ASEE 2022 ANNUAL CONFERENCE
Excellence Through Diversity
MINNEAPOLIS, MINNESOTA, JUNE 26TH-29TH, 2022 ASEE

Paper ID #37047

Development of Open-Source Comprehensive Circuit Analysis Laboratory Instructional Resources for Improved Student Competence

Sandip Das (Dr.)

Dr. Sandip Das is an Associate Professor in the Department of Electrical Engineering at Kennesaw State University (KSU). Dr. Das received his Ph.D. in Electrical Engineering from University of South Carolina, Columbia. His current research interests include photovoltaic solar cells for sustainable and renewable energy generation, semiconductor thin-films and nanocrystals for optoelectronic devices, hybrid piezo and triboelectric energy harvesting devices, applied electronics for measurement and instrumentation, and development of technology enhanced teaching tools and pedagogical framework for improved engineering education. Dr. Das has published more than 30 research articles in international journals and conference proceedings. He has designed and developed various hands-on teaching and learning tools for electrical engineering students. Dr. Das has lead several research projects as a Principal Investigator and has been funded by the Office of Undergraduate Research, Office of the Vice President for Research at KSU, and the U.S. Environmental Protection Agency. He has also led two projects for the development of open access laboratory instructional resources for Electronics and Circuit Analysis, funded by the Board of Regents, University System of GA.

Craig A Chin (Dr.)

Craig A. Chin, Ph.D. is currently an associate professor in the Electrical and Computer Engineering department at Kennesaw State University. His research interests include biomedical signal processing, machine learning, and engineering education.

Sheila Donehoo Hill

Over 25 years of teaching experience in Electrical Engineering and Electrical Engineering Technology, primarily Circuit Analysis and Electronics. Specializing in online/hybrid classes for the past five years.

Development of Open-Source Comprehensive Circuit Analysis Laboratory Instructional Resources for Improved Student Competence

Abstract:

Introductory Circuit Analysis laboratory exercises are critical for future student success in Electrical Engineering. Through circuit analysis labs, students are expected to grow and improve many important skills, such as being able to read and interpret written instructions, to recognize physical circuit components, to place those components properly on a breadboard and to build physical circuits by following circuit schematics. These labs will also serve to reinforce concepts and theories through experiments and enable students to apply the knowledge necessary to design circuits to meet specifications, followed by building and testing them. In addition, to accomplish these tasks in the lab, students must learn to operate different electronic power and measurement instruments. Over many semesters of instructional experience, we have observed that a significant proportion of students struggle to effectively translate and apply their understanding of electric circuit theories gained in the classroom environment to the practical lab environment. Students often struggle and display incompetence in building circuits correctly and in some instances, fail to complete experiments within the given time. As a result, the student learning experience and learning outcomes are adversely impacted. We believe that the main cause of such inefficiency and incompetence is the lack of preparedness to conduct experiments in the lab. In this work, we attempt to improve student competence and learning outcomes associated with ABET criterion 6 (an ability to develop and conduct appropriate experimentation, analyze, and interpret data, and use engineering judgment to draw conclusions) related to a Circuit Analysis lab at our university. We aim to achieve improved student learning through the development of enhanced comprehensive laboratory instructional resources including revised and redesigned lab-manuals, a series of virtual lab tutorials/audiovisual instructions to complement the written instructional materials, integrating industry-standard LTspice-based simulation exercises invoked through mandatory pre-laboratory exercises, developing lab exercises with more design emphasis, and creating lab datasheets to streamline and support efficient data collection process for students. In this funded project, all our developed resources will be open-sourced and made available to the public freely. In a pilot study, the enhanced lab instructional materials are implemented in two lab sections (treatment group) for four lab exercises. Two control lab sections are presented with the legacy lab materials. Instructional materials' quality and impacts are compared through a survey that solicits student perception of the lab learning experience. Details on the design of these comprehensive lab instructional resources and our observations on the improvement of student competence and learning outcomes are presented.

Introduction:

Engineering can be defined as the application of science and math to solve problems that often involve harnessing natural phenomena for the benefit of humanity. Proficiency in applying scientific and mathematical theories in the context of an engineering problem is not developed solely in a classroom environment, but through the practical, hands-on experiences that instructional laboratory exercises provide. For this reason, instructional laboratory exercises are an essential component of an undergraduate engineering program and are a key mechanism for satisfying ABET criterion 6: an ability to develop and conduct appropriate experimentation, analyze, and interpret data, and use engineering judgment to draw conclusions [1].

In electrical engineering programs, circuit analysis labs are designed to provide students with a variety of learning opportunities that a classroom environment will typically not support and to assist students develop many important skills relevant to the practice of the profession. Examples of specific skills taught in circuit analysis labs include:

1. Read and interpret technical documentation.
2. Recognize physical circuit components.
3. Build physical circuits by following circuit schematics.
4. Operate different electronic and power measurement instruments to measure circuit parameters.
5. Evaluate the validity/limitations of concepts and theories through experimentation.
6. Design circuits to meet specifications followed by building and testing them.

These skills are consistent with the fundamental objectives of engineering instructional laboratories [2].

