipped-classroom materials; progress reviews; or team-based problem solving efforts in the classroom.[11] Prodding students to articulate answers drives them towards completion of a task.[15] Prompting them with questions that require explanation and justification of their solutions at different phases of the project, as during frequent progress reviews, can assist them in planning, monitoring, and evaluating.[19] Therefore, requiring students to develop coherent arguments scaffolds them in solving ill-structured problems and also provides one of the best means to assess their ability to solve these problems.[11] Prompting students to provide written summaries of their solutions and subsequently evaluating these justifications and providing feedback are forms of student coaching.[14]

Another form of coaching is observing students during problem solving and offering feedback to direct their efforts in needed ways. Feedback informs students of the adequacy of their work and indicates important elements to consider.[15] One-on-one scaffolding, which is generally considered ideal in that it's tailored to individual student needs, is possible in a flipped or PBL classroom, given their structures.[15] Some have maintained that peers can also provide scaffolding, as might also occur in a flipped or PBL classroom.[20]

3. Methods

The laboratory portion of the course, which met weekly for 50 minutes, was conducted using elements of both flipped instruction and problem-based-learning for both semesters (i.e., fall 2014 and 2015). There were approximately 80 students in the laboratory during each of 2014 and 2015 semesters. For several of the laboratory sessions, students were instructed to arrive prepared to actively engage in MATLAB coding by reading material provided by the instructor beforehand, followed by an online quiz, as in a flipped classroom setting. This material contained worked MATLAB coding examples, one of the scaffolding mechanisms discussed in the literature. The instructor had noticed during the first semester that many students had forgotten their MATLAB knowledge, although they had taken a course as a freshman. As a consequence, students were spending a great deal of time and effort on the software and programming mechanics versus the open-ended problem itself.

The three MATLAB-based projects provided the focus for learning in the laboratory-based portion of the course, as in a PBL classroom. Class (i.e., laboratory) time was dedicated to problem solving by student teams in support of project completion. During the laboratory, the instructor and two teaching assistants (TAs) circulated throughout the classroom of 80 students, providing as-needed "coaching" to students, observing progress, and probing for issues, as in a flipped classroom. The students asked many questions as the instructional team circulated and observed. The instructional team prompted students with questions to assess their progress and scaffold their problem solving efforts.

This in-class format was observed by the assessment analyst over the course of multiple class sessions during the fall 2014 and 2015 semesters using the TDOP–Teaching Dimensions Observation Protocol.[21] With the TDOP, the total class period was divided into a series of five-minute segments, or time windows. For example, a 50-minute class had 10 observation segments. During each segment, the various activities within the protocol were recorded when observed. Using this data, the percentage of segments in which an activity or practice occurred was calculated. These percentages obtained in 2014 versus 2015 were statistically compared using Fisher's Exact test. Fisher's test can be used instead of a z-test of proportions when the numerators are small.[22]

Based on our TDOP data, the format of the course during the fall 2014 and 2015 semesters is described in Table 1. The two semesters were similar and statistically equivalent in terms of the percentage of segments in which each of the behavioral codes of interest was observed to have occurred ($\alpha=0.05$). Based on the assessment analyst's prior use of the TDOP, the inter-rater reliability associated with her use of the protocol was $\kappa=0.86$ (i.e., Cohen's kappa). Values of κ above 0.75 suggest strong agreement beyond chance.[23]

Table 1: Classroom Observational Data

TDOP Code	Code Description	Observation Percentage (% of total segments) Fall 2014 (%)	Fall 2015 (%)	Statistical Difference b/t Semesters?
DW	Active work by students at the desk	85.7	90.9	No
SCQ	Student comprehension/conceptual question	81.0	95.5	
MOV	Instructor movement & circulation among students	81.0	95.5	
PS	Problem solving by students	76.2	90.9	
ART	Verbal articulation of thoughts/ideas by students during active work	76.2	90.9	
CQ	Instructor questioning to check for understanding	47.6	50.0	
L, LPV, LHV, LDEM, LINT	Lecture of various formats	23.8	40.9	
DQ	1) Instructor question seeking a factual answer, or 2) Instructor request for a solution to a computational problem	19.0	18.2	

These data show that during both semesters, the laboratory sessions involved active work or problem solving by students for the most part (DW and PS codes), as they discussed solutions among themselves (ART). In addition, the instructional team circulated among the students

(MOV) to answer their frequent questions (SCQ) or check for understanding, progress, or issues (CQ). The instructor used micro-lectures during students' active problem solving in the 2015 semester to address issues noticed while circulating. These data demonstrate the problem-based, active nature of this laboratory during both semesters. In addition, the data demonstrate the scaffolding provided during both semesters in the form of instructor observation and support of problem solving and his prompting of students for their understanding or issues. Thus, during both semesters, our laboratory contained elements of both problem-based learning and flipped instruction.

