# Using Simulation Software for Electronics Engineering Technology Laboratory Instruction

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Abstract

To determine the effectiveness of offering electronics engineering technology laboratory courses on-line, computer simulations were compared with hands-on laboratories. Quantitative research on the achievement of students in each laboratory environment showed no statistically significant differences. Nevertheless, quantitative analysis of the students' attitudes revealed a statistically significant bias toward the hardware laboratory in learning troubleshooting. A concurrent qualitative investigation produced several thoughtful recommendations for improving the computer simulation laboratory experience. This paper reports the results of the quantitative research, but it focuses on the conclusions, recommendations, and implications of the qualitative study.

## I. Introduction

Northwestern State University of Louisiana has been improving its ties with area industry through partnerships. At the same time, the university is taking steps to increase access to education by using several technologically oriented methods in distance education. In part, these efforts have been motivated by a desire to expand the university's ability to offer courses to industry, its employees, and to other people who are not free to attend class during traditional classroom periods. While there are many examples of lecture and discussion-group classes on-line, one hallmark of an electronics engineering technology program is that laboratory classes accompany most lecture courses. Though most of our lecture classes can be delivered at a distance, it is not possible to duplicate the hands-on experience of an electronics laboratory over the Internet. Even so, an on-line electronics engineering technology program should include concurrent laboratory instruction.

In recent years, many computer-aided simulation software packages have become commercially available. Further, there have been research efforts to contrast the effectiveness of using some of the software packages with the effectiveness of the traditional hands-on laboratory exercises. Much of the research effort to date has been designed to investigate the use of computer-aided software as a method to enhance, enrich, or improve traditional lecture or laboratory courses rather than using simulation software in place of hardware laboratories.

In an on-line conference hosted by the Institute for Learning Technologies at Columbia University, Kastens[1] hypothesized that students would begin to learn more quickly when conducting laboratory exercises using simulated data rather than real data, but their learning would level out over time. When using real data, with its underlying complexities, the learning begins more slowly but builds rapidly—eventually outperforming the learning that occurs with simulated data. Kastens[1] contrasted the use of virtual laboratories and contrived data with the use of real laboratories and real data. However, his statements were only untested hypotheses that are based on his personal experience. He challenged others to test his hypotheses. Richard Clark[2] noted:

> Studies of the influence of media on learning have been a fixed feature of educational research since Thorndike (1912) recommended pictures as a laborsaving device in instruction. Most of this research is buttressed by the hope that learning will be enhanced with the proper mix of medium, student, subject matter content and learning task (p. 445).

After evaluating a number of meta-analyses and frequently contradictory literature, Clark[2, 3] remained convinced that media do not matter. He pointed out, "it is method of instruction [rather than media] that leads more directly and powerfully to learning" (Clark, 1983, p. 449). On the other side of the debate, Kosma[4] argues that media and methods influence each other. "In a good design, media and methods are inexorably confounded. Media constrain and enable methods…"(p. 11).

In 1989, Gokhale[5] compared a "canned" simulation program that required the students to apply "rules of logic" with hands-on laboratories in teaching logic circuits. He also examined the effects of sequencing of the instruction and the laboratory on teaching and learning. He found that there were no significant differences in posttest scores between the groups that used computer simulation and those that used the hardware laboratory. Garren[6] studied the use of computer-aided design software to create digital electronics circuits and perform laboratory experiments compared with using actual digital components in the laboratory to perform the same experiments. He found that the control and experimental groups were not significantly different in their performance on a posttest at the completion of the semester. Moslehpour[7] evaluated the effectiveness of using computer-aided simulation to supplement traditional laboratories in teaching basic electricity and electric circuits. "The overall outcome of this study suggested that students who used computer simulation as a tool for enhancing achievement in … (basic electronics) performed similarly, and in some cases worse, than students who had not received computer simulation" (p. 82).

## II. The Research Design

The current research effort, which is discussed in this paper, had three complementary tracks. The first of these was a quantitative study to examine the differences in achievement between two groups: one that used Electronics Workbench, a commercially available computer simulation software package, for electronics laboratory exercises, and the other that used traditional hardware laboratories. The second track was a quantitative study to examine the attitudes of the students toward each laboratory environment. The third was a qualitative case study designed to investigate differences in learning that may have resulted from using simulation software in lieu of traditional laboratories. After reporting the results of the two quantitative studies, this paper concentrates on the results of the qualitative study.