Over many semesters of instructional experience, we have observed that a significant population of students struggle to effectively translate and apply their understanding of electric circuit theories gained in the classroom environment to the practical lab environment and fully develop the six skills identified in the prior paragraph. Students often struggle with interpreting instructions given in the lab manual, they have difficulty in correctly identifying physical circuit components and they display ineptitude in building physical circuits correctly given circuit schematic representations. They also struggle to operate measurement instruments correctly. The culmination of these difficulties results in some instances where students fail to complete experiments within the given time. This in turn has an adverse impact on the student learning experience and the attainment of the ABET student outcome.

We believe a major cause behind the inefficiency and ineptitude exhibited by some students is due to the lack of preparedness to conduct experiments in the lab. Another potential reason is the variability in the quality of instructors [3]. Adjunct instructors are often assigned the responsibility for teaching circuit analysis labs and there is usually a much higher turnover rate for these instructors. We aim to achieve improved student learning through the development of enhanced comprehensive laboratory instructional resources.

The enhancements efforts include:

1. Revision, redesign and rewriting of the lab manuals.
2. Creation of a series of virtual lab tutorials/audiovisual instructions to complement the written instructional materials.
3. Integration of industry-standard LTspice-based extensive simulation exercises invoked through mandatory pre-laboratory exercises.
4. Development of design-based lab exercises.
5. Creation of lab datasheets to streamline and support an efficient data collection process for students.

The benefits of using virtual lab tutorial videos prior to lab sessions are supported by empirical investigations [4-7]. The effectiveness of using online pre-laboratory activities, which included videos and quizzes, was investigated by instructors of an Organic Chemistry I laboratory course [4]. Student surveys revealed that the videos helped them to feel better prepared to conduct their laboratory experiment as well as helped them to better understand the concepts presented in the experiment. Students also indicated that the videos assisted them in linking laboratory topics to the topics of the Organic Chemistry I lecture course. Another group of researchers investigated the impact of integrating a series of instructional videos with the standard pre-laboratory student preparation presentations and instructor demonstrations for an Organic Chemistry laboratory course [5]. They observed that students who viewed these videos experienced greater learning gains and completed their experiments in less time compared to the control group. An additional group of researchers examined the effectiveness of adding pre-laboratory instructional materials through online videos to the general chemistry laboratory [6]. They found that students were more efficient and demonstrated greater understanding of the rationale for procedures for two laboratory activities that used online pre-laboratory videos than those that used pre-laboratory lectures. In the domain of circuit analysis, researchers investigated the impact of various teaching practices in both lecture and laboratory sessions [7]. For laboratory sessions, a key teaching practice was a series of instructional videos that helped students become familiar with lab equipment and lab procedures. The impact of the videos was assessed using a survey and student feedback indicated that most students found the videos to be helpful. Class assignments and test results also supported the effectiveness of the adopted teaching techniques.

Hand computations are important for the introduction of circuit analysis concepts, but proficiency in simulation packages is important for analysis of complex circuits where hand computations would be time consuming and potentially intractable. Empirical studies have demonstrated that circuit simulations have a positive impact on student learning and attitude. In one such investigation, researchers examined the impact of integrating simulation components into laboratory experiments of an analog electronics course [8]. They found that student grades as well as student attitudes towards the course improved compared to course sections that did not include the simulation components. In another study, investigators used a problem-based learning approach to lab design called CLABS [9-11]. This model used prelab exercises that included simulation and pre-calculation of values as well as laboratory exercises that tied concepts and theories to realistic projects. Survey evaluations show that the CLABS laboratory exercises were rated positively for all components of the model.

Student experiences in applying the engineering design approach is an essential part of an electrical engineering program and corresponds to ABET criterion 2. As a part of our enhancement efforts, we develop laboratory exercises that will incorporate the engineering design approach as well as emphasize practical applications of the theories that students learn in Circuit Analysis lectures. The benefits of using a design-based laboratory format compared to the more standard experimental analysis format is exemplified by the work done Limberis and Yao [12]. These investigators created a temperature alarm laboratory design project that consisted of multiple design stages and utilized operational amplifier circuitry. Assessment of the effectiveness of this laboratory project involved instructor assessments and student self-assessments. The results of these assessments indicate that the design project had a positive impact on student learning and motivation.

The previous three paragraphs illustrate that our enhancement efforts in the areas of virtual lab tutorials/audiovisual instructions, LTspice-based extensive simulation exercises and design-based lab exercises have been successful in improving student learning in prior investigations. Our contribution to efforts to enhance circuit analysis lab exercises is in the creation of exercises that feature an integration of these previously separate enhancements with the intent creating a student experience in which the overall enhancement to learning is cumulative.

The Legacy Circuits Labs:

The legacy circuit analysis lab exercises contain written instructions, pre-laboratory exercises, figures and circuit schematics. Most of these exercises do not include any audiovisual tutorials, nor are the learning outcomes clearly and consistently presented for each exercise. Student opportunities for design practice are extremely limited in the legacy exercises.

