Using the learning cycle to develop freshmen's abilities to design and conduct experiments

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Abstract A series of three laboratory experiments has been developed for first-semester freshmen mechanical engineering students at the University of South Carolina. The topical content of the experiments includes statics, solid mechanics, fluid mechanics and direct-current circuit analysis. Each experiment actively involves the students, is inexpensive, safe and can be performed during a 50-minute class period. The experiments have been designed using concepts from Kolb's learning cycle, problem-based learning and scaffolding. The experiment sequence has been successfully used to introduce the students to engineering fundamentals, to develop their abilities to design experiments, and to motivate them to learn computer applications for data analysis.

Keywords experiments; statics; fluid mechanics; circuits; learning cycle

Introduction

Mechanical engineering undergraduates at the University of South Carolina are required to complete a course entitled 'The Student in the University' (UNIV 101). This three-credit freshman-level course was originally designed as a transitions course for students entering the university directly from high school [1]. Recognizing the importance of an introduction to the engineering discipline on student retention [2–5], special sections of UNIV 101 were created which would familiarize engineering students with the field. The engineering sections include the learning outcomes that the students demonstrate knowledge of engineering and demonstrate the ability to use a suite of computer applications.

As at many schools [6–9], the primary mechanisms originally selected for introducing engineering to freshmen were design projects and guest lectures. Results from the Gateway Engineering Education Coalition from 1992 through 1997 demonstrated that when professors facilitated active learning, as opposed to simply lecturing, freshmen changed their mindset about learning, and engineering student retention increased [5]. Therefore, this department initiated a pilot study [10, 11] to determine the benefits of student-conducted and student-designed laboratory experiences in UNIV 101. The pilot study was further motivated by the department's program assessment processes, which demonstrated the benefit of a capstone laboratory course [12] in developing the graduate's ability to design experiments, but which also indicated a need for better student preparation in this area. In reaction to the assessment process results, design of experiments is being introduced in several courses in the curriculum; the focus of this paper is on the freshman experiences.

Specifically, the freshmen conduct three experiments in the areas of solid mechanics, fluid mechanics and electrical circuits, and are increasingly involved in the design of each experiment.

The design of the freshman laboratory sequence is based on the learning cycle [13], a four-step model proven successful at introducing students to new information, especially scientific lessons. The four steps are: introduction; exploration; concept development; and application. The learning cycle is a core notion in constructivism theory and is an extension of Piaget's theory of intellectual development [14]. The premise is that 'they [learners] do not simply mirror and reflect what they are told or what they read. Learners look for meaning and will try to find regularity and order in the events of the world' [15]. New engineering concepts are difficult to make personally meaningful. Therefore, by requiring the students to become increasingly responsible for their learning, the engineering theory becomes a personally needed aspect of their successful completion of the activity. This is in contrast to some other freshman laboratory experiences [16–21], in which theory and procedures are outlined in detail for the students.

A challenge facing freshmen who are asked to design an experiment is a lack of the confidence that comes with experience. Therefore a scaffolding approach [22–26] is used to push the UNIV 101 students to function slightly beyond their previously demonstrated abilities. In each experiment, the students are provided less information at the beginning of their laboratory sessions and are responsible for more and more of their learning. During the first lab the students are provided with a very complete set of instructions. The handout for the second lab describes the background theory and experimental procedures, but students must develop their own data analysis proceedings, including the derivation of some equations. For the culminating lab experience, the handout provides only needed theory and required results. The students have to design an experiment that will provide the needed data, to write an experimental procedure and to develop and document an analysis method for generating the results. Details of each experiment are outlined in the following sections.

Full-body contact mechanics

The first in-class laboratory experiment is 'Full-body contact mechanics.' This introduces students to static reaction forces and to the mechanics of materials. The students apply static loads to a simply supported wooden beam, by standing on it. Support reactions are measured with bathroom scales and beam deflections are measured with a ruler. By varying the amount and location of the applied load, the students can perform a number of experiments. As shown in Fig. 1, a pine beam 5 cm × 10 cm (2 in × 4 in) and 1.6 m (8 ft) long is ideal for experiments using one average freshman as the applied load.

