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A Scaffolding Case Study for Teaching Engineering Problem Solving to Underrepresented Minorities

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Abstract

This paper presents a scaffolding strategy for teaching underrepresented minority students the techniques of engineering problem solving. The case study was introduced to engineering undergraduates at Central State University, a state-supported HBCU in southwest Ohio. The hard scaffolding effort involved the design of an instructional module consisting of a set of related problems with a gradually increasing level of difficulty. All problems have similar components and involve the same set of basic engineering concepts. The instructional strategy included soft scaffolding with a plan of alternating between "scaffold" and "no scaffold" as necessary. Research results showed positive student feedback and notable progress in problem-solving activities. Survey responses by participating students showed positive impact of the scaffolding strategy. Also, the students expressed strong interest to further improve their problem-solving skills through similar future sessions. The scaffolding case study required extensive planning and preparation for the class sessions. In addition, the instructor considered the dynamics of non-cognitive factors especially for minorities and small class size. Effective instruction at HBCUs requires more of these pre-planned case studies and/or mini-projects as well as individualized instruction tailored to academic needs.

Introduction

Many minority engineering students struggle in college because of their weakness in problem solving. This is generally due to the students' lack of conceptual understanding and difficulty in applying their mathematical knowledge while solving engineering problems[2,3]. Additionally, professors often assume that problem-solving ability naturally increases by mastering specific domain concepts as well as mastering relevant problem-solving heuristics and processes, and ultimately learning to put these concepts and processes together to solve problems. Our research[4] suggests that, for underprepared students, learning conceptual knowledge can best be achieved through practicing problem solving in a gradual learning approach supported by scaffolding techniques.

The paper describes a case study that implements scaffolding teaching techniques for problem solving for underprepared engineering undergraduates. The duration of the case study was one week stretched over three in-class sessions and one take-home assignment. The case study employs a set of well-structured problems designed for supplemental instruction in any engineering mechanics course, such as "Statics," "Strength of Materials," and "Machine Design."

This problem-based instruction focuses on the analysis of a mechanical system consisting of multiple springs with different configurations. Students were assigned one system configuration and were required to identify relevant concepts, formulate mathematical relationships, derive the system's governing equations and solve for the required unknown displacements.

Although the mathematical content and physical concepts required for these problems are fairly simple, some difficulties for "novice" students exist for developing, organizing and solving the system's linear equations. For "expert" students, the problem can be made more challenging by increasing the number of system components or by assuming spring stiffnesses to be different (k_1, k_2, etc.) instead of having same value (k). For the struggling students, the original system configuration can be changed into less difficult or slightly different systems to facilitate instructional scaffolding techniques. Students were guided to first work out the initial system with four springs, two in series and two in parallel, figure 1. During this scaffolded activity, students established their basic skills in formulating the mathematical model, applying the engineering concepts (such as Hooke's law, spring deflection, free-body diagram, and force equilibrium, etc.), and drafting the solution plan to obtain the final results. At these sessions, instructional soft scaffolds were offered by the instructor. By gradually increasing the system complexity, students enhanced their conceptual understanding, mathematical manipulation skills as well as problem-solving competency. During the student's growth in knowledge and skills, the instructor's scaffolding was gradually reduced and ultimately removed.

Research results showed positive student feedback and notable progress in problem-solving activities as well as improvement of their overall knowledge and skills.

Research Motivation

After several years of teaching minority engineering students, the challenges to the instructor become clear. There is general academic weakness among African American students due to several factors. Based on observations, it has been noted that in many HBCUs these factors include

- poor academic preparation, study habits and skills due to weak precollege education
- social and economic factors that distract from study and time management
- weak social and networking skills
- lack of interest and enthusiasm toward learning

The article[1], "Key Issues in the Persistence of Underrepresented Minority Students," supports our view. To combat the above factors, the author developed this research effort to enhance students' learning skills during their college education.

In order to effectively teach engineering courses, especially at HBCUs, new teaching strategies have to be adopted in the classroom. One of the most significant competencies in any engineering curriculum is problem solving. Problem solving is a higher level cognitive competency that requires basic conceptual knowledge and mathematical manipulation skills[3].