The research was conducted using one freshman-level, introductory laboratory course in direct current circuits (ET 1301) and one junior-level advanced electronics laboratory course (ET 3341). Fifteen ET 1301 students finished the semester and thirteen finished in ET 3341. Posttests were administered following each of the eight independent laboratory experiments assigned during the semester. By design, each student completed four of the eight laboratory exercises in the computer lab using Electronics Workbench simulation software. The experimental group students worked individually as though they were taking the laboratory at home or in the workplace. Each student also completed four laboratory exercises as part of a control group in the hardware laboratory. In the hardware laboratory, students worked in lab groups, which is typical for most of our traditional electronics laboratory courses.

Before the start of the semester, the students in each course were randomly assigned to control and experimental groups for each lab. The membership in each group was changed for each of the eight laboratory exercises. Care was taken to ensure that each student performed four labs in each environment. Further, approximately the same number of students was assigned to each group for each laboratory exercise.

Following each laboratory exercise, each student was required to complete a posttest instrument. These instruments tested only the concepts that had been presented in the corresponding laboratory exercise. The instruments were designed to measure how well each laboratory environment reinforced learning the theory and concepts presented that lab. Also after each laboratory exercise, each student completed a four-question attitudinal survey in addition to the posttest. The students responded on a Likert scale of 1 – 5. In these four questions, students were asked to evaluate their own learning of the following:

- the lab objective;
- the objective compared with how they would have done in the other laboratory environment;
- the theory compared with how they would have done in the other laboratory environment; and
- troubleshooting compared with how they would have done in the other laboratory environment.

Finally, throughout the semester students were asked to report on their experiences in the two different lab environments. To do this, I talked to students individually, in small groups, and in the classes as a whole. At the end of the semester, I conducted a focus group session with each laboratory class and recorded the ensuing exchanges. The students' responses to the attitudinal questions above precipitated much of the dialogue in the qualitative study. These conversations and focus group discussions formed the basis of the qualitative case study that is the subject of this paper.

## III. The Quantitative Research Results

The quantitative research showed no significant differences in conducting electronics laboratories by computer simulation and conducting the same experiments in the hardware laboratory when the lab exercises are used to reinforce theory. The averages compiled at the end of the semester provided the most compelling evidence for the findings. Paired sample *t*-tests showed no statistically significant differences between the control and experimental groups for either the freshmen or the juniors. The combined results from the freshman-level and the junior-level courses also showed no significant difference based on a paired-sample *t*-test. The two-tailed *t*-test results were $t(27) = -.828$, $p = .415$. The observed power (at $\alpha = .05$) was .052, but the effect size represented only 0.156 standard deviations. While the observed power of the experiment was low[8], the small effect size indicated that there was no practical difference between treatments.

The results of the Likert scale questionnaires were equally revealing. The freshmen showed no statistically significant differences in their responses to any of the four questions. This indicates that they did not have a preference for either environment in terms of learning the objective of the laboratory, learning the theory, or learning troubleshooting. In contrast to the freshmen, the juniors showed statistical significance in their answers to all four Likert scale questions. The juniors' responses indicated a preference for the hardware laboratory in learning the objective, learning the theory, and learning troubleshooting. The juniors' "statistically significant attitudes" did not match their actual performance, as there was no significant difference between their experimental and control mean posttest scores. Inasmuch as the juniors' mean posttest scores were higher in favor of the hardware lab after six of the eight lab exercises, their attitudes were reflected in their performance, but not to the same degree.

## IV. The Qualitative Results

During the semester, there were several opportunities to discuss the different laboratory environments with the students. These discussions were designed to help determine the causes of statistically significant differences between the treatments and to determine differences not uncovered by the statistical analyses. At the end of the research period, two formal focus group discussions were conducted.

Recorded below are highlights of the focus group dialogue. Specifically, the points listed here were used as bases for some of the conclusions and recommendations given later. Quotations are all from students who took part in the study.

1. In the discussions, both the freshman and the juniors thought that Electronics Workbench (EWB) was well suited to learning the theory. Some of their comments follow. "I think … that using EWB you learn the theory part of it. You see [the theory] right up there. For 'reality,' for really constructing one, you have to do that in the hardware lab." "I think it is easier on EWB to test out theory because you don't have the wires and everything." "It [EWB] was excellent for the theory. When you put [the circuit] on EWB, the values that come up [measured values] are the actual theoretical values. If you hook it up right, you are going to get the theoretical values."

