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Enhancing Student Learning through Simulation-Integrated Laboratories in Electrical Engineering Education

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Laboratory work is a core part of electrical engineering education, but many traditional lab formats tend to focus more on following procedures than on building real understanding and analytical thinking. This paper introduces and evaluates a different approach simulation-integrated lab framework implemented in two undergraduate courses: a junior-level Analog Electronics course and a senior-level Power Electronics course.

In this approach, circuit simulations are not just used after the experiment for verification. Instead, they are built into the pre-lab process as a required step. Students use simulations to predict circuit behavior, guide design decisions, and prepare for troubleshooting before they ever touch the hardware. During the lab, these simulations serve as a reference point to help students diagnose issues more systematically.

Survey data from 84 students across both courses show clear benefits. Students reported stronger conceptual understanding, better alignment between theory, simulation, and real measurements, and increased confidence when working with complex circuits. Most students also observed good agreement between simulated and experimental results and found simulations especially useful for identifying design mistakes, component issues, and implementation errors.

In addition, student feedback highlighted better preparation going into lab sessions, less reliance on trial-and-error debugging, and a stronger connection between mathematical analysis and real-world circuit behavior. Overall, the results suggest that incorporating structured pre-lab simulations can significantly improve learning outcomes and practical skills without requiring additional lab time or resources. The framework also proved effective at both junior and senior levels, making it a strong candidate for broader use across the electrical engineering curriculum.

1. Background and Related Work

Laboratory instruction has always been a key part of engineering education, especially in electrical engineering, where students must connect mathematical theory to real physical systems. Research consistently shows that effective labs should go beyond following steps; they should build conceptual understanding, encourage inquiry, and develop practical skills like measurement, data analysis, and troubleshooting [1], [2]. However, many traditional lab formats still emphasize completing procedures correctly rather than understanding why a system behaves the way it does. As a result, students often focus on getting the “right” answer without fully grasping the underlying concepts [3].

To improve this, educators have explored several approaches, including pre-lab activities, guided inquiry, and virtual or remote labs [4], [5]. Well-designed pre-lab work can make a meaningful difference students come in more prepared, spend less time on setup, and engage more deeply during the lab [6]. Studies show that structured preparation helps students enter clearer goals and work more efficiently [7]. That said, the impact of pre-lab activities depends heavily on how well they are designed and how closely they align with course objectives [8].

Simulation tools, especially SPICE-based circuit simulators, are now widely used in electrical engineering education [9]. They allow students to visualize circuit behavior, test different parameters, and explore non-ideal effects that are hard to observe in physical hardware alone [10]. Research shows that simulation can strengthen conceptual understanding and support more exploratory learning [11]. However, when simulations are treated as optional or separate from the main lab experience, students may see them as idealized and disconnected from real-world measurements [12].

There has also been growing interest in virtual labs and fully simulated experiments [13],[14]. While these approaches offer benefits such as accessibility and scalability, research continues to highlight the importance of hands-on experience for building practical skills, engineering judgment, and confidence in troubleshooting [15]. Because of this, hybrid approaches where simulation and physical experimentation are intentionally combined are gaining attention [16].

Even with these developments, there are still gaps in how theory, simulation, and hardware are integrated in core electrical engineering courses. In many cases, simulations are used only after experiments, mainly to confirm results, which limit their value as predictive and analytical tools [17]. In addition, relatively few studies provide clear evidence linking simulation-based preparation to improvements in both learning outcomes and student confidence, particularly in upper-level circuits courses [18].

This paper addresses these gaps by embedding structured, required simulation activities directly into the pre-lab workflow. Instead of treating simulation as an add-on, it becomes a central part of how students prepare, think, and reason about experiments. Using multiple assessment measures, this study shows that simulation-integrated labs can improve conceptual understanding, reduce experimental errors, and increase student engagement.

The study focuses on the following questions:

1. Does required pre-lab simulation improve students' understanding of circuit behavior?
2. Does simulation-based preparation increase confidence and troubleshooting ability in the lab?
3. Are these benefits consistent across both junior- and senior-level courses?

This work evaluates student perceptions of the simulation-integrated approach and does not attempt to measure causal learning gains against a control group.

2. Course Context and Laboratory Structure

The simulation-integrated laboratory framework described in this study was implemented in two undergraduate electrical engineering courses at different stages of the curriculum: a junior-level Analog Electronics course and a senior-level Power Electronics course. Applying the same approach across both courses made it possible to evaluate its effectiveness under varying levels of technical complexity, student experience, and application focus.