For example, the freshman who is the applied load stands at different locations along the beam at 0.3 m (1 ft) intervals, while others record the force read by each scale and the exact position of the applied load. Because the applied load is actually a distributed load (over the width of the freshman's two feet), the instructor has

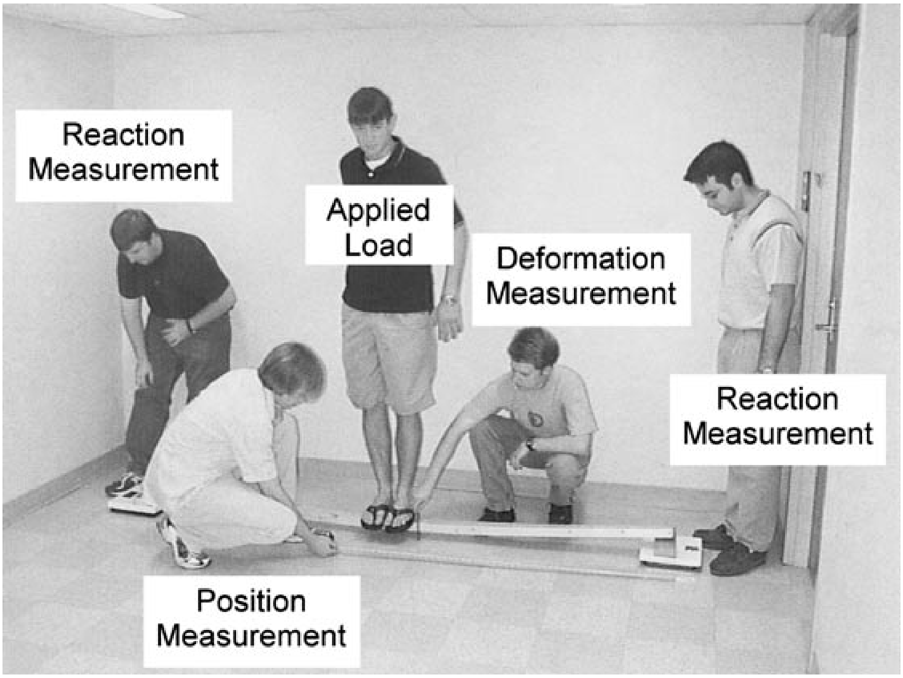

Fig. 1 *The 'Full-body contact mechanics' laboratory engages students in force, deflection and position measurements.*

the opportunity to discuss center of gravity and the equivalency of forces. This can lead to impromptu experiments as the applied load moves his or her feet farther and farther apart while attempting to keep the center of gravity in the same location. In another experiment, the applied load stands at the center of the beam while other students measure the distance between the beam and the floor at 0.3 m intervals along the length. Subtracting these distances from distance measurements made without the student standing on the beam gives the beam deflections.

In addition to introducing the students to laboratory procedures and engineering theory, this simple lab also serves as a vehicle to introduce the freshmen to data analysis tools. During the next class meeting, students meet with the instructor in a computer laboratory to perform the analysis portion of the assignment. Microsoft Excel is introduced, and the concepts of plotting engineering data are covered. The students develop a plot for the two scale values (reaction forces) versus discrete beam positions. This plot will clearly demonstrate the linear trend of the data. From the plot, students are challenged to develop a set of equations to calculate the values of the two scales for any non-discrete position on the beam. Students can develop two linear equations using the collected data based on the point–slope and slope-intercept equations. After the students complete these (manual) calculations, the concept of linear regression within Microsoft Excel is demonstrated. Each student completes a linear regression and compares the slope and intercept from computer-generated linear equations with his or her own calculations. To analyze beam deflections, students plot the deflection against the beam discrete positions based on the collected data. On the same plot, students graph the theoretical deflection against beam position based on traditional, simply supported beam deflection equations. This allows students to directly compare experimental and theoretical data. Students are required to write a formal laboratory report after completing the analysis. A prescribed format is given to them to follow to initiate some consistency in report writing that will be beneficial throughout the student's undergraduate career.