Students usually choose a short cut when studying or solving homework assignments by trying to solve the problems without capturing the conceptual knowledge. Therefore, they continue to be challenged in later engineering coursework because they never mastered the problem-solving process.

In previous research[2-4], the instructor has laid the foundation for tackling this academic concern by creating a set of basic engineering educational tools that lead to developing effective teaching and learning strategies. Given that most engineering curricula reached a saturation level that no additional courses can be added, any efforts to teach problem solving have to be efficient and quick for both the instructor and the students. In addition, students have to be motivated to accept any extra credit work and this work has to serve the objectives of the course.

Guided by published research on scaffolding techniques in problem-solving instruction[5, 7-9], this research paper aims at exploring a better teaching strategy for underprepared engineering undergraduates as well as expanding the author's prior research in the area of problem solving[2-4].

Case Study Scenario

This one-week case study was structured into three sessions. The following describes each session and the problems covered. Samples of soft scaffolds are listed to demonstrate situations in which student intervention was required.

Session - 1

The instructor selected an interesting homework problem[6] as the study problem for session 1, figure 1. In this problem, the mechanical system consists of four identical springs with a stiffness "k" and carries a weight "W." The horizontal bar is rigid and weightless. Required is the displacement of the rigid bar. The instructor discussed the homework problem and explained the underlying concepts to help students solve the problem.

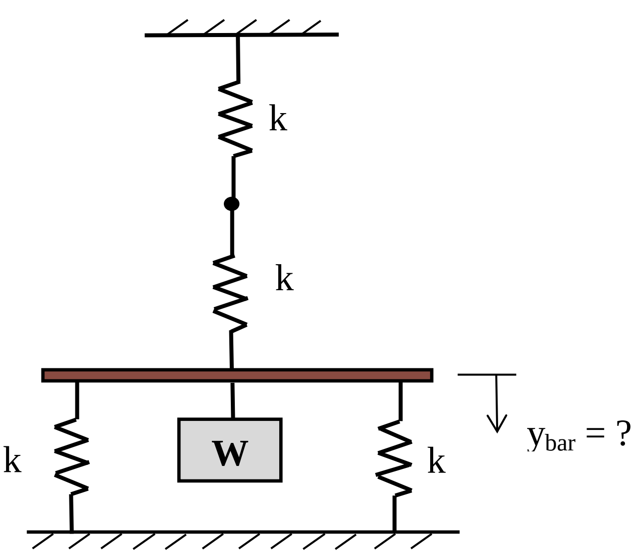

Figure 1. Scaffolding Session-1, Problem (1)
Given constants: weight W, spring stiffness k
Required: displacement of bar y_{bar} as function of W & k

Session - 2

In this session, the instructor laid out a set of four problems including the session-1 problem,