2.1 Analog Electronics Course Context

The Analog Electronics course is a core junior-level class that focuses on the analysis and design of analog circuits, helping students connect device-level behavior to overall system performance. The course covers key topics such as diode circuits, bipolar junction transistors (BJTs), MOSFETs, operational amplifiers, current sources, and differential amplifiers.

The laboratory component is project-based and emphasizes hands-on design, construction, testing, and analysis of circuits. Students work in a dedicated lab space equipped with standard instruments, including oscilloscopes, function generators, power supplies, and digital multimeters.

Lab assessment is structured in three parts. First, students complete pre-lab work that includes hand calculations and SPICE-based simulations to predict circuit behavior and define expected performance. This ensures that lab time is used efficiently for building and testing rather than initial design. Second, students complete a lab check-off, where their circuits are evaluated for design accuracy, build quality, and signal integrity. During this step, students are also expected to explain their design choices and interpret their measurements, reinforcing conceptual understanding. Finally, selected projects require formal written reports, which are graded based on technical accuracy, clarity, and completeness.

Over the fifteen-week semester, students complete five design projects. Each project follows a three-week cycle: the first week focuses on design and simulation, the second on hardware implementation and testing, and the third on data analysis and report preparation.

2.2 Power Electronics Course Context

The senior-level Power Electronics course builds on students' prior knowledge of circuits and electronics, with a focus on energy conversion, switching behavior, and system-level performance.

The course is organized into three main parts. The first introduces core concepts such as power electronic systems, harmonic analysis, semiconductor devices, and gate-drive circuits. The second focuses on controlled power converters, including DC–DC and DC–AC systems, common converter topologies (such as buck, boost, and buck–boost), PWM control techniques, basic inductor design, and single- and three-phase inverters. The third part covers rectifiers and SCR-based converters, including AC–DC rectifiers, AC–AC voltage controllers, and back-to-back converters, along with selected emerging topics to expose students to real-world applications.

The laboratory structure mirrors that of the Analog Electronics course. Students are required to complete analytical calculations and simulations before entering the lab, ensuring that experiments are guided by prediction and understanding rather than trial and error.

2.3 Common Laboratory Structure Across Courses

Using a consistent laboratory framework across both courses helped students develop a structured and repeatable approach to experimental work. In both settings, simulations were treated as predictive tools used before the lab, not just as a way to verify results afterward. This approach reinforced good engineering habits and allowed for meaningful comparisons of student experiences across different course levels.

Overall, the results demonstrate that the simulation-integrated laboratory model is both scalable and effective across the undergraduate electrical engineering curriculum.

2.4 Survey Data and Collection Timing

Survey data for this study were collected from multiple course offerings, including Fall and Spring sections of the Analog Electronics course and a Fall offering of the Power Electronics course. Due to scheduling constraints, surveys were administered at slightly different points in the semester, meaning that some students responded before completing the full set of laboratory activities.

Despite this variation, all course sections followed the same simulation-integrated framework. For analysis, responses from all sections were combined into a single dataset, since the instructional approach was consistent across offerings.

3. Assessment and Results

Student perceptions and learning outcomes are associated with the simulation-integrated laboratory approach evaluated using survey responses collected across both courses. In the Power Electronics course, 38 out of 42 enrolled students completed the survey. In the Analog Electronics course, 23 out of 23 students responded in the fall semester, and 23 out of 28 students responded in the spring semester. This resulted in a total of 84 survey responses across all course offerings.

The survey was designed to capture multiple aspects of the student experience, including perceived learning benefits, alignment between simulation and experimental results, confidence in troubleshooting, and overall laboratory effectiveness. It included:

- Categorical questions (Q1–Q5) evaluating the usefulness of simulation, agreement between simulation and hardware results, and the effectiveness of pre-lab preparation

- Likert-scale questions (Q6–Q7) assessing the role of simulation in troubleshooting and its impact on student confidence
- Open-ended questions (Q8–Q9) to gather qualitative feedback on learning gains and areas for improvement

Results are presented in aggregate due to the consistent implementation of the simulation-integrated framework across all sections. While survey timing varied slightly between semesters, this is noted as a potential influence on student responses.

3.1 Impact of Pre-Laboratory Simulation on Learning

Students were asked whether completing simulations before the lab improved their understanding of the experiments. The responses indicate a strong positive impact.