The MATLAB exercises and projects that formed the heart of the laboratory portion of the course were designed and administered in the 2015 semester with the specific goal of scaffolding the students. Although the classroom formats and project topics were very similar in the 2014 and 2015 semesters, the exercises and projects were administered differently, with intentional scaffolding provided in 2015. In 2015, MATLAB exercises 1 and 2 specifically guided students to decompose the solution process into its component parts–1) the generation of input signals to perturb the system, and 2) the simulation of the system in order to obtain its response–which were used to analyze a system that modeled human balance. In the 2014 semester, the instructor did not specifically guide students to decompose the problem into its component parts. In addition, in 2015 versus 2014, more worked MATLAB coding examples were provided as part of the assignment description. Our overall scaffolding approach is shown in Table 2.

Table 2: Scaffolding Approach

Completed By	Instructional Element	Implementation Details
Student	Worked examples & problem decomposition	• Flipped classroom pre-reading • In class MATLAB exercises 1 & 2
	Metacognitive/reflective exercises	• Project progress review
	Argumentation/Justification	• Project progress reviews
Instructor	Questioning & prompting (including metacognitive prompts)	• Flipped classroom pre-quizzes • In class problem solving sessions • Project progress reviews
	Observation & feedback (i.e., coaching)	• In class problem solving sessions • 24-hour return of progress reviews • Return of a project two weeks before the next project due

Another aspect of the scaffolding in 2015 was the implementation of a formative and timely feedback system to the teams on their project work, which contained guidance and suggestions from the instructor. In particular, each team had the opportunity to submit three progress (i.e., design) reviews per project. These progress reviews prompted each team to explain its proposed solution, provide an argument or justification for it, display graphs and figures, ask questions and raise concerns, and in general report on project progress. The progress reviews were neither mandatory nor graded and were intended as a feedback and communication mechanism between the students and instructor. In addition, one of the later progress reviews contained a metacognitive prompt to elicit perceived changes in the team's problem solving process over the course of the semester as well as to assess the helpfulness of the progress reviews. Responses to the two prompts in Table 3 were then analyzed using a grounded, emergent qualitative analysis, which resulted in a framework, with the framework enabling a subsequent content analysis.[24] The content analysis was done by two coders. One coder was the first author on this paper, and the other was a graduate student pursuing a PhD in industrial engineering. Even though the responses were double-coded, we calculated a first time reliability based on Cohen's kappa for the second prompt, given its more extensive content. This first time inter-rater reliability was $\kappa = 0.80$, showing strong initial agreement.

Table 3: Metacognitive Prompts

1	Has the progress report and feedback process been helpful to you? (A simple yes/no answer will suffice.)
2	Now that you are working on the final project, and reflecting on your experience during the other two projects, how has your problem solving approach changed since the start of the semester? Why do you think this is the case?

With a one-page limitation on each progress review, the instructor was able to review and return them within 24 hours for timely use and application of the feedback. In addition, since the students indicated a lack of sufficient time in 2014 to incorporate his feedback between projects, he returned each of the three projects in 2015 at least two weeks before the next project was due. There was a limitation of two pages in 2015 on the project report, versus six pages in 2014. This led to needed conciseness in the students' summaries and supported the instructor's ability to return them within two weeks. Also, the intermediate review via the progress reports led to quicker review of the final project report. As will be discussed more in the results section, we determined the progress report to be a key instructional and scaffolding aid.

4. Results

Our results showed a highly positive and desirable association between our scaffolding methodology and student outcomes. We compared the three final project scores between 2014 and 2015 and uncovered significant differences and large effect sizes. We also assessed the number of progress reviews submitted, as they were not mandatory. In addition, we qualitatively analyzed the students' metacognitive responses for salient themes.

4.1 Course Projects - Results

To directly assess our scaffolding approach, we compared projects 1-3 between 2014 (without the approach) and 2015 (with the approach). The projects were nearly the same between 2014 and 2015, with a difference only in the unknown (i.e., black box) system that the students were characterizing. The grader was the same during both semesters, and he used a rubric to evaluate the projects.

As shown in Table 4 and in support of our research hypothesis, there was a significant improvement between 2014 and 2015 in the first two projects, based on the Mann-Whitney test (p<0.0005). This non-parametric version of the independent-samples test of means was used given the smaller sample sizes of n=20 groups for each semester. In addition, the Cohen's d effect size was large for these first two projects, indicating practical or substantive significance as well.[25] For the third project, the difference was not significant, and the effect size was small. During both years, the average score on project 3 was high (~47/50). The instructor indicated that in 2014, there was some rebound on project 3 after the initial experiences of confusion and panic. A comparison of the two cohorts in terms of the average pre-course GPA showed there to be no difference in prior academic achievement between them (p~0.98).

Table 4: Project Score Comparisons

Project Scores	**2014**	**2015**	**Cohen's *d***	**Mann Whitney *p***
Project 1	32.4	41.8	1.43	<0.0005
Project 2	36.7	46.8	1.88	<0.0005
Project 3	47.2	47.4	0.04	0.31

The sample size was n=20 groups for each of 2014 and 2015.
The maximum number of points per project was 50.