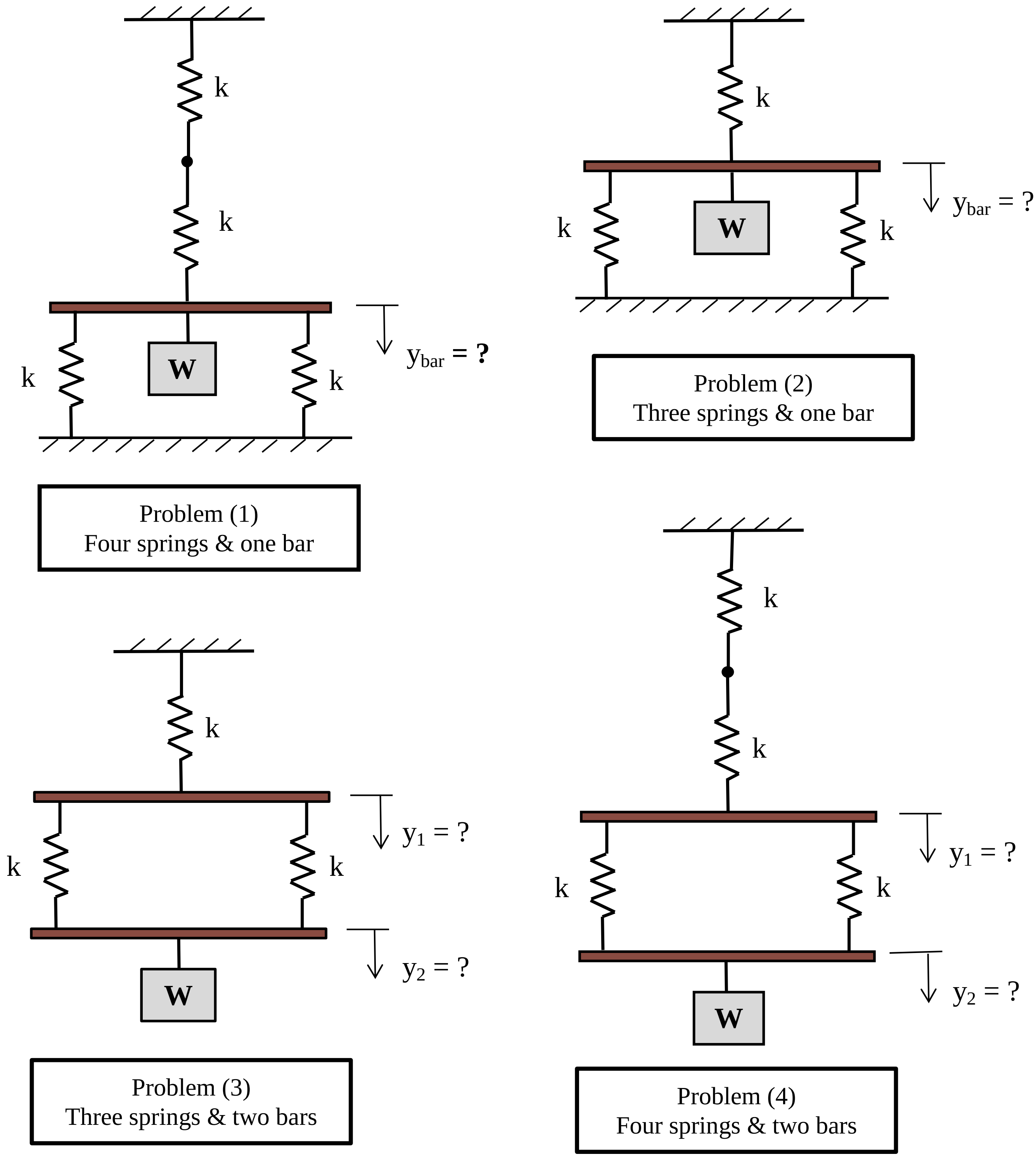

Figure 2. Scaffolding session-2 with four related problems
Given constants: weight W, spring stiffness k
Required: displacements of bars y_{bar}, y_1 & y_2

Problem (1), figure 2. The second problem was similar to the first one, with only three springs. For problem (2), no scaffolds were provided and the students were asked to solve the problem. Based on the differential in academic strength, it became clear that the class was then divided into two groups: experts and novices. Naturally, the novices asked the experts how to solve the problem (2). Through students' interactions, the answer was then out and the entire class understood it. Problem (3) had three springs but unlike problem (2) the fixed floor was removed and replaced by a second bar that supported the load "W." Students were asked to solve problem (3). The same concepts that were introduced for the first problem were applied again, i.e., the free-body diagram, Force equilibrium and Hooke's law. At this point all the students including the experts were puzzled by the second bar. There are two differences from the previous problems: i) the lower bar has another displacement, y_2, and ii) each of the lower springs had a deflection that is different than the first two problems. The instructor offered this soft scaffold:

> *[There is one difference from previous problems: Each of the lower springs has a deflection that is different from the first two problems. Using two displacements y_1 and y_2 for the upper and lower bars, the deflection of the upper spring is $\delta_1 = y_1$ but the deflection of the lower spring is $\delta_2 = (y_2\text{-}y_1)$.]* ***Scaffold # 1***

The students were now able to manage solving problem (3). The instructor then introduced problem (4), which is similar to problem (3) but has two upper springs in series, similar to problem (1). Obviously, problems with more springs require more equations and thus are more difficult than problems with fewer springs.

