Designing Effective Laboratory Courses in Electrical Engineering: Challenge-based Model that Reflects Engineering Process

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Abstract – In electrical engineering programs, physical laboratory courses should enable students to apply theory to design, to synthesize and analyze circuits and systems, and gain practical hands-on skills and knowledge required for their future career. However, students often have difficulty applying electrical theory to problem solving tasks, such as those encountered in lab experiments; therefore, an alternative approach to lab instruction is desirable. A study at Vanderbilt University explored the potential of organizing electrical engineering labs around challenges. A learning model called Software Technology for Assessment and Reflection (STAR) Legacy was adopted in designing the lab learning process. The model combines problem-solving challenges and instructional resources with web-based technology. This paper describes the structure of the innovative challenge-based lab design, and presents student and instructor evaluations of this design.

Index Terms - Challenge-based lab instruction, Electrical Engineering labs, Lab design model, Integrated lab-learning environment, STAR Legacy Cycle.

BACKGROUND

There is much discussion on knowledge that is attained from learning experiences that reflect the complexity of the real world, where this knowledge will be used [1]. Studies suggest that unless learners understand how to use knowledge as a problem-solving tool, they may characterize a problem at a superficial level, or may not recognize the problem when it occurs in a novel situation [2]. If instruction is designed in a way that helps the learner situate learning in an approximation of the real world, there is the potential to overcome the tendency for knowledge to remain inert [3]. A method for organizing resources around learning activities, or challenges, was developed by Schwartz et al [4]. They produced a software shell, STAR (Software Technology for Assessment and Reflection) Legacy, to help people visualize and manage inquiry in a manner that centers on learner, knowledge, assessment, and community [5].

I. The STAR Legacy Cycle

Instruction in physical lab courses requires the use of a variety of basic teaching skills; however, lab courses have elements that differ from other teaching forums. Different types of teaching and learning methods can be successful or unsuccessful depending on the goals of learning and the prior knowledge and skills learners bring to the task [6]. Modern learning theory shows that different kinds of learning goals require different instructional methods to achieve them.

Wiggins & McTighe [7] propose a design method for creating learning environments. They suggest that effective course design should first begin with the learning goals, that is, what students should know and be able to do. After the learning goals, a method of assessing student progress toward these set goals must be determined; finally, instructional methods must be developed that are best suited to enable students to learn effectively and accomplish the set goals. This “Working Backwards” method assumes that these three design steps are continuously evaluated.

The How People Learn (HPL) Design Framework by Bransford, et al [5] highlights a set of four overlapping lenses for analyzing the quality of various learning environments. These environments can be investigated at levels ranging from individual courses to programs as a whole. The lenses used for assessment categorize learning environments by their dominant focus: learner, knowledge, assessment, and community. Figure 1 shows the four overlapping lenses for analyzing the various learning environments.

FIGURE 1.
OVERLAPPING LENSES OF THE LEARNING ENVIRONMENTS
It is apparent that the “Working Backwards” strategy of Wiggins & McTighe [7] meshes with the HPL Framework by Bransford, et al [5]. The Working Backward strategy starts with a knowledge-centered component, since its first step is determining what students should know and be able to do at the end of a course. The second step is taken by determining what kinds of evidence will show that progress is being made, the knowledge-, assessment- and learner-centered overlaps in the HPL figure below. The third step is determining what instruction methods will allow the goals to be accomplished, the learner-, community-, assessment-, and knowledge-centered lenses overlap in the HPL.

The Working Backward and HPL strategies could potentially re-organize and restructure the traditional lab learning process; with the aid of appropriate learning technologies and instructive methods, a new, innovative lab model could be devised for physical lab courses.

II. Significance and relevance of The STAR Legacy Cycle to the engineering practice

The STAR Legacy Cycle, which has been used to develop the EECE 213 (and other EECE) labs, is shown in Figure 2.

In order to apply STAR Legacy in the design of electrical engineering lab courses, it is necessary to relate the cycle to a realistic engineering process.