The legacy circuit analysis labs consist of the following topics:

1. Use of MATLAB and Calculator in Circuit Analysis
2. Introduction to LTspice
3. Introduction to Circuit Measurement Techniques
4. Constructing and Analyzing Series and Parallel DC Circuits
5. Designing DC Circuits to Specifications
6. Designing DC Circuits to Deliver Specified Power in a Multi-Node Circuit
7. Maximum Power Transfer via Thévenin's Analysis
8. The Superposition Theorem
9. The Oscilloscope and the Function Generator
10. Transient RC and RL Circuits
11. Phasors and Impedances Used to Understand RLC Circuits

Students begin to build physical circuits during the third lab exercise after learning to utilize mathematical and simulation software during the first two exercises. The lab instructions for lab exercises 3 – 11 contain Equipment lists, although the lists do not specify which items are available in the lab and which are the student's responsibility. Students are provided with a picture of new lab equipment when it is introduced for the first time: the digital multimeter and dc power supply during lab exercise 3 and the oscilloscope and function generator during lab exercise 9. There are no subsequent equipment pictures after they are introduced. Students are also provided with four breadboarded circuit example pictures within the instructions for lab exercise 3, when they build their first circuit. They are not provided with breadboard pictures in subsequent lab exercises.

The legacy lab exercises do not include student data sheets – the collection and organization of the data is determined by the student and their understanding of the lab exercise and its requirements. Pre-laboratory exercises include calculation of circuit parameters and general instructions for simulating the circuits in LTspice prior to attending the lab in person.

Design and Structure of the New Labs:

The major influential factor behind undertaking of this project is instructor experiences observing students struggling every semester in the circuits lab. It is also aligned with our university wide efforts to improve student Retention, Progression, and Graduation (RPG) rates. Development of the lab resources is an ongoing effort. We have developed about 40% of the new labs and anticipate completing this project by the end of summer with intended full implementation beginning fall 2022. Redesign or redevelopment of lab manuals are not new approaches to improve quality of lab instruction and student learning. There are many literatures available on such efforts at various universities [13-15]. However, our work is comprehensive in nature and geared toward the development of a fully open-source and publicly available repository.

Our action plan consists of four major tasks: (i) redesign and write new lab manuals and create datasheets, (ii) develop LTspice-based pre-labs and video tutorials, (iii) develop "design and application"-oriented labs with handouts, and (iv) create introductory videos for in-lab exercises. In task 1, our goal is to fully revise the legacy lab manuals and redesign, reorganize, and rewrite them. In this process, we applied coherent formatting among all labs for improved readability. In addition, we created Microsoft Word-based structured data entry forms for in-lab and pre-lab data collection, data analysis and lab report submission. Each datasheet is specifically designed for a specific lab and they contain electronic forms or tables for experimental data entry and performing data analysis. The datasheets provide students a well-designed template and allow students to quickly document their experimental results – essentially making the data collection process efficient and frustration-free. Simulation is an important skill for students in engineering and STEM disciplines [16-20]. In task 2, we developed LTspice-based pre-labs and new video tutorials. Most of the prelab exercises integrate the use of industry-standard LTspice circuit simulator along with hand calculations for circuit analysis. To help students quickly explore and easily learn the LTspice software, a series of LTspice video tutorials with closed captions have been developed. In task 3, we intend to develop two new lab exercises that have more emphasis on 'design' aspect. To enable students to perform these design-focused labs, handouts will be prepared to provide information on general design principles/strategies. In task 4, we are creating "intro" videos for each in-lab exercise to better prepare students for the in-lab exercises. These videos contain a quick review of theoretical background, information on laboratory equipment operations, best practices for reliable measurements, and data analysis methods.

Examples and Comparisons of Lab Exercises:

Here, we present couple of examples of redesigned lab exercises. The first example lab exercise intends to engage students in applying the engineering design approach to create a series-parallel DC circuit to the specification. The older lab exercise (legacy lab) required students to design the series-parallel circuit of Fig. 1 by selecting resistors to meet a load current specification and a maximum source current specification.

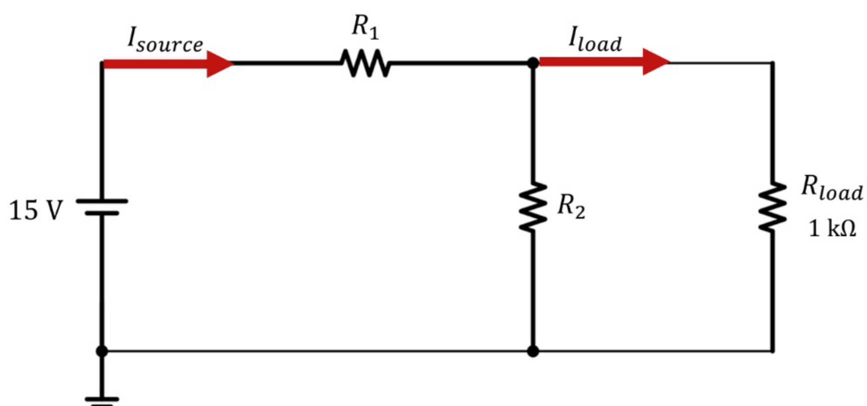

Figure 1. Schematic of Series-Parallel Combination Circuit.