After the first three problems, some of the expert students indicated that they could solve the problem (4). According to the theory of "Zone of Proximal Development" by Vygotsky[9,10], with improved students' understanding, the instructor should reduce or eliminate scaffolding. The scaffolding should be temporary until the learner reaches the target level of learning. Ultimately the students managed to solve this problem and the instructor was satisfied that the second session of instructional scaffolding ended with satisfactory results.

At the end of the 50-minute session, the instructor asked the students to turn in their in-class work as a homework assignment. As a reward for their work, most of them received the full score on this homework with a few minor errors. The instructor then gave a take-home assignment to follow up and determine if they truly understood the concepts and the problem-solving methodology. Figure 3 shows problem (5), the take-home assignment. It combines two systems; each is similar to problem (2) with one change. The top ceiling support is now modified by connecting the two models with a cord running over two fixed smooth pulleys, figure 3. Similar to problem (3), the spring deflection concept is defined as the net or relative displacement of the spring ends.

Session – 3

In this session, the students returned with their efforts on the take-home problem (5). The instructor was anxious to see if the students who collaborated with each other were indeed able to solve the problem. The instructor reviewed their work to solve for y_1 and y_2 and discovered that the students looked up the solution result of problem (2) and applied it “as is” to the new problem (5). The students gave the displacements y_1 & y_2 in problem (5) the same value as was determined in problem (2), with only one change for the system on the right; replacing the load "W" in problem (2) by “2W." The students chose a short cut and thus could not reach the correct solution. This came as a surprise to the instructor, and he now needed to provide the explanation for the error and keep the momentum of the class.

Comparing problem (2) with the two systems of problem (5), it is clear that the upper springs in problem (5) are no longer fixed at the top ends, but rather connected to each other. There is a possibility that the cord moves because of the imbalance in the loads (W and 2W). There would be a movement (to the right) for the cord connecting the two upper springs in problem (5).

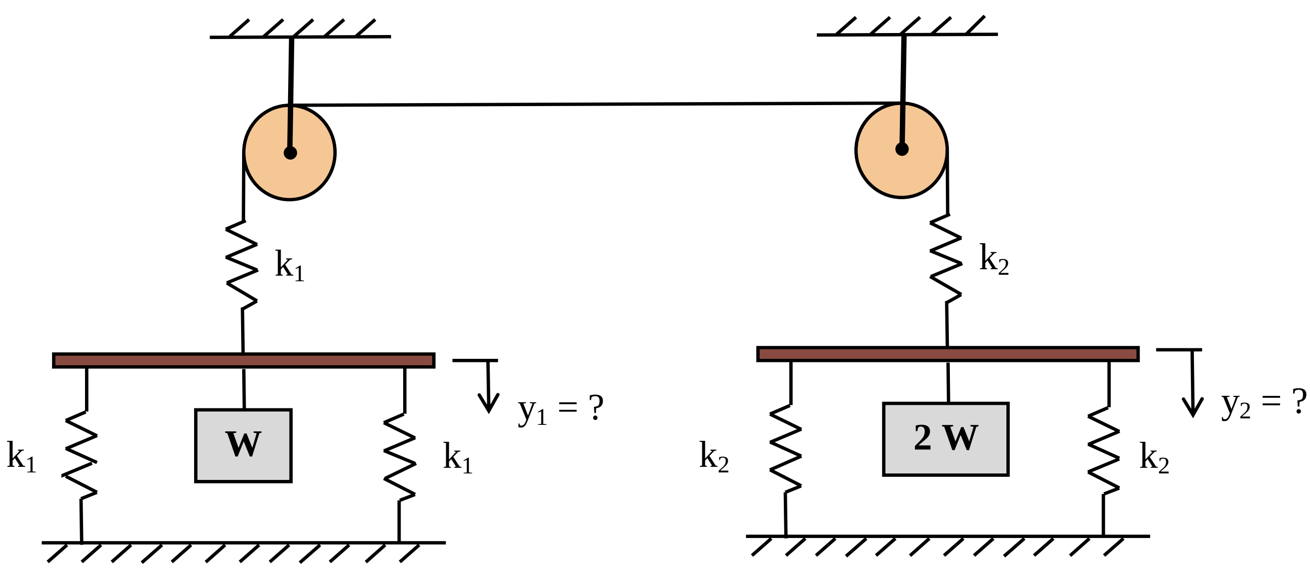

Figure 3 – Scaffolding session-3, Problem (5), Take home problem Combining two systems similar to problem (2)
Numerical values: W = 100 N & k_1 = k_2 =10 N/cm