- 73% of students (62 respondents) reported that simulations significantly improved their understanding
- 27% (23 respondents) reported a moderate improvement
- No students reported a negative impact

These results suggest that students saw simulation as a valuable part of the design process rather than just a required step. The consistently positive feedback indicates that students entered the lab with clearer expectations and greater confidence in their circuit designs.

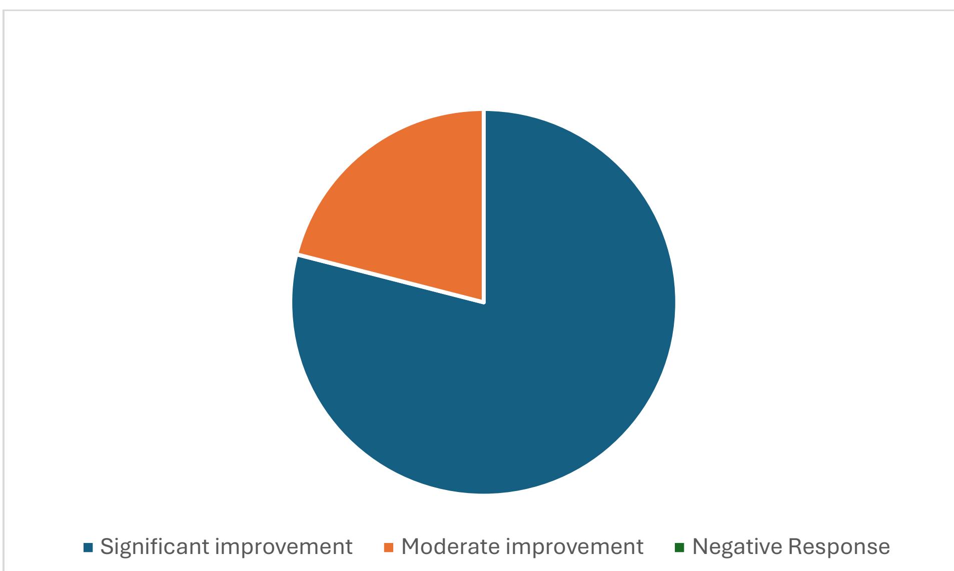

Fig1. Perceived learning improvement

3.2 Agreement Between Simulation and Experimental Results

Students were also asked how closely their experimental measurements matched their simulation predictions. Overall, the responses show strong agreement between simulated and measured results.

- 84% of students reported that measured values were within 30% of simulated values
- 11% reported differences in the range of 30–50%
- Only 5% reported deviations greater than 50%

A similar pattern was observed when comparing theoretical predictions with experimental outcomes, further reinforcing the role of simulation as a practical and reliable predictive tool—not just an idealized model.

These findings indicate that simulation-based preparation helped students develop realistic expectations of circuit behavior. It also supported their ability to interpret discrepancies caused by non-ideal components, measurement limitations, and implementation challenges.