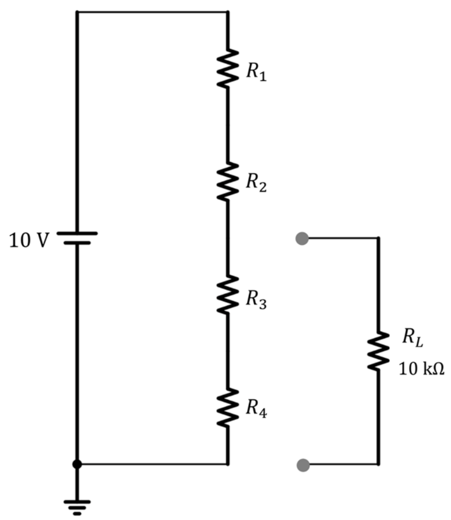

Figure 2. Voltage Divider Circuit.

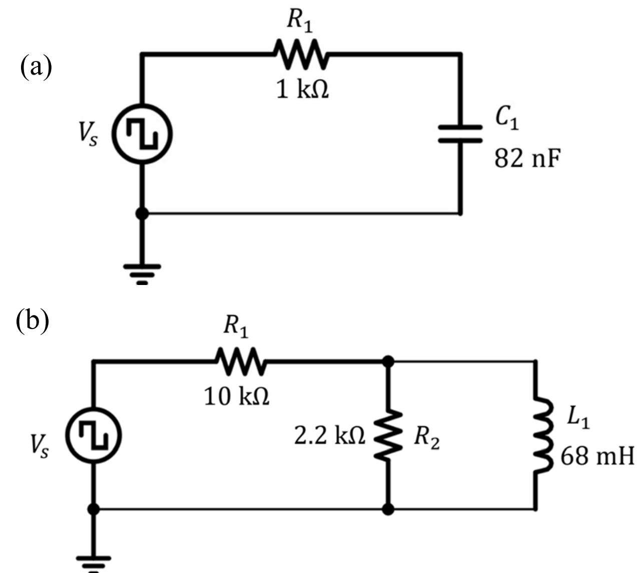

Figure 3. (a) Series R-C and (b) R-L Circuits.

Another example of lab enhancement is the addition of more directed prelab calculations and simulations to the transient circuit analysis lab exercise. In the legacy lab, the students are instructed to use a square wave to simulate transient conditions in resistive, R-L and R-C circuits as shown in Fig. 3. While the legacy instructions do include a prelab simulation component with detailed instructions, there are no analytical requirements prior to the lab exercise. The students are required to build the circuits and take measurements without a clear understanding of what to expect. The improved lab instructions provide a directed prelab that includes both LTspice simulation and analytical calculations, as well as separate datasheets for the prelab and lab exercise. Students are required to simulate all three circuits and calculate the voltage across the capacitor and inductor at different times during the charging and discharging phases of the components. Students are instructed to fill in the prelab values on their lab datasheet, providing feedback for them as they conduct the exercise in the lab.

Results and Discussions:

This research was conducted by three faculty members of the Electrical and Computer Engineering Department at Kennesaw State University who have several years of experience in teaching circuits lab at our institution. We have conducted this study on different lab sections taught by four different lab instructors in spring 22. Our assessment method comprised of a student survey for each lab exercise. Among the four lab sections, two sections were chosen to implement the new lab instructional resources and the other two sections were chosen to implement the legacy lab resources. All students were given an opportunity to earn extra credits through two different options – either by taking a lab quiz at the end of the semester or by taking the lab surveys after completing each lab. Total 47 students participated in the surveys, out of which 16 students were subjected to the legacy lab resources and 31 students were subjected to the new lab resources. We have implemented five new labs during the pilot run in spring 2022 semester and here we report the results based on these five labs. These five labs are – (i) Introduction to Circuit Measurement

Techniques, (ii) Constructing and Analyzing Series and Parallel DC Circuits, (iii) Designing DC Circuits to Specifications, (iv) Designing DC Circuits to Deliver Specified Power in a Multi-Node Circuit, and (v) The Superposition Theorem. Paper-based surveys from the participating students were collected and their responses to the survey questions were analyzed to evaluate the student perception and effectiveness of the newly developed lab instructional resources in comparison with the legacy labs. Our results show clear trend of improvements for the newly developed labs in comparison to the legacy labs as presented in the following sections. The set of survey questions used for this study are listed in Table 1 below:

Table 1: Survey Questionnaire

Q 1	The lab manual was well written and was easy to follow.
Q 2	The instructions in the lab manual were clear on how and where to document my experimental and/or simulation results to prepare the lab report.
Q 3	I had a clear idea about the lab objectives, what to expect and what to do before coming to the in-person lab.
Q 4	There was a pre-lab exercise and the pre-lab helped me to better prepare for the in-lab, hands-on lab exercise.
Q 5	**If** a student answered 'NA' for Q 4, then the student was asked Q 5(a) **(a)** There was no pre-lab exercise. I believe, a small pre-lab exercise would help to familiarize me with the lab topic and prepare me better for the in-lab, hands-on lab exercise. **Else**, the student is asked Q 5(b) **(b)** The LTspice simulations in the pre-lab were helpful to get a clear understanding of the lab objectives and what to expect in the hands-on lab session.
Q 6	There was/were tutorial video(s) associated with this lab, and these helped me to be better prepared for the in-lab, hands-on lab exercise.
Q 7	**If** a student answered 'NA' for Q 6, then only the student is asked Q 7 I believe, providing a quick tutorial/intro video regarding this specific lab would be helpful to familiarize me with the lab topic and could prepare me better for the in-lab, hands-on lab exercise.