The cycle was developed to organize instruction and manage learning activities and resources in a classroom setting; it has never been implemented in engineering lab course design [8]. Therefore, an objective of this study has been to evaluate the appropriateness of the cycle in a practical electrical engineering lab course.

Figure 3 shows the engineering project development process superimposed on the STAR Legacy Cycle. Activity-to-activity correlation of Figures 2 and 3 helps students understand the relevance of the STAR Legacy model and the realistic engineering basis for its use in the design of laboratory courses.

FIGURE 2
THE STAR LEGACY CYCLE

In Electrical Engineering at Vanderbilt University, the course EECE 213 Network Theory I is a requirement for sophomore engineering students in biomedical, computer, and electrical engineering programs. The labs corresponding to this course have been taught in the traditional method for years, demonstrating the application of electrical concepts and principles to design, synthesis, and analysis of basic electronic circuits.

During lab classes, the Teaching Assistant (TA) gives a group introduction, answers questions, and is available to help with individual problems. After completing the lab procedures, briefly outlined in the lab manuals, the traditional practice has been for students to record their results in lab notebooks, and submit the notebooks for grading.

The enforcement of lab notebook entries as the required form of presentation does not meet ABET Engineering Criteria 2000, which aims to develop formal presentation and technical writing skills. Assessment of notebook entries fails to adequately evaluate practical competencies gained from the activities and interactions, since the grading is essentially based on whether or not the results are correct.

A previous study into student learning in the same EECE 213 labs reported a number of problems with traditional lab instruction [11]. Students were often unfamiliar with the contents of labs, such as electronic components and test instruments. Two other related studies reported that student knowledge and understanding of basic electrical concepts were often disjointed [11], resulting in misconceptions and difficulties in problem-solving tasks.

In this study, it became necessary to confirm these student deficiencies. A survey was carried out every term during the years 2000, 2001 and 2002, before labs began, to determine the background of students enrolled for the EECE 213 labs. The results showed that many students had little prior knowledge of basic electrical circuit concepts and no practical competencies in basic electronic circuits, materials, and test instruments (see Table 1). A follow-up written test on circuit
concepts and practical lab knowledge confirmed the student weaknesses (see Table 2). After the first three labs, another survey showed that students had problems in many areas of the three labs (see Table 3). These surveys and the written test confirmed previous findings that many students were ill-prepared to perform the EECE 213 labs.

TECHNOLOGY-ENHANCED, CHALLENGE-BASED PHYSICAL CIRCUITS LABS AT VANDERBILT

Lab instruction and learning issues highlighted here raise the question, how can innovations in learning technologies and new outcomes in the learning sciences improve instruction and learning in engineering lab courses?

ABET Engineering Criteria 2000, which focuses on student outcomes, requires engineering faculty not only to develop methods and measures for evaluating their programs, but also to use the results to improve the instruction and learning process [9]. These requirements also apply to physical lab courses, which form a vital part of an accredited engineering program.

Based on the results of the surveys and test (see Tables 1, 2 and 3) the following lab innovations were developed, evaluated, and organized into a technology-enhanced, challenge-based learning environment for the EECE 213 circuits labs.

I. Computer-based instrumentation

In 1998, the Department acquired the National Instruments VirtualBench (NI VB) software and hardware to evaluate for use in the labs. NI VB is a stand-alone, software-based suite of instruments, including a 2-channel oscilloscope, function generator, and digital multi-meter.

In 2001, a comparative evaluation was carried out to determine student attitude and level of satisfaction between the NI VB instruments and the conventional bench top instruments. The class was divided in two groups. For the first four labs, one group used the conventional instruments while the other used NI VB. Then for the next five labs, the two groups switched instrument types. A self-reporting evaluation was then conducted. The evaluation results showed that students favored computer-based NI VB instruments over the traditional bench top instruments. Based on this evaluation, the Department replaced the conventional bench top instruments in the EECE 213 circuits labs with computer workstations.

