2026 ASEE ANNUAL CONFERENCE June 21–24, 2026 | Charlotte Convention Center, NC
Host Sponsor UNC Charlotte
Paper ID #53631

Adapting an In-Person Circuits Laboratory for a Fully Online Summer Course: Design, Implementation, and Assessment

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Abstract

This paper reports the adaptation of a traditional ten-week in-person Circuits I (Introductory Circuit Analysis and Design) laboratory for a compressed six-week fully online summer course. In this implementation, students completed remote hands-on laboratory activities using portable hardware kits, LTspice simulations, required pre-laboratory preparation, and synchronous online support. Transitioning hands-on engineering laboratories to remote formats poses challenges, including reduced tactile guidance, limited "over-the-shoulder" support, equipment access constraints, and the need for effective remote troubleshooting. This study examines whether an intentionally redesigned remote laboratory experience can support the core learning objectives of the in-person format. Using a quasi-experimental case-study design across four offerings, Spring 2024 and Spring 2025 in person and Summer 2024 and Summer 2025 online, with total survey $N \approx 140$, we analyze Likert-scale survey metrics and open-ended feedback related to accessibility, difficulty, theoretical understanding, and skill acquisition. Descriptive results suggest that the online summer cohorts reported similar levels of theory understanding and safety confidence, while reporting lower perceived instructor accessibility and slower iteration during debugging. Course-level grade averages are included as contextual evidence but are not used to isolate the effect of laboratory modality. A notable Summer 2025 disruption associated with shipping delays illustrates that logistics are part of the pedagogical infrastructure for remote laboratories. We detail the vertical-integration redesign and provide practical recommendations for implementing remote circuits laboratory instruction in similar course contexts.

1 Introduction and Background

Hands-on laboratory experiences are a defining component of electrical and computer engineering education, particularly in foundational courses such as Circuits I. These laboratories help students develop physical intuition, measurement skill, troubleshooting ability, and confidence working with real electrical systems. Historically, these competencies have been developed through synchronous, on-campus laboratory sessions using professional benchtop instrumentation and direct, face-to-face guidance from instructors and teaching assistants.

The COVID-19 pandemic accelerated adoption of remote and online laboratory instruction, forcing engineering educators to adapt traditionally hands-on courses to nontraditional delivery formats. Laboratory courses posed particular challenges during this transition because of reduced tactile experience, fewer opportunities for immediate troubleshooting support, and limited access to laboratory-grade equipment. In response, many institutions adopted take-home laboratory kits, simulation-based substitutes, or hybrid approaches to support hands-on learning at a distance [1, 2, 3, 4, 5, 6]. Prior studies suggest that thoughtfully designed remote and virtual laboratories can support learning outcomes comparable to traditional in-person laboratories while offering flexibility and potential cost advantages [16, 17, 22]. At the same time, researchers have reported challenges related to communication, collaboration, troubleshooting, and the absence of "over-the-shoulder" instructional support [13, 18, 21]. These mixed findings underscore the importance of intentional design in remote laboratory instruction rather than treating remote laboratories as direct substitutes for their in-person counterparts. Additional comparative studies have also examined transitions between remote, virtual, and in-person engineering laboratories, reporting a range of trade-offs in student experience and learning support [7, 8, 9, 12, 11].

In this paper, *online* refers to the overall course delivery modality, including lectures, communication, assignments, and assessment delivered through online platforms. *Remote laboratory* refers specifically to laboratory experiments completed off campus using mailed hardware kits, student-accessible instrumentation, and simulation tools. We use these terms distinctly throughout the paper to differentiate the course modality from laboratory execution.

Beyond emergency remote teaching, demand for flexible instructional modalities remains high. This is especially true for summer academic sessions, which often serve transfer students, major changers, and students retaking prerequisite courses who may not be able to remain on campus for a full academic term. In this context, remote laboratory offerings may provide a pathway for maintaining degree progress and accessibility. However, for such offerings to be pedagogically defensible, they must preserve core learning objectives rather than merely provide a logistical substitute for in-person instruction. Related work has also shown that student motivation, course context, and learner background can shape outcomes in online and face-to-face instructional comparisons [14, 10, 23]. In addition, remote hands-on experiences in undergraduate electrical and computer engineering have been explored as a way to preserve practical engagement when students are not physically present in a traditional laboratory [24].

Circuits I represents a compelling test case for remote laboratory instruction. As a gateway course for electrical engineering programs, Circuits I emphasizes fundamental circuit analysis while also requiring students to develop hands-on skills in circuit construction, measurement, and debugging. These skills are traditionally acquired through repeated, instructor-guided laboratory practice. Whether a condensed online course with remote laboratory activities can adequately support these outcomes remains an important question.

This paper examines a case study in which a ten-week, in-person Circuits I laboratory sequence was adapted for a six-week fully online summer course. Rather than directly replicating the traditional laboratory experience, the remote laboratory format was redesigned around a portable hardware platform, integrated simulation workflows, and a flipped instructional model. Because the remote laboratories followed the lecture sequence, students were expected to complete asynchronous lecture material before laboratory activities, supported by required pre-quizzes that served as preparation checks. The primary objective of this study is to investigate whether the redesigned remote laboratory experience supported the course learning objectives and to identify benefits, limitations, and trade-offs associated with this modality.