The demographic distributions (gender and ethnicity) for the participating students are shown in Fig. 4. The lab sections for 'treatment' and 'control' groups were chosen arbitrarily. It turned out that the treatment group (who were subjected the new labs) had a much higher minority population (about 80%) compared to the control group (37.5%). The survey questions were accompanied with the standard options of 'Strongly Agree', 'Somewhat Agree', 'Neutral', 'Somewhat Disagree', 'Strongly Disagree', and 'N/A'. For easy quantitative analysis purposes, integer numbers or points were assigned to each of these response options. 'Strongly Agree' was assigned 5 points, ‘Somewhat Agree’ was assigned 4 points and similarly the other options were assigned points in descending order. ‘N/A’ was assigned a ‘0’.

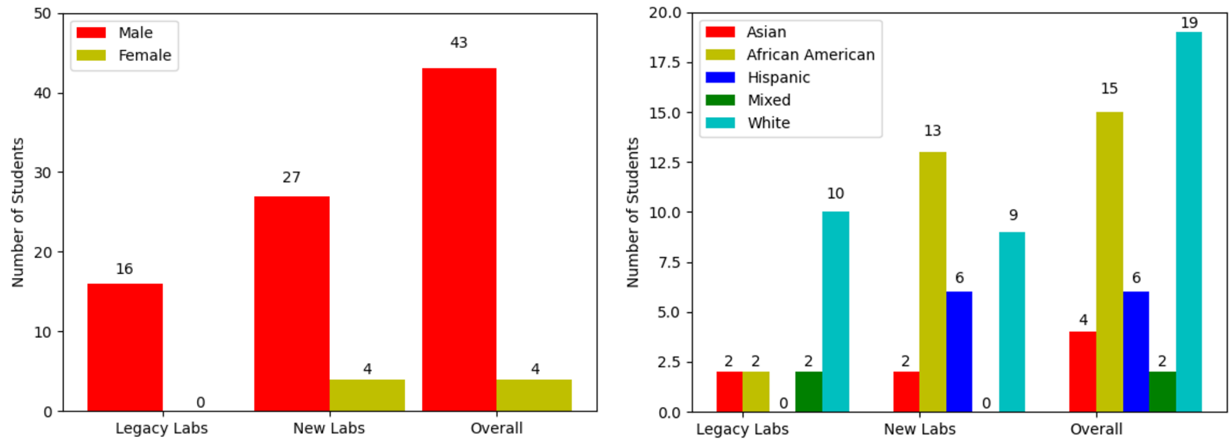

Figure 4. Demographics of the Students.

We have collected survey responses from both ‘treatment’ and ‘control’ groups for all of the above-specified five new hands-on labs this semester during our pilot runs. Survey data for these new labs were collected and compared with the legacy labs. The mean for each survey question was computed for both legacy and new labs (i.e. control group and the treatment group). The result is presented in Fig 5.

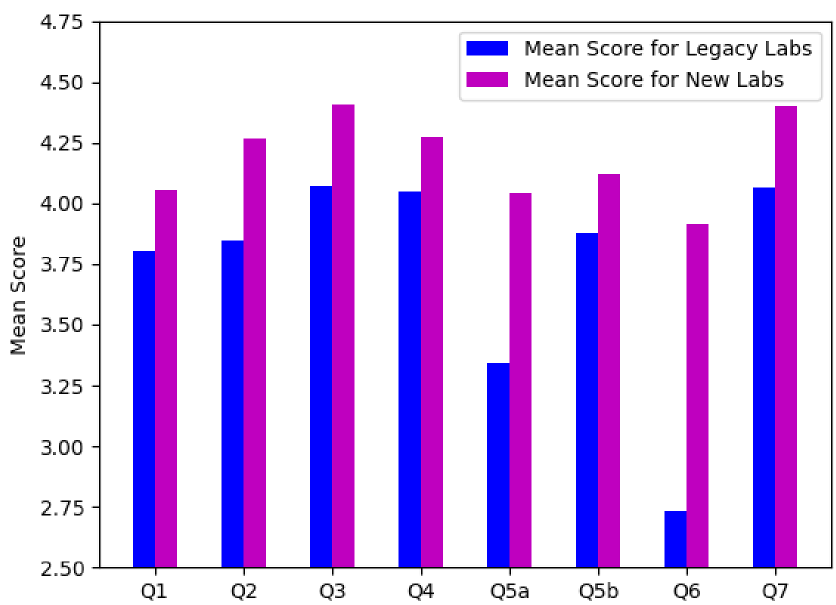

Figure 5. Survey Response Results.