2. Both the freshmen and the juniors believed that the hardware laboratory was better suited to learning troubleshooting of circuits similar to those experienced in the labs. These are typical comments. “EWB won’t help you learn to troubleshoot because everything always works provided you hooked it up right.” “You can’t enhance your troubleshooting technique on EWB. That’s my biggest problem in every lab—hooking the circuit up right.” “But, as far as troubleshooting and practical application goes, the hardware lab is much better.”

3. One student commented that the computer labs did help. “Electronics Workbench is sufficient for learning concepts—it’s fine. The hardware lab helped if you had it set up right. If you didn’t have it set up right, it kind of got confused. It was more like learning how to build it correctly than learning the theory.”

4. A freshman commented on the fact that, in many of their labs, they tested concepts before they were presented in the lecture. “It helped me learn to see it work before we had it in the lecture. Seems like you can get a grasp of complicated stuff a lot quicker—a lot easier.”

5. A freshman stated that students are more familiar with computers than with hardware laboratory equipment and the circuits. That made Electronics Workbench an easier environment for getting started.

6. In a junior-level focus group, there was a discussion about the possibility that Electronics Workbench is a good way to get started in learning electronics laboratories. “Freshman and sophomore classes may be better for EWB than later courses.” “Hands-on labs are especially difficult in lower level classes when the equipment doesn’t work properly.” “Eventually, one needs to get the hardware experience.” The freshmen tended to agree because there is less frustration, less mess, less chance for error, simpler components and meters. “In the hardware lab, you get wires confused. One time, I tried to check current with a voltmeter.”

7. One junior pointed out that it is easier to go from hardware to computer than from computer to hardware. A freshman said, “I think that if I had no electronics background, and I took everything on the computer, I’d be sitting here wondering, ‘what does a resistor really look like? Can I actually build a circuit? Sure, you can do it on the computer, but how do you really do it [on a real circuit]?’ I’d still be wondering without the experience in the hardware lab.”

8. Both classes agreed that in situations where computer simulation is the only possible environment for laboratory experience, it would work. “I believe that you can learn it, if that’s all you had.” “Yes, you could do it. They could pass the class, but [miss the “real world” experience].” “It [EWB] would be beneficial for designers, but not as good for technicians out in the field.” “Use circuits with bad resistors [or other components].” “Provide circuits that need troubleshooting.”

9. The fifth focus group question was: “How would you compare the EWB laboratory with an actual hardware lab experience?” The following two responses were agreed upon

> almost unanimously in both groups. A freshman reported, “My suggestion is that you really shouldn’t have one without the other, because on the one hand you get technical experience with the hands-on stuff. With the other you get theory. When you put them together, you get all of it.” When asked if we should have every lab twice, he responded, “Pretty much.” A junior responded, “They really complement each other.”

The students’ responses to this last point seem intuitive—the computer experience combined with the hardware experience should be better than either treatment performed alone. As already mentioned, Moslehpour[7] found the contrary to be true. Interestingly, his research revealed no statistically significant differences between students who used computer simulations in addition to the hardware experience and those who completed the exercise solely in the hardware lab.

The focus group discussions were more helpful in discovering practical differences in the treatments than were either of the quantitative analyses. Much of the information from these discussions will prove helpful in further research and in practical application of computer simulations.

## V. Conclusions

### 1. Differences between the freshmen and the juniors

The quantitative tests did not show statistically significant differences between lab environments for the freshmen or the juniors. Nevertheless, the quantitative data from the posttest scores and from the Likert scale instruments showed some differences between the data from the freshmen and the data from the juniors. One example was the smaller effect size found between the group means for the freshmen. More obvious was the difference in attitudes reflected on the Likert scale instruments. However, it was the qualitative research that helped decipher the differences between freshmen and juniors, which may be attributed as much to their background and experience as to the treatments. The freshmen had little, if any experience in using electronic equipment whether real or simulated. They were learning two methods for conducting electronics experiments simultaneously. Thus their attitudes were not biased by their experience. Further, their attitudes did not change over the course of the semester. The mean differences in their posttest scores and in their attitudes were not significant.