4.2 Progress Review - Results

Starting in the 2015 semester, each team was encouraged to submit three progress reviews for each project before it was due. Given 20 teams, up to 60 progress reviews per project could have been submitted to the instructor. Although the progress reviews were neither mandatory nor graded, the instructor received approximately two-thirds of the requested submissions for the first two projects and about 50% for the final project. In addition, for each project, 18 of the 20 teams submitted at least one of the three progress reviews; thus, the students in general engaged with them. Interestingly, the two teams that did not submit any progress reviews were the same for each of the three projects. One of these teams had the second-lowest score in the class for all three projects. For project 1, this team's score was approximately 10 points below the average, and for each of projects 2 and 3, the difference was about five points. The other team had the lowest score in the class on project 3, with a difference of about seven points from the mean. Conversely, for projects 1 and 2, the teams with the best score each submitted the maximum three reviews, and for project 3, three of the four teams with the best score submitted the three reviews. This demonstrates that there may be a relationship between engagement with the progress reviews and performance on the project.

Based on a semi-structured interview with the instructor, he believes the progress reviews were a key scaffolding approach in 2015. They enabled the students to present their analysis, justifications, and questions ahead of time, before the project was due. Thus, the progress reviews tended to drive professional habits related to time management and completing work incrementally and iteratively. This observation is triangulated in the metacognitive data submitted by the students, to be discussed next. In addition, the progress reviews became a "build-as-you-go" tool for some teams, prompting them to write portions of the final report as they progressed with their analysis. In fact, the instructor is considering formally implementing the "build-as-you-go" strategy next time.

4.3 Metacognitive Prompts - Results

In the 2015 semester, 17 of the 20 teams (85%) responded to our two metacognitive prompts. In response to question 1 about the helpfulness of the progress reviews, all 17 teams responded "yes" to being helpful, with two teams expounding on their positive responses. In fact, both teams requested additional feedback in terms of both concreteness and suggestions for betterment. Other themes mentioned about the progress reviews included the ability to pose questions to the instructor in context as well as the promotion of time management and quality-driven, proactive, thoughtful, and incremental work.

For the second prompt about perceived changes in the team's problem solving approach and reasons for it, 14 teams provided content that we were able to code. The most frequently-mentioned themes, with the associated number of teams in parentheses, were as follows: efficient practices, to include responsible coding (7); application or integration of concepts (5); collaboration, coordination, or teamwork (5); delegation or division of tasks (5); enhanced time management or preparedness (5); and increased confidence or comfort level (4). Themes mentioned by at least two teams included decomposition of the problem, instructor help or support, understanding of the real world application, trial and error or iterative activity, and verification of the solution.

Support for these themes can be found in the problem solving and education literature. Mastery of complex tasks requires not only decomposition of problems and skillsets but also the use of skills in combination, or integration.[16] For mastery, students must understand when to apply certain skills.[16] Verification of a solution to a problem is another step that is emphasized in the literature.[26,27,28] Further, a scientific expert can solve typical problems quickly and without much reflection, in part because of good initial representation of the problem.[29] To become a solid problem solver, an engineer must have the skills to coordinate activities within a team.[26] Gaining and having confidence in one's ability, or self-efficacy, is also important to mathematical literacy and complex problem solving and can influence goal setting, courses of action, effort, perseverance, and ultimate accomplishment.[30,31] In comparison to a good problem solver, a novice problem solver lacks confidence and experience; the skilled problem solver is confident and believes that problems can be solved through thoughtful and persistent analysis.[32]

5. Discussion and Conclusion

Based on an interview with the instructor, he was very pleased with the results of the scaffolding approach in 2015. He concluded that the method had been successful in enhancing the open-ended problem solving skills of the students relative to the 2014 semester. The improvement in project scores between 2014 and 2015 has also preliminarily demonstrated the success of the approach, in support of our research hypothesis. In addition, we identified a potential relationship between students' engagement with the progress reviews and achievement on the projects. The instructor plans to continue the approach going forward, with potential enhancements such as the build-as-you-go strategy and others that may surface from course-evaluation data.

In discussing other topics during semi-structured interviews, the instructor noted many fewer MATLAB-related coding problems in 2015 vs. in 2014, with syntax or mechanics-type issues at a minimum in 2015. This was likely due in part to the various scaffolding offered, such as in-class support and worked examples. He felt that for the most part, students implemented his various types of feedback within their projects in 2015. He was also satisfied with the justifications that students provided for their chosen solution paths, with just a few teams not providing sound or concrete arguments. In terms of improvements that were possible in the students' work, he observed a lack of consistency at times in the presentation of their graphs and figures. Encouraging students to build upon their MATLAB code from project to project and reusing it could definitely remedy this observed inconsistency. Relative to changes in the research approach going forward, we identified (during the coding) changes in how the reflective questions could be posed to the students, including the structure of the questions.

Acknowledgements

The authors wish to thank Scott Streiner, a PhD student, for assistance in coding the metacognitive prompts as well as Brent Clark, an engineering supervisor, for his help in better positioning and organizing the abstract.

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