We present a detailed comparison of the traditional in-person and remote laboratory formats, including laboratory structure, topics covered, required equipment and software, and instructional support mechanisms. Multi-term survey results from Spring in-person and Summer online offerings are analyzed descriptively to assess perceived learning outcomes, accessibility, and student confidence. Quantitative findings are triangulated with qualitative student feedback to contextualize observed trends.

The contributions of this work are threefold. First, we provide a curriculum redesign framework based on vertical integration, in which laboratory objectives are compressed and integrated rather than eliminated to accommodate an accelerated term. Second, we present multi-term comparative evidence across instructional modalities, offering insight into the feasibility of sustaining remote laboratories beyond emergency contexts. Third, we offer implementation recommendations that address logistical constraints, instrumentation limitations, and student support structures. These findings may be useful to electrical and computer engineering educators seeking to design, evaluate, or refine remote laboratory experiences in foundational courses.

2 Course Design and Implementation

2.1 Traditional 10-Week In-Person Format

At our institution, Circuits I is a required, 4-credit introductory course in circuit analysis and design for students entering the electrical and computer engineering program. The course is traditionally offered in a ten-week academic quarter, typically during Spring term, and consists of three hours of lecture and a two-hour laboratory session each week. The extended duration of the quarter allows for a linear progression through the laboratory curriculum, with time for concept introduction, hands-on practice, troubleshooting, and reflection.

The laboratory component is central to the course design. It provides the primary setting in which theoretical concepts introduced in lecture are reinforced through physical implementation, measurement, and debugging. Over the ten-week term, students complete seven laboratory experiments spanning core topics in DC analysis, network theorems, operational amplifiers, and transient response. This traditional in-person offering provides the instructional baseline against which the redesigned remote laboratory format is evaluated.

2.1.1 Laboratory Environment and Equipment

In the traditional in-person format, laboratory sessions are conducted in a dedicated instructional electronics laboratory equipped with professional-grade benchtop instrumentation. Each lab station includes regulated DC power supplies, digital multimeters (DMMs), oscilloscopes, function generators, and solderless breadboards, along with a shared inventory of passive and active components. This environment mirrors the instrumentation students are likely to encounter in upper-division laboratory courses and industry settings.

Students typically work in pairs at a shared lab bench. This structure supports peer learning and collaborative problem-solving, allowing students to discuss circuit behavior, compare measurements, and jointly debug wiring or conceptual errors. However, paired work can also lead to unequal division of labor, with one student assuming primary responsibility for circuit construction while the other focuses on data recording or report writing. Although this dynamic can be mitigated through instructor intervention, it remains a structural characteristic of the traditional format.

Each laboratory section is staffed by an instructor or teaching assistant who provides real-time guidance, verifies circuit operation, assists with troubleshooting, and supports safe equipment use. The physical proximity between students and instructors enables immediate, "over-the-shoulder" feedback, which is a key advantage of in-person laboratory instruction.

2.1.2 Pedagogical Approach: Discrete and Sequential Skill Building

The traditional Circuits I laboratory curriculum follows a sequential structure designed to emphasize incremental skill development. Each laboratory experiment targets a focused set of learning objectives, allowing students to master one conceptual or analytical technique before progressing to more complex topics. Pre-laboratory assignments typically require analytical calculations and/or LTspice simulations, while in-lab time is devoted to physical implementation, measurement, troubleshooting, and comparison among theoretical, simulated, and experimental results.

The seven laboratory experiments in the traditional format are summarized below:

1. **Lab 1 (LTspice Simulation)**: Introduction to circuit simulation, schematic capture, and DC operating point analysis.
2. **Lab 2 (Series DC Circuits)**: Experimental verification of series resistance relationships and voltage division.
3. **Lab 3 (Parallel and Series–Parallel Circuits)**: Verification of Kirchhoff's Current Law (KCL) and current division in multi-branch networks.
4. **Lab 4 (Nodal Analysis)**: Analysis and measurement of bridge networks and multi-source topologies using nodal methods.
5. **Lab 5 (Thevenin Equivalents)**: Determination of V_{th} and R_{th} and experimental verification of maximum power transfer.
6. **Lab 6 (Operational Amplifiers)**: Inverting, non-inverting, and summing amplifier configurations, including gain verification and saturation behavior.
7. **Lab 7 (RC and RL Transient Response)**: Measurement of natural response and experimental determination of time constants, $\tau = RC$ and, where applicable, $\tau = L/R$.

Collectively, these experiments emphasize accurate measurement, systematic debugging, and physical intuition regarding circuit behavior. Students document their work through structured lab reports or worksheets that include circuit schematics, analytical calculations, measured data, and discussion of discrepancies between theory and experiment.