The juniors were old hands at hardware laboratories. Every electronics course that they had taken previously was accompanied by a (hardware) laboratory course. To them, the computer simulation was a new experience. While they had been taught to use Electronics Workbench in several courses, their grades had never depended upon using it. Their prior experience with the hardware lab, coupled with technical difficulties during the conduct of two of the later lab exercises, may have contributed to the erosion of attitudinal support for the computer simulation. Our older version of Electronics Workbench lacked some capabilities that were needed for two of the later advanced electronics labs and forced us to use some approximations in the computer treatment to complete the lab exercise.[*] These problems contributed to certain frustrations on the part of the experimental group during the final lab—the single laboratory exercise that showed the largest difference in means between groups.

When the experimental and control posttest means of the ET 1301 freshmen were compared, the experimental (simulation) means were, by visual inspection, higher after six of the eight labs. Conversely, for the ET 3341 juniors, the control (hardware) means were higher following six of the eight labs. The juniors had used the hardware equipment and laboratories for about five semesters (and in five or more courses) prior to taking the ET 3341 lab course. During many of the qualitative discussions during the semester, they clearly favored the more familiar hardware laboratory environment. While binomial statistical analysis showed that chance was a reasonable explanation that the juniors would have six higher hardware mean scores out of eight labs, their bias toward the hardware lab may provide further amplification of these results.

The freshmen did not have a predisposition for either environment. In fact, an alternate explanation for their results (six higher computer mean scores out of eight labs) is that the freshmen did not have experience with the hardware laboratories and equipment. In qualitative discussions, they indicated that the computer environment was easier for setting up the circuit and taking the required measurements, while the hardware laboratory was frequently confusing and frustrating. These comments may help explain their performance in the experimental groups.

Another factor that favored the hardware laboratory students was the location of the instructor, who remained in the hardware laboratory during the lab exercises for both the ET 1301 and the ET 3341 courses. This design was to ensure that the hardware labs would be similar to any other hardware lab course offered on campus at the University. Further, the instructor would not be physically present during computer-simulated laboratory exercises for remote students. Rather, the instructor would be available electronically just as he was available physically for consultation with the experimental-group students during the research. There was no attempt to collect quantitative or qualitative data to examine the effect of location of the instructor. Instead, the design attempted to replicate as closely as possible two environments—courses for remote students and on-campus courses. It was for this same reason that students worked with lab partners while completing the hardware lab experiments and worked alone in the computer laboratory.

2. Suggestions for improvement

The qualitative data collected during the research contributed extensively to developing suggestions for improving both the computer-simulated labs and the hardware labs. Formal and informal discussions with the students reinforced some of the attitudes measured by the Likert scale questions and introduced some new factors into the research. The students in both courses agreed that Electronics Workbench is well suited to learning electronics theory. While they said that the hardware laboratory experience was excellent, they believed that computer simulations like Electronics Workbench could be used effectively for electronics laboratories—especially in situations where a hardware laboratory is unavailable.[**]

The freshmen mentioned that having circuits and concepts introduced in the laboratory before they were taught in the lecture course helped them understand the material better. Gokhale[5] found similar results when he tested the sequence of instruction. He found that students who experienced a laboratory exercise (by simulation or by hardware) before they were given a reading assignment on the same material performed significantly better than those who were given the reading assignment before the lab exercise.

Both the freshman and the junior groups reported that troubleshooting was better learned in the hardware laboratory environment. Contributing to this is the fact that the circuits were more difficult to set up in the hardware laboratory than they were on Electronics Workbench. Therefore, they had to spend considerably more time in the hardware laboratory troubleshooting and correcting their circuits. We discussed methods to increase the effectiveness of Electronics Workbench in learning troubleshooting. During the conduct of the present research, the laboratory exercises were designed so as to require the student to build the circuit prior to testing it. However, Electronics Workbench allows the instructor to construct circuits with simple or challenging faults that can be hidden from the student. The student can then be required to troubleshoot the circuit to determine the hidden fault. The students recommended the incorporation of circuits for troubleshooting in future computer simulation laboratories.

It should be noted that quantitative data relating to troubleshooting were not collected explicitly during the posttests. The idea that troubleshooting would be better learned in the hardware lab resulted from a pilot study conducted during the semester prior to the collection of the data that are presented here. The two questions about learning theory and learning troubleshooting were intended to elicit more feedback in these two areas. Further, as will be noted later, the qualitative research led to several suggestions for improving the chances of learning troubleshooting in the computer simulation laboratories.