The instructor first offered a few question prompts, but the students could not figure out the proper solution path for the problem. The instructor then offered an important soft scaffold:

> *[To solve the problem correctly, one needs to introduce a displacement variable for the cord between the two pulleys, say y_3, figure 4. The deflection of the upper left spring, δ_1, is the difference between y_1 and y_3, and for the upper right spring, the deflection, δ_2, is the difference between y_2 and y_3. These relations are: $\delta_1 = y_1 + y_3$ & $\delta_2 = y_2 - y_3$.]* ***Scaffold # 2***

Attempting to solve for three variables (y_1, y_2, and y_3), students developed only two equations for the free-body diagrams for the two bars, and therefore a third equation was needed. Another soft scaffold was then given to reveal a hidden key concept for the problem:

> *[Assuming smooth pulleys, the force in the left upper spring k_1 is equal to the force in the right upper spring k_2. This force equality is $k_1*(y_1+y_3) = k_2*(y_2-y_3)$ and is the third needed equation.]* ***Scaffold # 3***

The instructor offered this final dose of scaffolding to help students write the three equations needed to solve for the three variables y_1, y_2, and y_3. Finally, the students realized how to navigate their path to successfully solve the target problem.

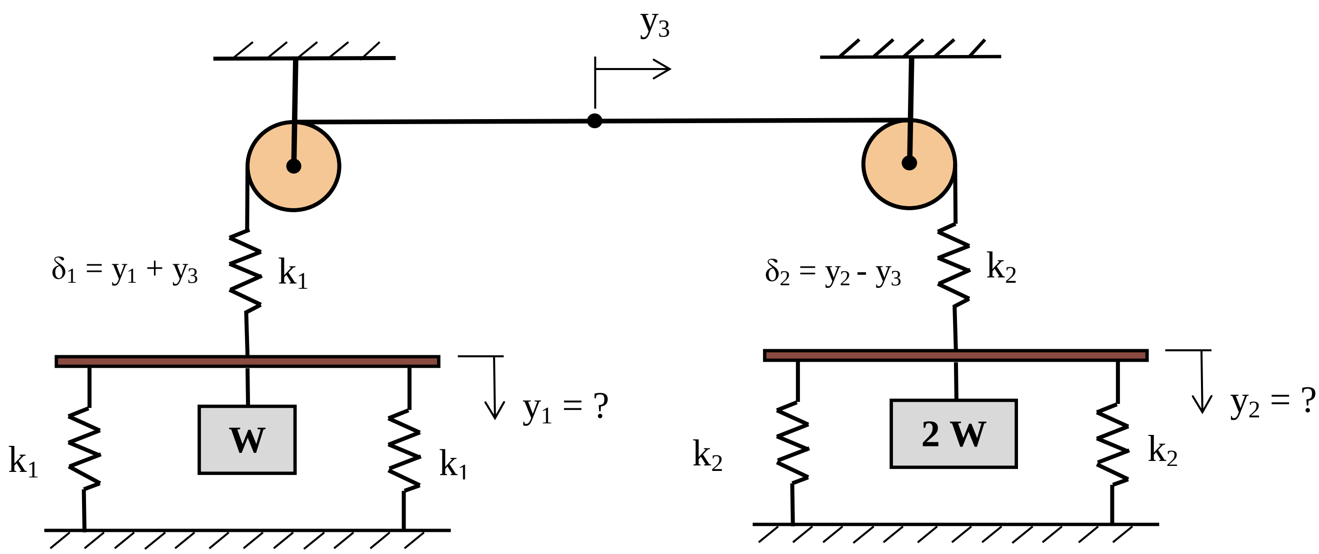

Figure 4 – Problem (5) – Adding the displacement variable "y_3," needed for describing upper spring deflections δ_1 & δ_2

At the end of the third session, a survey was distributed to participating students. The following are their compiled comments:

1. **Lessons learned**
   - *I learned the concepts by applying them over and over in different problems*
   - *Learned how springs function when arranged in series and in parallel*
   - *Learned how we apply free-body diagrams to help solve for force balance. Applying FBDs the right way is very critical to get the right answer*
   - *I learned to be patient and focused while solving complex problems*
   - *Understand how to analyze movement of bars with different displacements y_1, y_2, etc.*

2. **How did you improve understanding concepts?**
   - *I learned the difference between the deflection of a spring hanging on a fixed end and the deflection of a spring with two moving ends*

- *I have now better understanding of Hooke's law as applied to different situations*
- *I understand the relevant concepts better by working on easier problems after the instructor explained the first problem in details*
- *Concepts become very clear after practicing many problems*

3. How did you improve your problem-solving skills?

- *Working with different problems side by side allowed me to improve on problem solving and elevate my skills in analyzing different problems and comparing them with each other*
- *After solving the first two problems, with professor's guidance, I was able to continue working on other problems without much help. This was a good exercise for me*
- *The professor clarified the concepts and put details in explaining the first problem. After that, problem solving became easier regardless of the problem complexity*

4. Overall impression on the sessions

- *I think the sessions were overall good and we should do it more often*
- *Very detailed problem-solving sessions*
- *The mathematics part of solving three equations in y_1, y_2 and y_3 (in problem 5) was very difficult to finish solving in terms of k_1 and k_2. I wonder if there is a way to get the solution through a scientific calculator. The problem became manageable after simplifying it by setting all spring stiffnesses to be equal to "k"*
- *The professor was well prepared and he put many details in these sessions. He explained the concepts and how to apply them correctly in different cases*
- *I like that I was able to keep doing different problems regardless of the problem configuration or complexity*

Concluding Remarks

Although a class size of five students is small, it was beneficial to both the students and instructor to conduct this scaffolding exercise. In such a small class, the instructor was able to offer focused instruction supported by individualized scaffolding. In the first session, all five engineering students were excited and focused. Not knowing that this session is the first of a series of sessions, most students showed great interest in solving the in-class assignment, problem (1). During the second session, because of the differential in academic strength, the class became divided into two groups: three experts and two novices. In sessions 2 & 3 and between the sessions, the expert students worked on the problems and were very engaged in most class discussions. One of the novice students attempted to get answers from the other experts but did not understand the concepts or learn the methodology of problem solving. In session 3, the experts showed progress and became deeply engaged in solving the target problem. They even overpowered the instructor when he asked them to stop working with k_1 and k_2 in problem (5) and simply replace them with one stiffness "k." Instead, they continued to make an effort despite the difficulty they encountered. The instructor let them continue and commended them on their effort and persistence. Overall the sessions worked out as planned and delivered very satisfactory results.

The case study focused on a specific domain of spring systems as part of the engineering mechanics area. The study handled the concepts of free-body diagram, static equilibrium and force concepts, spring deflection and Hooke's law. The knowledge and skills gained during this case study included problem formulation, understanding and applying the concepts, the mathematical manipulation and problem-solving skills. The gain in problem-solving skills in this case study can be expanded and transferred to other engineering problem domains and courses. The problem-solving skills gained in these sessions are considered helpful to students when working on engineering projects later in the curriculum.

The main challenge in conducting these sessions was the academic diversity within the class. The instructor offered the students individualized scaffolding and also allowed the experts to work as peer tutors for the class novices. The other challenge for the instructor was to know when to offer scaffolds and when not. Also, it was an experience to know when to push students to work and continue working as well as when to encourage and compliment them on their hard work.

The primary lesson learned through this case study is that effective teaching requires extensive planning and preparation for the class material. In addition, executing the scaffolding sessions is time-consuming and requires extra energy by the instructor. Furthermore, the instructor needs to consider non-cognitive factors such as working with minority students, and small class size. Another important lesson is to simplify the problems and remove any mathematical complications that may distract students and discourage them from engaging in class work. Effective instruction for underprepared students at HBCUs requires more of these pre-planned case studies and/or mini-projects as well as individualized instruction tailored to meet students' needs.

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