2.1.3 Instructional Structure and Constraints

Laboratory sessions are scheduled once per week at a fixed time and location, and access to equipment is limited to the scheduled session duration. While this structure supports focused, instructor-guided experimentation, it also limits opportunities to revisit experiments outside scheduled lab hours. Completion within the two-hour laboratory window is therefore an implicit design constraint, and extended troubleshooting or exploration is often deferred.

Despite these constraints, the traditional in-person format provides a well-established framework for developing foundational circuit analysis and laboratory skills. Its clear sequencing, instrumentation-rich environment, and immediate instructional support make it an appropriate benchmark for evaluating alternative delivery modalities.

2.2 Transition to a 6-Week Fully Online Course with Remote Laboratories

Adapting the Circuits I laboratory from a traditional ten-week, in-person format to a condensed six-week fully online summer course required redesigning both instructional delivery and laboratory structure. The primary challenge was not only the absence of physical laboratory space, but also the need to support academic rigor, learning objectives, and hands-on competency development within a shorter timeline and remote laboratory context. Rather than attempting to replicate the in-person laboratory directly, the remote format was designed to use portable hardware, simulation, and structured online support.

The redesign was guided by three principles: (1) supporting core learning objectives, (2) explicitly scaffolding measurement and troubleshooting skills that are typically supported through in-person guidance, and (3) compressing laboratory content through vertical integration rather than eliminating topics. This section describes the instructional structure, hardware platform, and curriculum redesign strategy used in the six-week online course.

2.2.1 Flipped Classroom Model and Remote Support Structure

The online Circuits I course used a flipped classroom model to make effective use of limited synchronous time. Content traditionally delivered during in-person lectures and pre-lab briefings was moved to asynchronous formats, allowing live sessions to focus on experimentation, troubleshooting, and individualized support. Because remote laboratories followed the lecture sequence and laboratory kits were introduced beginning in Week 3 after shipping, students were expected to complete relevant lecture modules before each lab. The instructional structure consisted of:

- **Asynchronous content**: Approximately five hours per week of recorded lecture videos, including theoretical instruction, LTspice demonstrations, breadboarding techniques, and measurement procedures.
- **Synchronous interaction**: A three-hour live laboratory session conducted by video conferencing, supplemented by a two-hour weekly Q&A or help session.
- **Remote support tools**: Real-time troubleshooting using Zoom camera feeds and screen sharing, combined with asynchronous peer-to-peer discussion platforms such as Discord.

This structure allowed students to engage with theoretical material at their own pace while reserving synchronous sessions for experimental work and problem-solving. During live laboratory sessions, students were encouraged to share views of their breadboards or LTspice simulations, enabling instructors and teaching assistants to provide virtual "over-the-shoulder" guidance. All synchronous sessions were recorded and made available to students to support accessibility, accommodate connectivity challenges, and reinforce learning through review.

2.2.2 Hardware Platform: The Blue Board Portable Laboratory Kit

A cornerstone of the remote laboratory implementation was a portable laboratory kit designed to provide essential benchtop functionality in a home setting. The kit was centered on a purpose-built hardware platform known as the "Blue Board," developed by Dr. John Lund.

The Blue Board integrates regulated, isolated power rails, including +5 V and $\pm$12 V, powered via USB, along with accessible test nodes to support safe and reliable measurement. As shown in Figure 1, the board consolidates power regulation, current limiting, and measurement access onto a single PCB. The use of isolated supplies reduces the likelihood of ground-loop-related failures, which are common sources of component damage and student frustration in beginner remote laboratory setups.

Each student received a complete kit by mail prior to the start of the term, including the Blue Board, a solderless breadboard, jumper wires, passive and active components, and a digital multimeter if needed. The kit supported DC circuit analysis, operational amplifier experiments, sensor-based applications, and RC transient measurements without relying on traditional benchtop instruments such as oscilloscopes or function generators. Where waveform visualization was required, LTspice simulations complemented physical measurements and served as a "digital twin" of the experimental setup.

Figure 2 shows the physical implementation of the Blue Board and a representative at-home student laboratory configuration. The compact form factor and labeled interfaces allowed students to assemble and troubleshoot circuits independently while maintaining correspondence with simulated models. This approach is also consistent with recent work emphasizing equitable access and engagement through student-owned hardware platforms and portable laboratory kits, which have been shown to support hands-on learning beyond traditional laboratory spaces [15, 20].