Head pressure

The second laboratory experiment performed during a class period is 'Head pressure'. This introduces students to the fluid mechanics principles of conservation of mass flow rate and the Bernoulli equation. The experimental apparatus is a PVC pipe, 76 mm (3 in) in diameter and 1.5 m (60 in) long, which is capped at one end and open at the other. As shown in Fig. 2, the pipe is stood on the end and filled with water by a hose at the other end. Holes drilled along the height of the pipe (which may be plugged) allow water to flow out; a slot in the top end, which is covered with clear packing tape, makes it easier to keep the water column height constant. A number of experiments can be performed with this apparatus by varying the number of unplugged holes and the height of the water column. Interesting results are obtained using three 6 mm (0.25 in) diameter holes in the side of the tube, drilled at 0.3, 0.6 and 0.9 m (12, 24 and 36 in) from ground level and a total water column height of about 1.4 m (56 in), as described below.

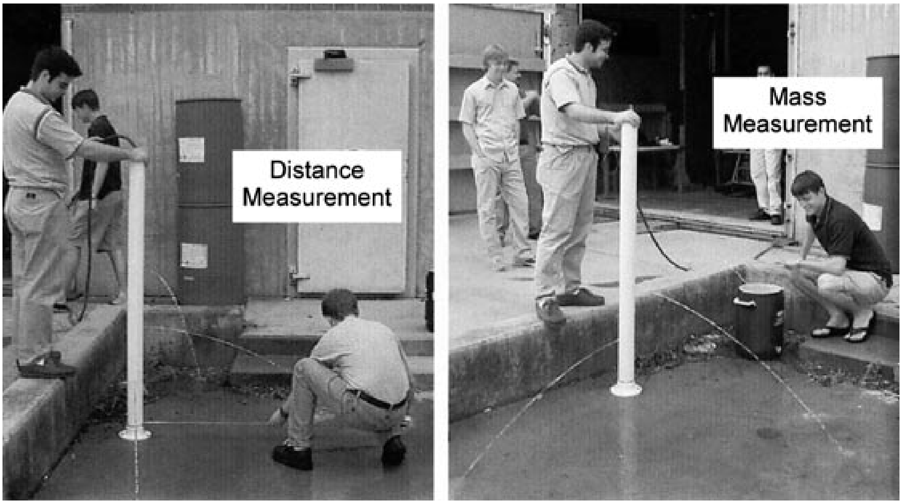

Fig. 2 *In the 'Head pressure' laboratory, freshmen determine flow velocities from mass and time measurements, distance measurements, and the Bernoulli equation.*

At the beginning of the laboratory session, students are asked to predict which hole will have the highest flow rate of water coming out. They usually choose the bottom hole and can explain that this is because the pressure will be greatest there. Then the students are asked to predict from which hole the water jet will shoot the farthest before it hits the ground. They generally choose the bottom hole because it will have the highest flow rate. Then the tube is filled with water with a hose and the inlet flow is adjusted until the water level remains constant. The students use a tape to measure the horizontal distance each jet has traveled when it hits the ground. They are presented with a discrepant event, because the top and bottom jets travel the same distance, and the middle jet travels the farthest. Slowly, the students come to the realization that both the jet velocity and the height of the hole determine the distance traveled. They then use the tape to measure the hole heights and water column height. The second set of measurements made by the students involves collecting and weighing an amount of water from each jet and from the hose for measured times.