It is evident that for all questions from Q1 to Q7, the mean scores are higher for the new labs compared to the legacy labs. For Q1–Q4, the improvements in average scores are 0.247 points, 0.42 points, 0.337 points, 0.225 points, 0.708 points, 0.242 points, 1.79 points and 0.336 points, respectively. These values correspond percentage increases of 6.5%, 11%, 8.3%, 5.6%, 20.9%, 6.2%, 43% and 8.3%, respectively. Q1 and Q2 responses reflect that students found the new lab manuals easier to follow, which provided clear guidance to the students on how and where to document their experimental and/or simulation results.

This demonstrates that our task 1 strategy is successful and implementing lab-specific customized 'datasheets' are highly effective in providing better guidance to the students. Q3 and Q4 responses indicate that students subjected to the new lab resources had more clear ideas about the lab objectives and what to do in the lab before coming to the in-person lab sessions. This demonstrates that our task 2 strategy worked well, which integrated LTspice-based pre-labs that played helpful role in preparing the students. Strategically designing pre-labs with LTspice simulations have multi-fold benefits. Students work throughout the week before performing the hands-on lab work which keeps them more engaged with the lab related activities. Through the pre-labs they get to thoroughly practice various theoretical aspects of a lab exercise and reinforce their lecture knowledge even before doing the hands-on labs. The newly designed and redesigned pre-labs with integrated LTspice simulations act as a bridge between the theory learned in the lecture classes and the hands-on lab experiments – thus better preparing the students for the in-lab experiments. In addition, they obtain experience of using an industry-standard simulation software which is a highly marketable skill for the industry. Through the simulations, they also verify their analytical hand calculations, which boosts their confidence level. Furthermore, the LTspice simulation-based validation steps in the prelab helps to reduce students' errors by allowing them to double check any possible mistakes in their hand-calculations. Q5 response results attest the fact that the newly designed prelab exercises are valued more by the 'treatment' group as they experienced the benefits of the pre-labs more than the 'control' group. A significantly higher (21%) score for Q5(a) is a signature that evidences the positive impacts of our newly designed pre-labs. Responses of Q6 indicate that our task 4 strategy to introduce tutorial videos have contributed to significantly improve student learning and their lab experiences. Unlike the LTspice simulations, the tutorial

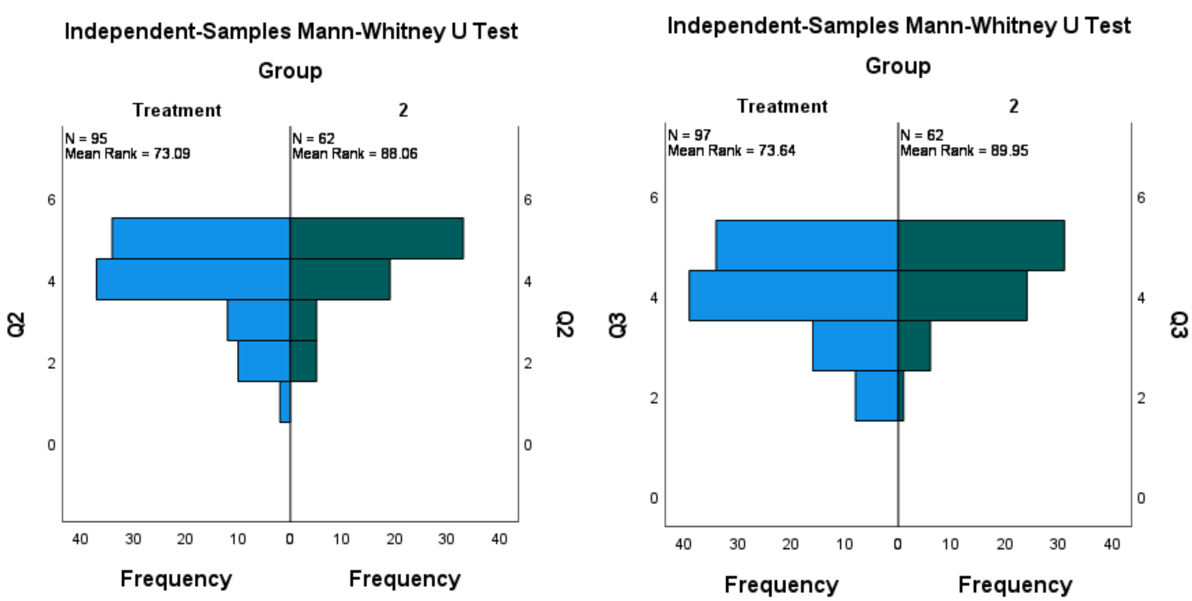

Figure 6. (left) Frequency Plots for Legacy and New labs for Q2 and, (right) Frequency Plots for Legacy and New labs for Q3.

videos provided further details concerning the experimental aspects to help students to translate the theoretical knowledge easily to circuit building and in-lab measurements using benchtop instruments. Out of the five labs studied in this work, we have introduced videos targeting three lab exercises to the ‘new lab’ sections. It is evident from the 43% higher score for Q6 that these short video tutorials had major impacts on the ‘new labs’ students unlike the ‘legacy labs’ students who were subjected to the older instructional resources comprised of only couple of older videos with no direct link to a specific lab exercise. Q7assesses the students’ perception of the benefits of adding audio-visual resources in the lab instructions. The results show that both the control group (legacy lab students) and the treatment group (new lab students) have strong feelings on the usefulness of video tutorials to teach and prepare them better for the hands-on labs.