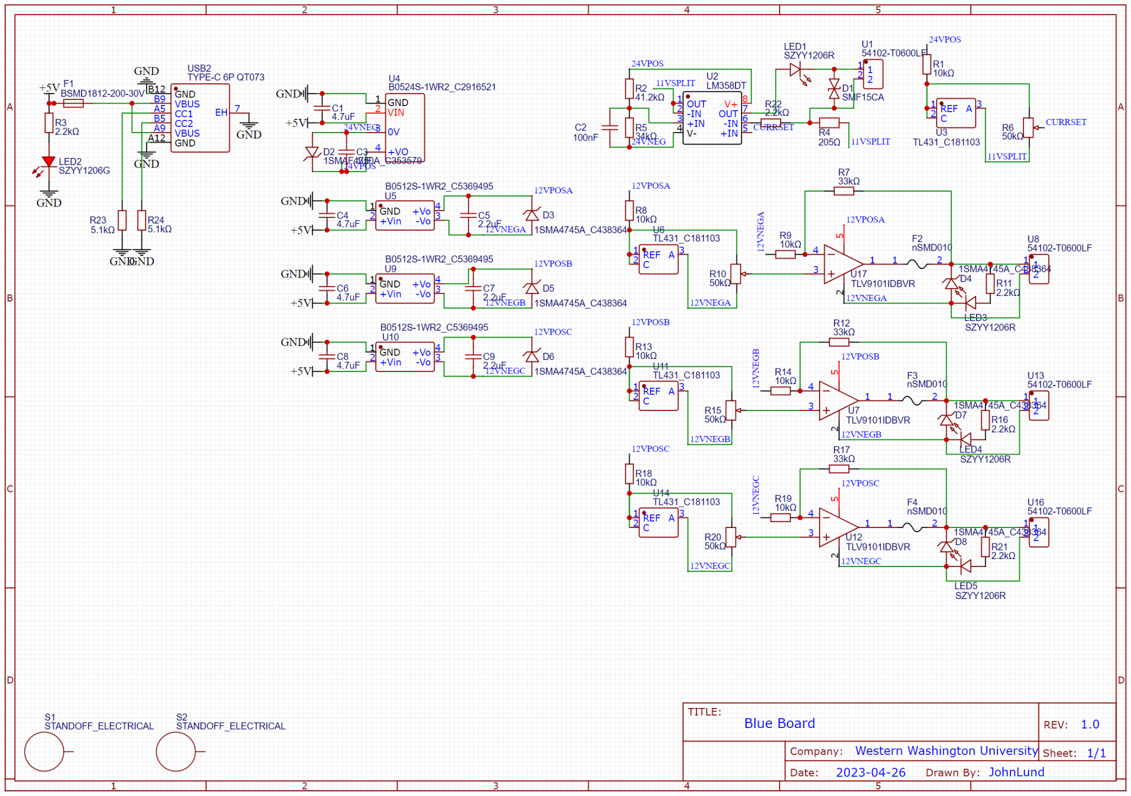

Figure 1: Schematic view of the Blue Board portable platform used for remote Circuits I laboratories. The board integrates regulated, isolated power rails and measurement-accessible nodes to support safe and reliable breadboard experiments in remote settings.

2.2.3 Curriculum Redesign Through Vertical Integration

The reduction from ten weeks to six weeks required a restructuring of the laboratory curriculum. Rather than directly replicating the seven in-person experiments, the remote laboratory sequence was redesigned as four integrated projects. Each remote laboratory vertically integrated learning objectives that were previously distributed across multiple in-person experiments.

The four remote laboratories were structured as follows:

1. **Remote Lab 1**: Breadboarding fundamentals, basic instrumentation, and voltage/current divider circuits, integrating introductory simulation and measurement practices.

2. **Remote Lab 2**: Advanced circuit analysis, including nodal, mesh, and superposition techniques, with experimental validation of Thevenin-style equivalents.

3. **Remote Lab 3**: Operational amplifier circuits combined with sensor-based applications, such as NTC thermistor interfaces and LED indicators.

4. **Remote Lab 4**: RC transient response, including time constant estimation, leakage effects, and non-ideal component behavior.

This vertically integrated structure allowed students to revisit and apply foundational concepts across different contexts, reinforcing learning while reducing redundancy. Importantly, LTspice simulations were not treated as optional pre-lab exercises, but as required components of each experiment. Students predicted circuit behavior through simulation before construction and then validated those predictions through physical measurement. This simulation-first workflow strengthened the connection among theory, simulation, and experiment while also serving as a quality-control step. By comparing expected and measured behavior, students could identify implausible data before experimental errors compounded, which is particularly valuable in remote laboratory settings.

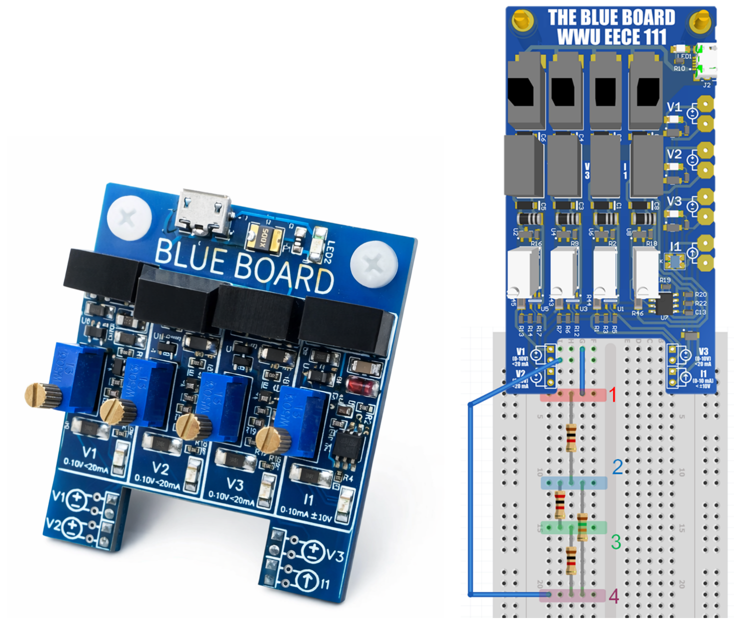

Figure 2: Physical implementation and usage of the Blue Board portable laboratory platform: (a) assembled Blue Board showing integrated power regulation and labeled interfaces; (b) example at-home student laboratory setup combining the Blue Board with a solderless breadboard and passive components during a remote Circuits I experiment.