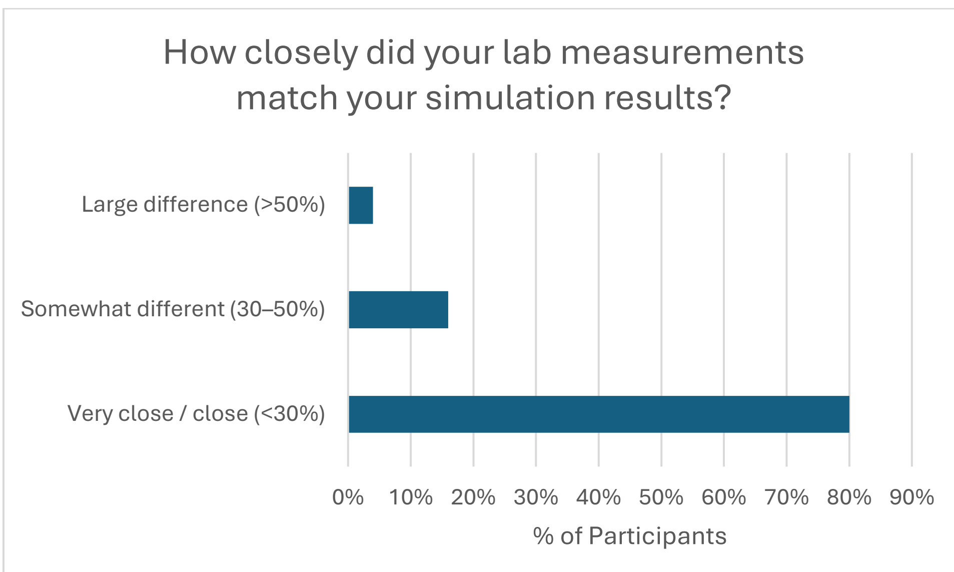

Fig 2. Simulation vs. hardware agreement

3.3 Troubleshooting and Confidence

Students were asked to rate how useful simulation was for troubleshooting (Q6) on a scale from low to high. Responses were heavily concentrated at the upper end, with most students selecting ratings between 7 and 10. As shown in Fig. 3, only a small number of students viewed simulation as minimally helpful. Survey responses also point to clear improvements in both confidence and troubleshooting ability. Many students reported that simulations helped them determine whether issues were caused by design decisions, incorrect component values, or physical implementation errors. Several noted that simulation made it easier to identify wiring mistakes or incorrect parameter selections early, allowing lab time to be spent more efficiently on analysis rather than trial-and-error debugging.

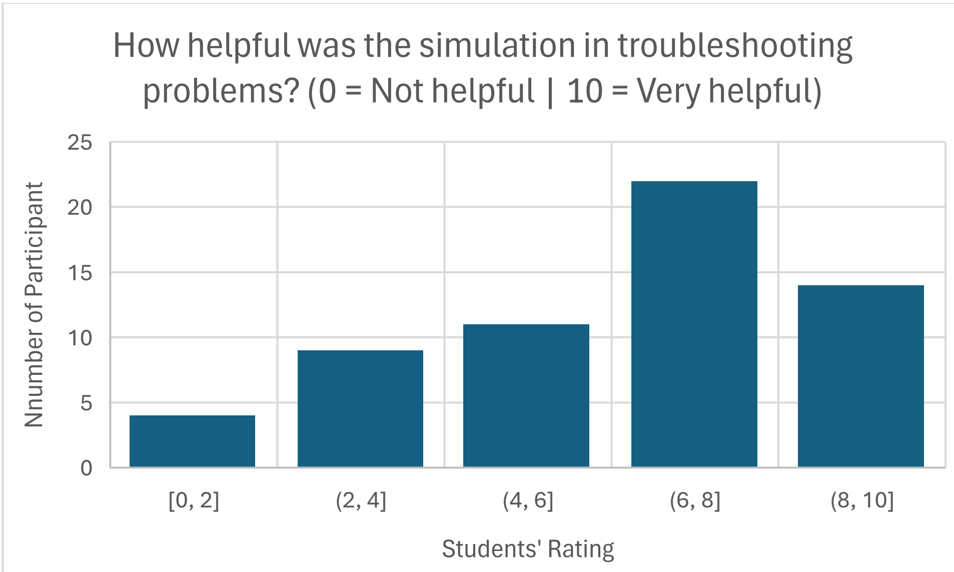

Fig3. Troubleshooting usefulness

This increase in confidence was especially noticeable in the Power Electronics course, where switching behavior and non-linear effects can be difficult to interpret without prior exposure. Overall, the response distribution suggests that students were actively using simulation during the lab—not just beforehand—to diagnose issues, verify assumptions, and isolate the root causes of unexpected behavior. Instead of relying on guesswork, students used simulation as a structured tool to guide troubleshooting.

To evaluate broader learning outcomes, students were also asked to rate their confidence in interpreting differences between theoretical predictions, simulations, and real hardware after completing the lab (Q7). Responses again clustered toward the high end, with most students reporting confidence levels between 7 and 10.

These results indicate that the simulation-integrated approach supported more than just task completion—it helped students develop a deeper understanding of circuit behavior. In particular, students reported greater confidence in reasoning across theory, simulation, and physical implementation, which is a critical skill in engineering practice.

3.4 Qualitative Student Feedback

Open-ended responses provided additional insight into how students experienced the simulation-integrated labs. Several consistent themes emerged:

- **Improved preparedness:** Students reported entering the lab with a clearer understanding of expected waveforms, operating points, and performance metrics
- **More efficient troubleshooting:** Simulations were frequently used as a reference when diagnosing differences between expected and measured results
- **Stronger conceptual connections:** Many students noted that simulations helped bridge the gap between mathematical analysis and real circuit behavior

Representative comments included:

- "Having a basis of results to compare against made it much easier to troubleshoot."
- "The simulation helped me understand what was actually happening in the circuit before building it."
- "Being able to change component values in simulation helped me predict how the circuit would behave in the lab."