In addition to these analysis, Mann-Whitney U tests were conducted to assess and get more insight on the differences between legacy and new lab respondents for Q1 – Q7. A significant difference was observed for Q2 (U = 3506.5, p = .031), Q3 (U = 3624.0, p = .019), Q5b (U = 1843.0, p = .044), and Q6 (U = 233.5, p = .028). The frequency plots for Q2, Q3, Q5b and Q6 are shown in Fig. 6 and Fig. 7, respectively.

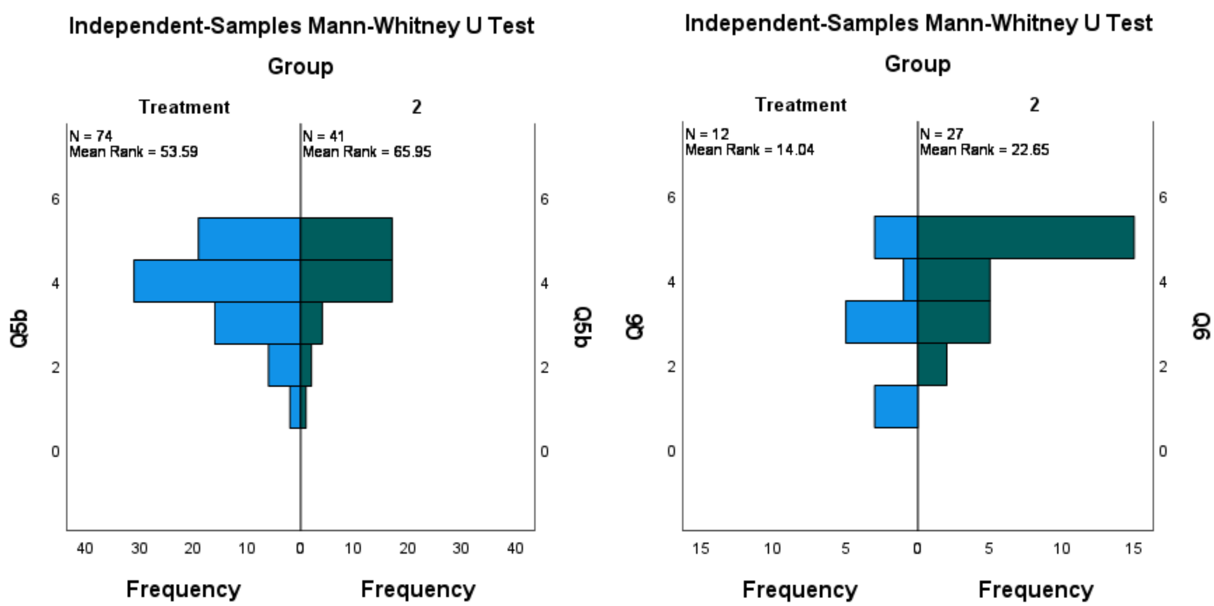

Figure 7. (left) Frequency plots for Legacy and New labs for Q5b, and (right) frequency plots for Legacy and New labs for Q6.

In addition to the student survey, faculty experience and perception was recorded from the faculty who had the experience of teaching the legacy circuits labs with the older instructions (in previous semesters) as well as teaching with the newly developed lab resources this semester. The faculty faced much less numbers of ‘what to’ and ‘how to’ questions in the lab and had a smoother lab running experience with the new lab instructional resources implemented. There was less confusions among students in the lab. Also, students acted more confidently when any difficulty was faced in the lab or a wrong measurement result was obtained. They immediately recognized wrong measurement data, thanks to the newly developed pre-lab exercises and in many instances, they took self-driven successful corrective actions when such situations were encountered.

Conclusions:

In summary, our comprehensive development of introductory circuit analysis lab resources is proving to be a great improvement over the previous learning resources. With the pilot run this semester using five new labs, we have already noticed reduced amount of student frustration, fewer how-to questions during the lab sessions, faster and more streamlined in-lab data collection by students without much confusion, better simulation skills using LTspice and a more pleasant lab experience by students, as well as the lab instructor. Our survey results indicated an overall improvement in every aspect. Notably, our treatment group was comprised of a large number of students from underrepresented minority backgrounds who have historically showed lower success rates or higher 'D', 'W', 'F' rates. A considerable improvement of this student population can therefore make a big difference for the overall student success rate. We conclude that similar comprehensive approach can be developed and implemented for many other introductory undergraduate electrical engineering courses at other institutions. Our fully developed lab resources will be open-sourced and made publicly available at the end of the summer and full implementation will commence in fall 2022.