2.2.4 Alignment of Learning Objectives Across Modalities

Although the number of laboratory experiments was reduced, the core learning objectives of the traditional curriculum were intentionally retained and redistributed. Table 1 summarizes the alignment between the in-person and remote laboratory sequences, highlighting how learning objectives were redistributed and integrated in the remote format rather than removed.

Table 1: Alignment of Core Learning Objectives Across In-Person and Remote Laboratory Formats

Learning Objective	**In-Person Labs**	**Remote Labs**
DC circuit fundamentals	Labs 2–3	Remote Lab 1
Measurement techniques	Distributed across labs	Explicitly scaffolded
Network analysis methods	Labs 3–5	Remote Lab 2
Operational amplifier circuits	Lab 6	Remote Lab 3
Transient response and time constants	Lab 7	Remote Lab 4

This mapping illustrates that the remote laboratory redesign emphasizes integration and reinforcement of concepts rather than a one-to-one correspondence with individual in-person experiments. In the following sections, this redesign is evaluated through comparative analysis of multi-term survey data and student feedback.

2.3 Comparative Analysis Framework

To evaluate the redesigned six-week remote Circuits I laboratory, a structured comparative analysis framework was adopted. Rather than relying solely on outcome metrics, the comparison examines how instructional design choices, laboratory structure, and support mechanisms differ across modalities and how these differences shape student learning experiences. The Spring in-person offerings serve as the baseline instructional model, while the Summer online offerings represent the redesigned remote implementation. Because cohort populations differed across terms, including a larger proportion of transfer students in summer offerings, this analysis is descriptive rather than causal and is organized around five primary dimensions:

1. **Course structure and pacing**, including term length, weekly time allocation, and sequencing of lab activities.
2. **Laboratory content organization**, focusing on whether learning objectives are addressed through discrete experiments or vertically integrated projects.
3. **Instrumentation and technical resources**, encompassing both physical hardware and simulation tools available to students.
4. **Instructional interaction and student support**, including modes of troubleshooting, accessibility of instructor feedback, and opportunities for peer interaction.
5. **Assessment and verification of learning**, examining how experimental competence and conceptual understanding are evaluated across formats.

Table 2 summarizes the side-by-side comparison of the in-person and remote laboratory formats across these dimensions. The table highlights both structural differences driven by modality constraints and intentional design choices introduced in the remote format. As shown in Table 2, both formats target the same core learning objectives but differ in how those objectives are operationalized. The in-person laboratory emphasizes incremental skill acquisition through discrete experiments supported by immediate physical guidance, while the remote laboratory compresses and integrates objectives to accommodate a shorter term and off-campus constraints. In particular, the remote laboratories rely more heavily on simulation as a predictive and explanatory tool, using LTspice as a digital counterpart to physical experimentation. This framework informs the assessment methodology and results presented next.

Table 2: Comparison of Circuits I Laboratory Formats

Aspect	**Spring In-Person Laboratory, 10 weeks**	**Summer Remote Laboratory in Online Course, 6 weeks**
Course schedule	3 hr/week lecture + 2 hr/week lab	Asynchronous videos + 3 hr live remote lab + 2 hr Q&A
Lab organization	7 discrete weekly labs	4 vertically integrated project-style labs
Instrumentation	Bench PSU, DMM, oscilloscope, function generator	Blue Board platform, DMM, components; LTspice central
Instructional interaction	Face-to-face guidance; immediate physical troubleshooting	Zoom camera/screen sharing; asynchronous support; recorded sessions
Student collaboration	Paired work at lab benches	Primarily individual; optional asynchronous peer support
Assessment methods	In-person checkoffs and lab reports	Online reports with photos/screenshots; live or recorded verification

2.4 Learning Objective Coverage and Alignment

To address concerns that fewer labs may imply reduced coverage, both formats were mapped to a shared set of core laboratory learning objectives common to introductory circuits.

2.4.1 Learning Objective Mapping

Table 3 shows that the two formats address aligned learning objectives. In the traditional format, objectives are distributed across narrowly focused weekly laboratories; the remote format consolidates objectives into fewer, comprehensive experiments guided by an accelerated schedule. Notably, simulation shifts from a primarily preparatory role to a central analytical tool in every remote lab. This change compensates for limited instrumentation and reinforces professional workflows that combine prediction, measurement, and validation.

2.4.2 ABET Student Outcomes Alignment

As an additional alignment check, Table 4 maps major laboratory activities to a simplified set of ABET student outcomes commonly used in engineering programs. The purpose is to show that the redesigned laboratories address core outcomes related to experimentation, problem solving, communication, and teamwork/ethics where applicable.