Students also offered constructive suggestions, such as improving clarity in pre-lab instructions, incorporating more design-focused experiments, and providing additional guidance for more complex simulations.

3.5 Summary of Findings

Overall, the survey results show that integrating structured simulations into the laboratory workflow had a strong positive impact on student learning, confidence, and engagement. Students reported better alignment between theory, simulation, and experimental results, along with more efficient and effective use of lab time.

These benefits were consistent across both the junior-level Analog Electronics course and the senior-level Power Electronics course. That said, some differences in emphasis emerged: Power Electronics students more often highlighted the role of simulation in troubleshooting complex, non-linear behavior, while Analog Electronics students tended to emphasize improved conceptual understanding during the design phase.

Together, these findings suggest that the simulation-integrated approach is effective across multiple levels of the electrical engineering curriculum and supports both conceptual learning and practical skill development.

4. Limitations and Discussion

This study has several limitations that should be considered when interpreting the results. First, the findings are based on self-reported survey data rather than direct measurements of learning outcomes. While these responses provide valuable insight into students' perceptions, they may not fully capture actual conceptual gains.

In addition, the study does not include a control group, which limits the ability to directly compare students who used simulation-integrated preparation with those who did not. The sample is also drawn from a single institution, which may limit how broadly the results can be generalized.

Survey timing varied across course offerings, with some responses collected before students completed the full set of laboratory activities. Although similar trends were observed across both the Analog Electronics and Power Electronics courses, results were analyzed in aggregate, and differences related to course level or survey timing were not examined in detail.

5. Discussion and Implications

Despite these limitations, the results consistently indicate that embedding structured, required simulation activities into the pre-laboratory workflow has a positive impact on student learning and engagement. Across both junior- and senior-level courses, students reported that simulations improved their ability to design circuits, interpret experimental results, and troubleshoot effectively.

One of the key findings is that students began to view simulation as a tool for design and reasoning, rather than simply a way to verify results after the fact. By completing simulations before entering the lab, students were encouraged to make predictions and test their understanding in advance. This approach more closely reflects real engineering practice and contrasts with traditional lab models that focus primarily on following procedures.

The strong agreement between simulation predictions and experimental results further supports the value of simulation as a practical and reliable tool. At the same time, differences between expected and measured outcomes created meaningful learning opportunities. These discrepancies prompted discussions about non-ideal components, tolerances, and measurement limitations, helping students develop a more realistic understanding of circuit behavior.

High ratings for troubleshooting usefulness and post-lab confidence suggest that this approach also supports the development of professional skills. Students reported increased confidence in diagnosing problems and explaining system behavior, indicating growth in higher-level competencies such as analysis, problem-solving, and experimental reasoning.

Qualitative feedback reinforces these findings. Students highlighted that simulations reduced uncertainty and made lab time more efficient. Instead of relying on trial and error, they were better prepared to identify likely sources of error and focus on analysis. At the same time, feedback requesting more guidance, particularly in early stages suggests that structured support is important when introducing simulation-based workflows, especially in lower-level courses.

Overall, the results suggest that simulation-integrated laboratories can improve learning outcomes without requiring additional lab time or resources. This approach aligns well with ABET outcomes related to problem-solving, experimentation, and the effective use of modern engineering tools. Maintaining a consistent structure across courses also helps students develop a repeatable workflow, reinforcing engineering habits that carry into advanced coursework and professional practice.

6. Future Work

Future work will focus on several areas, including longitudinal assessment of student development, refinement of pre-laboratory scaffolding, and direct comparison with traditional laboratory formats. These efforts will help more clearly quantify learning gains and further validate the effectiveness of this approach.

Even with its limitations, this study provides strong empirical support for intentionally integrating simulation into core electrical engineering laboratory courses.

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Appendix

Survey questions:

1. Did completing the simulation before the lab help you design your circuit?
2. How closely did your lab measurements match your simulation results?
3. How closely did your lab measurements match your hand calculations?

4. Did you have to change component values or the circuit design during the lab to make it work?
5. What was the biggest issue you encountered in the lab?
6. How helpful was the simulation in troubleshooting problems?
7. After doing the lab, how confident are you in interpreting differences between simulation and real hardware?
8. In one sentence: What part of the simulation helped you the most?
9. What would improve the lab experience (Hand calculation, simulation, hands-on, etc)