During the next class meeting, the students meet with the instructor at the computer laboratory to analyze the results: MathCAD is introduced as the analysis tool. The students must use their experimental data to calculate the average flow velocity of the water from each hole using two methods. First, students calculate the average flow velocity based on the flow rate determined from the amount of water caught in the bucket and the dimensions of the exit hole. Second, the average flow velocity is found using the measurements of distance to impact and height of the hole from the ground, along with equations from particle dynamics. Next, the theoretical exit velocity is calculated from Bernoulli's equation. Finally, the students are required to compare the three exit velocity calculations graphically and also show the conservation of mass. This laboratory pushes the students to plan more of their experiment, because the material provided to the students includes the experimental procedure, but not all of the theory and data analysis procedures.

Resistance is futile

The electrical circuits experiments, 'Resistance is futile', is designed to teach both introductory electric circuit theory and experimental design. The simple circuit, shown in Fig. 3, consists of a 1.5 volt battery, a resistor in series and two resistors in parallel, all mounted on a small board. A multimeter is also provided. This set-up allows for instruction of basic circuit topics, including Ohm's law, addition of resistors in both series and parallel, and Kirchhoff's laws. The students are provided with a handout containing the basic theory and the objective to experimentally determine the values of the three resistors without removing any of them from the circuit. The students are asked to submit final reports formatted similar to the handout for the 'Full-body contact mechanics' lab, containing background and experimental procedures sections, with sufficient information for another engineering freshman to perform the experiment without assistance.

The learning cycle is fully embraced during this laboratory experience to create student interest in the new material. One method that is effective with college

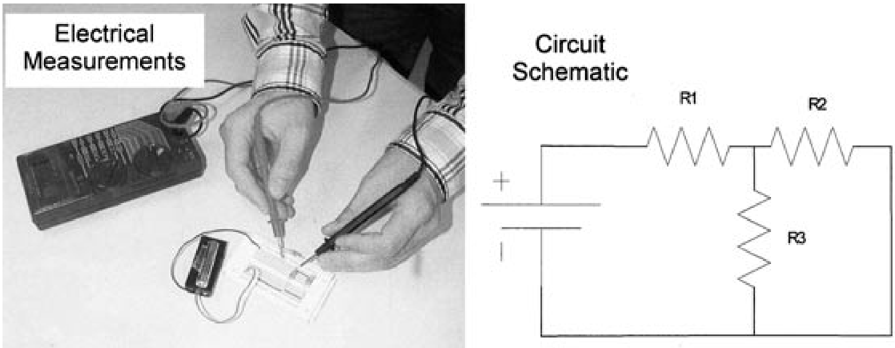

Fig. 3 *The 'Resistance is futile' laboratory requires students to design their own experimental procedure to determine the value of three resistors without removing them from the circuit.*

students is the posing of challenging questions. For example, during the circuit laboratory introduction, the student's challenge was to determine the resistor values without disassembling the circuit. The challenge was presented as a role-playing scenario to best intrigue the student. Students were asked to imagine that they were engineers who needed to diagnose the failure of a piece of manufacturing equipment. Since it was a sensitive piece of machinery, their job was to determine which resistor went 'bad' without disassembling the machine.

This laboratory also presents the opportunity to use a discrepant event to motivate student interest. The circuit used during the laboratory has an inherent discrepancy if a student tries to directly measure resistance across each of the three resistors. Two of the resistors are in parallel (resistors R2 and R3 in Fig. 3), so that when resistance is measured across each of these, the two measurements will exhibit an identical value. However, the two resistors clearly have distinct color bands, and, therefore, distinct values. This creates the discrepant event: the digital multimeter reads the same resistive value for both resistors, but the color bands indicate they have different values.