Acknowledgements:

The comprehensive lab instructional resource development discussed in this paper have been carried out with funding support from the Georgia Board of Regents through Affordable Learning Georgia, Affordable Materials Grant #M166. The authors would also like to acknowledge the lab instructors, Dr. Tete Tevi, Dr. Walter Thain, Prof. Charles Duvall, and Prof. Caroline Cranfill, who have helped in taking and collecting student surveys throughout the spring 2022 semester.

References:

[1] L. D. Feisel and A. J. Rosa, "The Role of the Laboratory in Undergraduate Engineering Education", *J. Eng. Educ.*, vol. 94, no. 1, pp. 121–130 (2005).

[2] L. D. Feisel and G. D. Peterson, "A colloquy on learning objectives for engineering education laboratories", 2002 ASEE Annual Conference, Montreal, Canada. doi: 10.18260/1-2--11246.

[3] T. Kotulski and S. Murray, "The national engineering laboratory survey", (2010).

[4] J. L. Chaytor, M. Al Mughalaq, and H. Butler, "Development and Use of Online Prelaboratory Activities in Organic Chemistry To Improve Students' Laboratory Experience", *J. Chem. Educ.*, vol. 94, no. 7, pp. 859–866, (2017).

[5] L. S. Nadelson, J. Scaggs, C. Sheffield, and O. M. McDougal, "Integration of Video-Based Demonstrations to Prepare Students for the Organic Chemistry Laboratory", *J. Sci. Educ. Technol.*, vol. 24, no. 4, pp. 476–483 (2015).

[6] M. Stieff, S. M. Werner, B. Fink, and D. Meador, "Online Prelaboratory Videos Improve Student Performance in the General Chemistry Laboratory", *J. Chem. Educ.*, vol. 95, no. 8, pp. 1260–1266 (2018).

[7] Y. Lin and T. D. Morton, "Novel Practices in Teaching Circuit Analysis in an EET Program", *2013 ASEE Annual Conference and Exposition*, Atlanta, Georgia. doi: 10.18260/1-2--22316.

[8] K. B. Baltzis and K. D. Koukias, "Using Laboratory Experiments and Circuit Simulation IT Tools in an Undergraduate Course in Analog Electronics", *J. Sci. Educ. Technol.*, vol. 18, no. 6, pp. 546–555 (2009).

[9] M. Mehrübeŏlu, F. Attarzadeh, and D. Gurkan, "Comparative evaluation of laboratory teaching in an AC circuit analysis course", *39th IEEE Frontiers in Education Conference*, 2009. doi: 10.1109/FIE.2009.5350432.

[10] F. Attarzadeh, "Innovations in Laboratory Development for Computer Engineering Technology Programs", *Technol. Interface J.*, vol. 9, no. 1 (2008).

[11] D. Gurkan, F. Attarzadeh, D. Benhaddou, V. Gallardo, and S. Chacón, "Learning-Centered Laboratory Instruction for Engineering Technology", 2006 GSW *Conference*. doi: 10.18260/1-2-620-38855.

[12] L. Limberis and J Yao, "Temperature Alarm Laboratory Design Project for a Circuit Analysis Course in a General Engineering Curriculum", *2011 ASEE Annual Conference and Exposition*, Vancouver, BC. doi: 10.18260/1-2--18685.

[13] A. Kaur and T. Swift, "Structured Redesign of a Circuits Laboratory", *2019 ASEE Midwest Section Conference*, Wichita, KS. https://peer.asee.org/33926.

[14] J. A. Reising, "Sophomore Circuits Course Sequence Revision: An Integrated Laboratory/Lecture Approach", *2000 ASEE Annual Conference*, St. Louis, Missouri. doi: 10.18260/1-2--8703.

[15] C. Choi, "An Introductory Laboratory Course for Electrical Engineering Majors", *2017 ASEE Annual Conference & Exposition*, Columbus, Ohio. doi: 10.18260/1-2--27583.

[16] A. J. Magana, G. S. Coutinho, "Modeling and simulation practices for a computational thinking-enabled engineering workforce", *Computer Applications in Engineering Education*, vol. 25, pp. 62–78 (2017).

[17] S. Solmaz, J. L. D. Alfaro, P. Santos, P. V Puyvelde, and T. V Gerven, "A practical development of engineering simulation-assisted educational AR environments", *Education for Chemical Engineers*, vol. 35, pp. 81–93 (2021).

[18] S. Das, "Design and Implementation of MATLAB-Simulink Based Solar Cell Modeling and PV System Design Exercises for Advanced Student Learning", *2018 ASEE Annual Conference & Exposition*, Salt Lake City, Utah. doi: 10.18260/1-2--30263.

[19] I. Rahman, and M. Johari, "Students' understanding and skills on voltage and current measurements using hands-on laboratory and simulation software", Education and Information Technologies (2022). doi: 10.1007/s10639-022-10890-3.

[20] D. Ibrahim, "Engineering simulation with MATLAB: improving teaching and learning effectiveness", Procedia Computer Science, vol. 3, pp. 853-858 (2011).