II. Web-based lab courseware and learning resources

In the traditional lab environment, there are no lab resources available to students, apart from the limited information in the lab manuals, that provide detailed information on things such as electronic components and their proper use; realization of physical circuits from circuit schematics; circuit construction using lab materials; calculation of significant circuit parameters; or proper use of test instruments. Also, while objectives are often listed in the lab manuals, no effort is made to relate the lab concepts to real world settings, making it difficult for students to see the practical applications of the concepts. Therefore, many students simply follow the lab procedures in order to fulfill course requirements, without any real understanding and appreciation of where and how the concepts are applied.

Also, in traditional labs, the lab instructor is the only source of assistance for conceptual and procedural difficulties that students encounter. Much of the instructor’s time is spent addressing student procedural problems rather than aiding in conceptual discussions. This dependence on instructor assistance often results in decreased interest and motivation [1].

These issues can be addressed with the aid of technology. Independently accessible web-based tutorials would provide the resources pertinent to successfully carrying out lab procedures. Such sources of information would be available for access during the labs, as well as for pre-lab and post-lab activities. Students could learn new concepts, or correct misconceptions, at any stage of the lab experience. This would prepare students for the labs, address conceptual and procedural difficulties, improve lab efficiency, understanding, and improve the lab learning process.

Web-based lab instruction, tutorials, and other learning resources pertinent to the EECE 213 circuit’s labs were designed and developed, and made available on the Lab’s website (http://eecs.vanderbilt.edu/courses/ee213).

Evaluations were carried out to determine student attitude and level of satisfaction with the web-based tutorials and learning resources.

II. Challenge-based lab design using the STAR Legacy Cycle

After introducing the computer-based lab environment, the Legacy Cycle was used to design the lab instruction and organize the lab activities around challenges. The existing nine EECE 213 labs were redesigned using the Working Backwards strategy [7]. Lab activities were organized using the Cycle, which reflects the project development process in engineering. The HPL framework was useful in determining the methods to introduce challenges, helping students generate ideas, embedding assessment, and in designing multiple learning activities to foster deeper understanding.

The Legacy Cycle was divided into the three segments that make up the total lab learning experience:

1. Pre-Lab
   - Challenges
   - Generating Ideas
   - Multiple Perspectives and Resources (On-line Pre-lab tests, web-based tutorials and learning resources)
   - Research and Revise (Pre-lab design and evaluation)

2. During Lab
   - Test Your Mettle (experiment)

3. Post-Lab
   - Go Public (formal lab report)

When designing the lab instruction, the main objectives of each lab was anchored to realistic electrical engineering problems in “The Challenge” (problem definition) of the Legacy Cycle (see Figure 2).
To engage students in the critical thinking process, they are asked to generate ideas on how they would address the problem presented in the challenge. This is the “Initial Thoughts” stage of the Cycle.

The “Perspectives and Resources” stage of the Cycle presents opinions of experts on the challenge, definitions, tutorials, and other relevant resources. On-line pre-lab tests, designed to prepare students on the lab materials, are also linked to this stage.

The prototype design of a possible solution to the challenge problem occurs in the “Research and Revise” stage of the Cycle. Here, the pre-lab design calculations and theoretical performance analysis take place. Also, evaluations are done to ensure that the theoretical performance parameters meet the requirements defined in the challenge problem definition.

The “Test Your Mettle” stage of the Cycle takes place during the lab class, where the students build their designed circuits and follow experimental procedures to test and make practical measurements.

The “Go Public” stage of the cycle is where the formal technical writing takes place. To satisfy ABET requirements in technical communication/presentations, the new challenge-based labs require students to submit formal lab reports based on the industry standard.

**EVALUATIONS AND RESULTS**

Evaluation of engineering courses usually focuses on the cognitive knowledge gained by students. However, the main purpose of this paper is to introduce to engineering education a new, technology-enhanced, challenge-based lab environment that has the potential to address problems inherent in the traditional lab method. The evaluation process for this new lab environment consisted of self-reporting attitudinal surveys of traditional lab method. The survey was divided into four areas: test instruments, components, circuit construction, and circuit analysis. The new challenge-based labs require students to submit formal lab reports based on the industry standard.