Table 3: Mapping of Laboratory Learning Objectives Between In-Person and Remote Formats

Learning Objective	**Spring In-Person Labs, 7 Labs**	**Summer Remote Labs, 4 Integrated Labs**
LO1: Apply Ohm's Law and KVL/KCL	Labs 2–3, series/parallel verification and KVL/KCL	Remote Lab 1, dividers, measurement scaffolding, and KVL/KCL
LO2: Construct and debug DC resistive networks	Labs 2–4, networks and nodal analysis in bridge circuits	Remote Labs 1–2, integrated networks and structured debugging
LO3: Use simulation tools to predict behavior, LTspice	Lab 1 and selected pre-labs, primarily preparatory	Remote Labs 1–4, required in every lab through a digital-twin workflow
LO4: Apply circuit theorems, including Thevenin equivalents and superposition	Labs 4–5	Remote Lab 2, analysis and validation
LO5: Analyze transient response in first-order circuits	Lab 7, RC/RL time constants	Remote Lab 4, RC transient response, leakage, and non-ideal effects
LO6: Analyze AC steady-state / frequency response, where applicable	Optional extensions or instrument-based demonstrations using oscilloscope and function generator	Embedded through simulation and limited hardware verification, as feasible

Table 4: Lab Activities Mapped to ABET Student Outcomes, Simplified

ABET Outcome, Simplified	**Evidence in Lab Activities, Both Modalities**	**Where Emphasized**
SO1: Solve complex engineering problems	Circuit analysis, nodal/mesh/superposition methods, theorem application, and measurement topology choices	Spring Labs 3–5; Remote Lab 2
SO2: Engineering design under constraints	Selecting component values, verifying performance, and designing measurement strategies under instrumentation constraints	Remote Labs 1–4; Spring Labs 2–7
SO3: Communicate effectively	Lab reports with schematics, calculations, measured data, and interpretation; remote students document work with photos/screenshots	Both; remote labs emphasize photo/screenshot evidence
SO4: Ethics and professional responsibility, safety	Safe wiring practices, avoiding equipment damage, and understanding grounding and isolated supply implications	Both; remote labs emphasize Blue Board safety
SO5: Teamwork and collaboration	In-person pairs coordinate building and recording; remote students use peer troubleshooting through Discord and structured Q&A	Spring labs emphasize pairs; remote labs emphasize asynchronous peer support
SO6: Experimentation and data interpretation	Planning and performing experiments, analyzing discrepancies, validating simulation against measurement, and interpreting non-ideal effects	Both; remote labs emphasize simulation–measurement coupling
SO7: Acquire and apply new knowledge	Learning LTspice and measurement procedures, adapting to a new hardware platform, and using recorded demonstrations	Both; remote labs emphasize self-paced learning

3 Assessment Methodology

To evaluate the redesigned Circuits I laboratory, we employed a quasi-experimental assessment design based on multi-term survey data. The analysis compares student perceptions and self-reported learning outcomes across four course offerings: Spring 2024 and 2025, which used the traditional in-person laboratory format, and Summer 2024 and 2025, which used the remote laboratory format within a fully online course. Across all offerings, the core course content, learning objectives, and grading criteria were held constant, enabling comparison across instructional modalities.

Rather than attempting randomized assignment, which is impractical in this academic setting, this approach leverages naturally occurring instructional variations across terms. The inclusion of two offerings per modality reduces sensitivity to cohort-specific effects and supports longitudinal interpretation of trends. However, because students self-selected into course terms and modalities, the results should be interpreted as comparative case-study evidence rather than as a controlled causal study.

3.1 Quantitative Survey Instrument

Student feedback was collected using end-of-term surveys administered during the final week of each course offering. Surveys employed a 5-point Likert scale, where 1 indicated strongly disagree and 5 indicated strongly agree, and focused on students' perceived learning, accessibility, and laboratory experience.

For longitudinal consistency, eight core survey items that appeared verbatim across all four offerings were selected for analysis. These items assessed:

- perceived gain in practical laboratory experience,
- instructor accessibility during laboratory activities,
- ability to iterate efficiently on problem-solving,
- perceived safety and confidence when failures occurred,
- appropriateness of laboratory difficulty,
- accessibility of laboratory activities,
- ability to complete laboratory tasks in a timely manner, and
- confidence in understanding underlying circuit theory after completing the lab.

For each item, mean response values and response counts were computed for each term. No weighting was applied across terms. Results are reported both by individual offering and in aggregated form by modality, comparing in-person laboratory offerings with remote laboratory offerings in the online summer course. Because no formal statistical hypothesis tests were conducted, all comparisons in this study are interpreted descriptively and are intended to identify patterns across offerings rather than establish statistical equivalence or causality.

3.2 Qualitative Data Collection and Triangulation

In addition to quantitative Likert-scale items, the survey included open-ended prompts inviting students to reflect on their laboratory experience, perceived strengths and weaknesses of the format, and any logistical or instructional challenges encountered.