The students suggested that using both hardware and computer simulation methods to complete every laboratory exercise would increase their learning. This conclusion has intuitive and pedagogical appeal. Repetition is often used to enhance the learning process. Moslehpour's[7] research did not support this idea. His control group performed electronics laboratories in a hardware environment while the experimental group used computer simulation laboratories to complement the hardware experience. Overall, Moslehpour[7] found no significant differences between the groups. Interestingly, the control group performed marginally better. Pedagogically, it is not feasible to perform every laboratory exercise twice, once in each environment. There are scarcely enough laboratory hours to cover every course topic adequately. Administering two laboratory exercises on each topic would reduce the number of topics that could be covered in a semester.

## VI. Recommendations for Improving Delivery of Electronics Laboratories via Computer Simulation

A number of recommendations for improving computer-based laboratories were discussed during the qualitative data-gathering sessions during the semester. The suggestions ranged from having the students perform every lab twice, once in the hardware lab and once by computer simulation, to providing canned circuits that require the student to use troubleshooting techniques. As this research was focused on the question of using computer-simulated laboratories in situations where hardware lab equipment is not normally available, the recommendations enumerated here are suggestions to improve electronics laboratory courses delivered by computer simulation. Even so, many of the suggestions could be used in hardware laboratories as well as computer-based laboratories. Further, computer simulations—especially improved simulations—could be used to enhance the hardware laboratory experience. Despite Moslehpour's[7] report that there were no significant differences between students who used computer simulations to enhance their hardware lab experience and students who used only the hardware lab, the students in this research thought that "two labs were better than one." They judged that the computer simulation could be used to complement the hardware laboratories. Considering the results of this research and those of Moslehpour[7], one could speculate that it would be useful to combine the advantages of the computer simulation (ease of setup, exact measurements, reinforcement of theory) with the advantages of the hardware laboratory (hands-on experience, learning troubleshooting) to enhance the students' overall learning experience and to appeal to different learning styles.

The students offered many suggestions for improving computer-simulated laboratories, including ideas for providing some of the hardware experience to the computer user and ideas for enhancing the laboratory exercises themselves. Contrasted with students of five or ten years ago, most of today's students arrive at college with adequate skills to operate a computer. Most have had experience with the Microsoft Windows operating environment. For them, Electronics Workbench is just another applications program. On the contrary, electronics test equipment is not commonplace in the home or in secondary schools. To illustrate the issue, the "pre-lab" administered to the ET 1301 students was designed to give them experience in both laboratory environments before the start of data collection. The control and experimental groups completed the pre-lab exercise in their designated environments, then repeated the same exercise in the other environment. Both groups took approximately two hours—or one lab period—to complete the exercise the first time. During the repeated exercise, the hardware group that moved into the computer lab finished in about thirty minutes. Conversely, the experimental group that repeated the exercise in the hardware lab required almost two hours to repeat the exercise. (Note that the students did not have to recalculate the theoretical values, but they had to build the circuit, take the experimental measurements, and make the comparisons.) The hardware experience transferred easily to the computer, but the computer experience did not help much when the students were required to construct the circuit physically and to use the more complex laboratory equipment for the first time.

To help solve this problem, students who are using computer simulations should be provided hardware experience by some method. Expense and safety concerns preclude purchasing a suite of hardware laboratory equipment for each student. Other factors, such as time and geographical distance, often keep the student from coming to the hardware lab. In order for geographically remote students to receive some of the experiences of the hardware lab, the students who participated in the research offered several suggestions. Video information—in any of several motion and still formats—showing the use of hardware equipment and of actual hardware experiments could be provided. Remote students could receive kits of actual parts that could be assembled into working circuits. Finally, remote students could be required to gather in a hardware laboratory for a single day of intensive familiarization with the equipment.

This final suggestion would be feasible for students who were "not too remote" from the main campus. However, it would be impractical, or difficult without extensive coordination, to make hardware laboratories available for widely dispersed groups of students. Further, the quantitative research does not indicate that actual hardware experience is required. Nevertheless, the investigator and the students involved in the research believed that familiarization with the hardware laboratory, the equipment, and the components would be beneficial and should be used when possible.

Even if actual hardware laboratory experience were impossible, the students thought that the laboratory exercises themselves could be improved to make the computer-simulated exercises more like the hardware experience. These suggestions were generated in response to the qualitative data indicating that troubleshooting was better learned in the hardware laboratory. Students thought that the instructor should provide pre-built or canned circuits with faults inserted for certain laboratory exercises. The students would be required to troubleshoot and repair the circuit. The simulation software allows the instructor to insert faults and password-protect the changes to prohibit students from viewing the changes in the component-properties window. The students must make laboratory measurements to determine the faults.