### I. Student prior knowledge and practical competencies and difficulties in the lab

Before the labs began, students enrolled for the EECE 213 labs were surveyed to assess their prior knowledge and practical competencies in different areas. The survey was followed by a written test.

Table 1 shows the results from the survey. The sample size N was 191 students, enrolled in Spring 2000, Fall 2000, and Spring 2001 semesters.

The survey was divided into four areas: test instruments, components, circuit construction, and circuit analysis. The first area represents the different instruments used during the labs, such as the oscilloscope or digital multi-meter, and evaluated the students’ abilities in using their operation. The second area evaluated the students’ knowledge of components and their practical uses. The third area represents circuit analysis, such as interpreting measurements from the oscilloscope or producing graphs of measured data.

For each area, a series of questions were asked; the students responded to the questions using the following scale: 1-strongly disagree, 2-disagree, 3-neutral, 4-agree, 5-strongly agree. So, for example, if a student felt confident in constructing a circuit, he or she would respond with a 4 or 5; if not, then a 1, 2 or 3. The results in the table represent the averages of these responses for each area.

#### TABLE 1

**RESULTS OF STUDENT PRIOR KNOWLEDGE AND PRACTICAL COMPETENCY EVALUATION.**

<table>
<thead>
<tr>
<th>Competencies</th>
<th>Mean</th>
<th>S. D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Test Instruments</td>
<td>2.75</td>
<td>1.19</td>
</tr>
<tr>
<td>B Components</td>
<td>2.82</td>
<td>1.21</td>
</tr>
<tr>
<td>C Circuit Construction</td>
<td>2.80</td>
<td>1.33</td>
</tr>
<tr>
<td>D Circuit Analysis</td>
<td>2.74</td>
<td>1.09</td>
</tr>
</tbody>
</table>

The results in Table 1 indicate an overall weakness in the students’ prior knowledge and competencies when they begin the EECE213 labs. The results show consistency across the three semesters, which suggests that the combined results in Table 1 are stable.

In order to confirm the results in Table 1, an in-class prior knowledge and competency test was administered at the beginning of Lab #1. The test was multiple-choice, and required simple calculations and reasoning. The test was taken by 93 students, all randomly selected. Table 2 shows the percentage of correct and incorrect answers.

#### TABLE 2

**RESULT FROM STUDENTS’ PRIOR KNOWLEDGE AND PRACTICAL COMPETENCY TEST**

<table>
<thead>
<tr>
<th>Question</th>
<th>Correct</th>
<th>Incorrect</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The impedance of a capacitor is:</td>
<td>53</td>
<td>47</td>
</tr>
<tr>
<td>2. How is the impedance of a capacitor related to frequency?</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>3. How is the impedance of capacitors related to their capacitance value?</td>
<td>66</td>
<td>34</td>
</tr>
<tr>
<td>4. How will you convert from pico-Farad (pF) to microfarads (μF)?</td>
<td>34</td>
<td>66</td>
</tr>
<tr>
<td>5. The phase angle in RC circuits is a function of frequency. What is the maximum phase angle obtainable?</td>
<td>48</td>
<td>52</td>
</tr>
<tr>
<td>6. The cutoff or break frequency, ωc, can be express in terms of R and C. Which relationship is correct?</td>
<td>68</td>
<td>32</td>
</tr>
<tr>
<td>7. What is the significance of the cutoff or break frequency (ωc) in low pass filters?</td>
<td>39</td>
<td>61</td>
</tr>
<tr>
<td>8. The “half power” magnitude is defined as the point at which magnitude of Vo is:</td>
<td>47</td>
<td>53</td>
</tr>
<tr>
<td>9. How would you convert frequency in radians/second to frequency in Hertz?</td>
<td>59</td>
<td>41</td>
</tr>
<tr>
<td>10. For a low-pass RC filter, one “time constant” is defined as the time taken for the capacitor to charge up to:</td>
<td>33</td>
<td>67</td>
</tr>
<tr>
<td>11. The time constant of a series RC circuit is determined by:</td>
<td>61</td>
<td>39</td>
</tr>
<tr>
<td>12. The impedance of an inductor is:</td>
<td>52</td>
<td>48</td>
</tr>
<tr>
<td>13. The impedance of an inductor is a function of frequency. How is it related?</td>
<td>68</td>
<td>32</td>
</tr>
</tbody>
</table>
There was a need to determine the exact difficulties students faced as a result of their weaknesses in prior knowledge and competencies. This was done using a self-reporting evaluation after the completion of Lab #3. The evaluation consisted of the same format and questions as the one given to assess the students’ prior knowledge and competencies.