Qualitative responses were analyzed using a lightweight thematic coding approach. Initial codes were derived inductively from recurring response patterns and included themes such as flexibility and scheduling, troubleshooting and access to help, independence and ownership of experimental work, equipment limitations, and logistical constraints. Responses were then grouped into higher-level themes and used to contextualize quantitative findings, particularly in cases where anomalous trends appeared in the survey data, such as reduced ratings associated with shipping delays or compressed timelines. This mixed-methods approach provided triangulation between numerical trends and student narratives, allowing quantitative findings to be interpreted with richer contextual evidence.

3.3 Course-Level Performance Context

To provide additional context beyond laboratory-specific survey outcomes, overall course grades and final exam averages were reviewed across the four offerings. Average final course grades were 83.17/100 in Spring 2024, 85.60/100 in Spring 2025, 83.32/100 in Summer 2024, and 81.25/100 in Summer 2025. These results place overall course performance in a similar range across offerings, although they should be interpreted cautiously given differences in student populations and summer-course pacing.

Final exam averages showed a similar pattern, although direct comparison is limited because exam scales differed across offerings. The final exam averages were 78.58/100 in Spring 2024, 68.09/80 in Spring 2025, 73.81/100 in Summer 2024, and 71.80/100 in Summer 2025. These measures are included as contextual indicators rather than as direct evidence of modality effects. Because overall course grades reflect lecture, homework, examinations, and laboratory work collectively, they do not isolate the contribution of laboratory format alone.

The online summer cohorts included a relatively larger proportion of transfer students from community colleges than the Spring cohorts, which may also influence these comparisons. Taken together, these course-level outcomes provide supporting context that the remote laboratory implementation was not associated with obvious declines in broader course performance, while avoiding stronger causal claims.

3.4 Limitations of the Assessment Approach

Several limitations should be noted. First, survey data capture student perceptions rather than direct measures of learning gains. Second, response rates varied by term, particularly in summer offerings with smaller enrollments. Third, because students were not randomly assigned to Spring and Summer offerings, cohort differences may have influenced the results. In particular, the summer offerings included a relatively larger proportion of transfer students, and student preparation, work commitments, and reasons for enrollment may have differed across cohorts.

In addition, the present design does not fully separate differences caused by laboratory content redesign from differences caused by delivery modality. The remote laboratories differed from the in-person laboratories not only in location and instructional interaction, but also in pacing, instrumentation, individual versus paired work, and degree of required simulation. External factors such as shipping delays and students' off-campus work commitments may also have influenced responses in ways not directly attributable to instructional design.

Despite these limitations, the use of multiple terms, consistent survey items, course-level contextual data, and complementary qualitative analysis provides a useful framework for evaluating the redesigned remote laboratory implementation. The following section presents the results of this assessment, including longitudinal survey trends, aggregated modality comparisons, and qualitative themes emerging from student feedback.

4 Results and Findings

This section presents results from the comparative analysis between the traditional in-person Circuits I laboratory offerings and the remote laboratory offerings embedded in the fully online summer course. Findings are organized around three complementary perspectives: (1) longitudinal quantitative survey trends across four course offerings, (2) self-reported skill acquisition indicators specific to the remote laboratory format, and (3) qualitative themes derived from open-ended student feedback. Together, these results characterize student experience, perceived learning, and instructional trade-offs associated with the remote laboratory implementation.

4.1 Quantitative Survey Trends Across Modalities

Table 5 summarizes mean responses to eight common Likert-scale survey items collected across four offerings: Spring 2024 and Spring 2025, which used the in-person laboratory format, and Summer 2024 and Summer 2025, which used the remote laboratory format within the fully online course. In addition to term-level means, aggregated averages by modality are included to support descriptive comparison between the in-person and remote formats.

Table 5: Common Likert Survey Items Across Four Offerings and Aggregated Comparison by Modality (Mean Scores on a 1–5 Scale, with Response Count n)

Item (1–5)	**Sp24** (n=55)	**Sp25** (n=45)	**Su24** (n=16)	**Su25** (n=22)	**In-Person Avg.**	**Remote Avg.**
Lab activities helped me gain practical experience.	4.62	4.53	4.31	4.45	4.58	4.38
The instructor was accessible during labs.	4.33	4.56	4.19	3.45	4.44	3.82
I was able to quickly iterate on problem solutions.	3.89	3.89	4.13	3.36	3.89	3.74
If failure occurred, I was confident it would not cause harm to lab equipment or myself.	4.27	4.47	4.63	4.23	4.37	4.43
The level of difficulty of the lab is appropriate.	3.91	4.20	4.13	4.00	4.05	4.06
I found lab activities to be accessible.	4.31	4.40	4.63	3.95	4.35	4.29
I was able to complete lab tasks in a timely manner.	3.95	4.09	4.31	3.23	4.02	3.77
After completing the lab, I was confident that I understood the theory.	4.04	4.18	4.25	3.95	4.11	4.10

Overall, the aggregated results suggest that students in the remote laboratory offerings reported experiences broadly similar to those in the in-person format on several high-level measures. Self-reported confidence in theory understanding and perceived laboratory difficulty remained close across modalities, suggesting that the redesigned remote laboratories supported the intended conceptual experience. Because no formal statistical tests were conducted, these observations are interpreted descriptively rather than as evidence of equivalence.