The current research did not attempt to measure the differences between learning theory and learning troubleshooting. Yet one laboratory exercise incorporated troubleshooting—Laboratory 3 of the ET 1301 course. During this laboratory, the students were asked to determine values of "unknown" resistors. Included in the circuits were "short-circuited" and "open-circuited" resistors. In this case, the computer-simulated laboratory exercise incorporated the suggestion from above—canned circuits were provided to the students who were required to determine resistor values and the short-circuit and open-circuit faults. The difference in the mean posttest scores between the two groups following this laboratory was only 0.18 points out of 100. The results of this laboratory indicate that it should be possible to incorporate some of the hardware lab troubleshooting experience in computer-simulated laboratory exercises.

The advanced electronics students suggested that writing laboratory reports would be a helpful part of the learning experience. For these students, the research design constituted a major pedagogical change in laboratory procedures. They were accustomed to writing lab reports after completing their laboratory exercises rather than being subjected to multiple-choice posttest instruments. Laboratory reports force students to develop a different understanding of a laboratory exercise than does an instrument like the posttest quiz. While the research design necessitated changes from the usual, laboratory reports are normally required during electronics laboratory courses—whether the lab exercise is completed using computer simulation or hands-on lab equipment.

The discussion of lab reports adds an additional factor that has not been discussed previously because laboratory reports were not part of the research design. By default, Electronics Workbench uses ideal circuit components and nearly ideal test instruments, which give ideal answers for most measurements. This presents a problem when students are preparing lab reports. One of the major elements of a formal laboratory report is to explain the causes of differences between the theoretical (or ideal) values and the measured (or real) values. If the measured values are ideal, the student will not develop an understanding of component tolerances and non-ideal phenomena. To keep this from becoming a problem, Electronics Workbench offers devices with random tolerances, devices for which faults can be inserted, and instruments with less than ideal characteristics. Again, the instructor could provide canned circuits (or components and test equipment) with non-ideal characteristics for the students to use during any given lab exercise. Laboratory reports would then be based on explaining the differences between theoretical values and measured values—just as in the hardware laboratory where actual components and measuring equipment are used.

## VII. Implications of the Study

Curricula in electronics engineering technology are frequently billed as "hands-on" programs. Often, persons who like to work with their hands are attracted to an engineering technology degree program. Even so, the job market, especially the job market for engineering technology graduates, is requiring more computer-based design and problem-solving skills than ever before. At the same time, higher education is moving headlong into distance education—exploiting many of the means of delivering courses to the waiting public. Internet delivery of credit courses has wide appeal to potential students who, for a variety of reasons, cannot attend on-campus classes.

While some courses lend themselves easily to the Internet environment, electronics laboratory courses have always used expensive laboratory test and measurement equipment and actual circuit components to build and test circuits. Yet with computer simulations—especially those as sophisticated as the newer versions of Electronics Workbench (especially Multisim)—students can duplicate most, if not all, of the laboratory experience on their personal computers.

## VIII. Summary

The quantitative part of this research supports the conclusion of Clark[2] and others that media do not matter. Whether the laboratory exercises were conducted in the traditional hardware laboratory or in the computer laboratory using simulation software, students learned their lessons. Students who cannot attend laboratory classes on campus could take the same courses using computer simulation without fear that their experience or achievement would be somehow less than it would have been attending classes on campus. At the same time, the qualitative research has uncovered differences not explored by the quantitative research. Incorporating the recommendations garnered from the qualitative research—especially elements of both hardware and simulation—into the laboratory pedagogy should help improve students' experience regardless of the environment in which the laboratory is conducted.

Endnotes

[*] Recent versions of the Electronics Workbench simulation program overcome these slight difficulties. The older version installed in our computer laboratory during the conduct of the study was more than adequate for the DC circuits laboratory exercises.

[**] This opinion has been further corroborated during a separate qualitative analysis conducted during the summer of 1998. Electronics Workbench was introduced in an environment where non-credit electronics classes were being taught in a regional industrial plant. The students in those classes felt that the simulation software was extremely helpful in learning the theory that they were being presented in the classroom. In that environment, no hardware laboratory equipment was available.

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