For this analysis, evaluations from 75 students, enrolled in the Spring 2001 class, were used. The response scale was identical to the one used before: 1-strongly disagree, 2-disagree, 3-neutral, 4-agree, 5-strongly agree. The responses were averaged for each section as well.

III. Computer and use of computer-based NI VB instruments in the circuits labs

The Spring 2001 class carried out four labs using conventional bench top instruments, then the next five using computer-based instruments (NI Virtual Bench 2.1.1 and hardware). A self-reporting evaluation was done to assess the students’ attitudes and level of satisfaction after they had used both the conventional bench top instruments and the computer-based instruments in the lab.

The results of the evaluation showed that the students found the computer-based instruments easier to operate than conventional bench top instruments. Students also agreed that it took less time for them to become familiar with the features of computer-based instruments, compared to conventional

<table>
<thead>
<tr>
<th>Lab Activities</th>
<th>Mean</th>
<th>S. D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Instruments</td>
<td>2.51</td>
<td>1.10</td>
</tr>
<tr>
<td>Components</td>
<td>2.80</td>
<td>1.08</td>
</tr>
<tr>
<td>Circuit Construction</td>
<td>2.76</td>
<td>1.14</td>
</tr>
<tr>
<td>Circuit Analysis</td>
<td>2.92</td>
<td>1.07</td>
</tr>
</tbody>
</table>

Table 3 shows that many students did face difficulties in these four areas. As part of this study, these results were used to develop web-based tutorials, designed to provide assistance to the students and better prepare them for the labs.

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The results in Table 4 show that the majority of student assessments fell into the “somewhat agree, agree, and strongly agree” ratings in response to many of the evaluation statements. This shows that a lot of students reacted positively to the new design and realized its significance.

CONCLUSIONS

The results in Tables 1 and 2 confirmed earlier studies that engineering students taking labs in the EECE 213 course have major deficiencies in prior knowledge and competencies relating to electronic concepts and practical circuit skills. As a result, students faced varying degrees of difficulty in many areas of the labs.

Results from student and TA assessments showed that both the students and TAs were satisfied with the computer-based instruments, preferring them to conventional bench top instruments. Also, both felt that the combined computer, computer-based instruments, and web-based lab resources provided a good lab-learning environment.

Additionally, results from both student and TA assessments of the challenge-based lab instruction showed that students and TAs alike were satisfied with the new design, and recommended similar environments for other lab courses.

The EECS Department was satisfied with the outcome as well; it approved the implementation of this new lab-learning environment, and other lab courses in the department have now being redesigned. In addition, the EECS Department replaced the NI VB systems in the labs with the state-of-the-art ELVIS systems from National Instruments. Approval has been given by the Department to extend the work to the EECE 235 Electronics and EECE116 Digital Logics labs.

RECOMMENDATION

Based on the results presented here, the new challenge-based, lab-learning model has demonstrated its potential to improve the lab learning experience and address some of the issues inherent in traditional engineering lab courses. This model is based on the realistic engineering project development cycle, relating lab concepts to practical engineering applications. Therefore, it would be safe to recommend that this new model be considered for implementation in physical lab courses in engineering.

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REFERENCE