Following these introductions, the students begin the exploration phase of the learning cycle. During this stage, the students are encouraged to take an active role by investigating the posed problem. Students examine the governing equations, the circuit, and the digital multimeter. Through these explorations, they develop the needed experimental procedure and the simultaneous equations to solve for the unknowns. Therefore, students are responsible for their own construction of knowledge and understanding of the theory. Once the students have had sufficient exploration time, the class is convened for the learning cycle's third phase: concept development. At the beginning of the second laboratory meeting, the instructor leads a class discussion to review each group's plans for completing the laboratory. The students are able to hear how the others plan to approach the problem and have the opportunity to refine their experiment. These informal presentations can lead to discrepancies among procedures and conclusions. This provides the opportunity for the instructor to guide the class to the correct conclusions, and it is through this discussion that students continue to learn the newly presented material. During concept development, the instructor has the opportunity to discuss terminology and to introduce supporting material, such as text reading. It is important that textbook material is presented *after* exploration. By doing so, the students are able to confirm their own findings. This promotes understanding of theory and enhances the students' responsibility for their learning. In contrast, if the accepted textbook material is presented first, the students will be confirming accepted material. This discourages students from finding their own answers and advocates the notion that only experts can have accepted theories. After discussions, the remainder of the period is used for students to collect voltage, current, and resistance data from their circuit.

Prior to meeting for the third laboratory session, students are required to complete their analysis method as homework. The students meet with the instructor in a computer lab and use MathCAD to complete the analysis. The nature of the laboratory requires the students to solve simultaneous equations; therefore, this time is used to introduce MathCAD's iterative capabilities. Through the concept development phase, the students will gain an accurate approach to the laboratory, and this leads to the fourth phase: application. It is during the application phase that students complete the laboratory assignment. The student or student group will use the procedures and analysis developed during the exploration phase, and refined during concept development, to answer the questions provided with the laboratory handout.

Evaluation

Several class periods after the completion of 'Resistance is futile', the students in the pilot study have been given a survey to determine their attitudes toward designing their own experiment and their ability to learn material themselves. The students had the opportunity to strongly agree, agree, feel neutral, disagree, or strongly disagree with the statements. Key results were as follows:

1 All students either strongly agreed or agreed that the laboratory experience reinforced the introductory electric circuit theory.
2 All students either strongly agreed or agreed that designing the experimental procedure challenged them to understand the underlying theory better.
3 All students either strongly agreed or agreed that, compared with the first two experiments, the 'Resistance is futile' laboratory required them to think more creatively.
4 Most students (86%) agreed that the laboratory session helped them to realize they could learn engineering material without being taught by an instructor. The remaining students felt neutral about the statement.
5 All students disagreed that they learned less during the 'Resistance is futile' experiment than in the other two laboratory sessions.

Considering the results of the survey, the requirement to design the experimental procedure and analysis routine enhanced the students' understanding of electric circuit theory. Although this is a pilot study, the above results indicate promise for broader implementation in the future. Students were required to think more creatively, but the addition of creative thought did not detract from their ability to learn the theoretical material. Furthermore, the laboratory experience helped the majority of the students to feel more responsible for their own education. They recognized they were able to learn complex material without being spoon-fed.

A second evaluation tool being used is the end-of-semester student survey given to all UNIV 101 engineering sections. Because only two of 11 engineering sections of UNIV 101 have performed the experiments during the past two years, a comparison can be made as to the effect of the laboratory on student attitudes. According to student survey results, students in the lab pilot sections consistently report greater satisfaction with the computer tool training component of UNIV 101. This is attributed to the fact that they used their own laboratory data as the basis of the computer training, so that the information became personalized and more meaningful. Written student comments were also positive, and included the statement 'Our section learnt more than the others'.

Conclusion

A series of simple experiments on mechanics, fluid dynamics and electrical circuits has been developed to enhance freshmen's abilities to apply engineering concepts and to design experiments and to motivate the learning of computer tools. These hands-on experiences enable the students to increase their knowledge base and understanding by personalizing information. By designing their own experimental procedure and analysis methods, the students generate a personally meaningful scenario, one in which they use and expand the given information to reach a needed conclusion. Based on the results of two semesters of pilot testing, the experimental sequence is viewed as successful, and should be readily adaptable by other engineering programs.

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