Two dimensions showed more noticeable differences. Instructor accessibility declined in the remote offerings, reflecting the added friction of troubleshooting through video conferencing, camera feeds, and screen sharing rather than immediate in-person guidance. Students also reported somewhat lower ratings for timely task completion in the remote format, particularly in Summer 2025. This pattern appears sensitive to compressed timelines and logistical constraints, including kit delivery issues, rather than attributable solely to laboratory design.

Conversely, confidence related to safety during experimental failure remained high in both modalities and was slightly higher in the remote offerings. This result supports the role of the Blue Board platform in enabling safe at-home experimentation. Course-level grade averages, discussed in the assessment methodology, provide additional contextual evidence that these survey trends did not coincide with obvious declines in broader course performance, while still reflecting the limitations of cross-cohort comparisons.

4.2 Skill Acquisition Indicators

To complement the common survey metrics, students in the Summer offerings were asked to self-assess their proficiency in core laboratory skills related to hands-on circuit work. Table 6 summarizes self-reported expertise across Summer 2024 and Summer 2025.

Table 6: Self-Reported Expertise in Core Laboratory Skills, Remote Cohorts

Skill Area (1–5)	**Summer 2024**	**Summer 2025**
Circuit assembly (breadboarding)	4.25	4.10
Circuit measurement (DMM use)	4.38	3.90
Circuit calculation/analysis	4.28	3.40

Students reported strong confidence in physical assembly and measurement skills across both remote offerings, suggesting that individual at-home experimentation can support hands-on skill development even without access to full benchtop instrumentation.

The lower circuit calculation and analysis rating in Summer 2025 is consistent with the broader pattern of reduced accessibility and timely completion ratings observed in the same term. Because Summer 2025 also experienced logistical disruptions and compressed timelines, this decline should be interpreted cautiously. The available data do not determine whether the change was caused by remote delivery, cohort differences, shipping delays, or interaction among these factors.

The relatively stronger ratings for breadboarding and DMM use also highlight the value of the simulation–measurement workflow embedded throughout the remote laboratory sequence. By requiring students to compare simulated predictions with physical measurements, the labs provided a structured way to identify implausible data and troubleshoot experimental results.

4.3 Qualitative Themes from Open-Ended Responses

Analysis of open-ended survey responses revealed three recurring themes that contextualize the quantitative findings.

Flexibility versus friction. Students valued the flexibility afforded by asynchronous lectures and at-home experimentation. However, some noted tension between this flexibility and required synchronous check-ins, particularly when balancing the accelerated summer course with work or other commitments.

Independent debugging and ownership. A notable benefit of the remote modality was increased individual responsibility for circuit construction, measurement, and troubleshooting. Because students worked primarily with their own kits rather than in fixed lab pairs, they reported greater ownership of the experimental process. This structure may also reduce the unequal division of labor sometimes observed in paired in-person labs.

Troubleshooting limitations. Reduced immediacy of instructor feedback emerged as the primary challenge. While video-based support and screen sharing partially mitigated this limitation, students contrasted remote assistance with the efficiency of in-person guidance. This theme aligns with the lower instructor accessibility ratings in the aggregated survey data.

Taken together, these qualitative insights suggest that the remote Circuits I laboratory preserved many perceived benefits of hands-on experimentation while introducing distinct experiential trade-offs. These findings inform the design recommendations discussed in the following section.

5 Discussion

5.1 Learning Trade-Offs and Pedagogical Shifts

The results suggest that the remote Circuits I laboratory supported many intended learning outcomes while altering the nature of student engagement. Across all four offerings, self-reported confidence in theory understanding remained broadly similar between in-person and remote laboratory formats, suggesting that the redesigned remote laboratories supported conceptual learning. At the same time, several trade-offs emerged that reflect structural differences between physical and remote instruction.

One notable trade-off was reduced immediacy of instructional support in the remote format. Lower ratings for instructor accessibility and timely task completion, particularly in Summer 2025, highlight the friction introduced by remote troubleshooting. In the absence of physical "over-the-shoulder" guidance, students were required to articulate problems more explicitly and rely on visual documentation, including photos, live camera feeds, and screensharing, to obtain assistance. While this sometimes delayed resolution of simple errors, it may also have encouraged more systematic debugging practices and clearer technical communication.

Conversely, the remote modality introduced pedagogical shifts that many students perceived as beneficial. Working individually with personal lab kits reduced the "free-rider" dynamic sometimes observed in paired in-person labs and increased ownership of circuit construction and measurement. Qualitative responses suggested that students felt more responsible for troubleshooting and verification, which may have contributed to confidence in hands-on skills.

Another significant shift was the central role of simulation. In the remote laboratories, LTspice functioned as a required predictive tool rather than an optional pre-lab exercise. This simulation–measurement workflow positioned simulation as a practical "digital twin," aligning student practice with professional engineering workflows. Together with the survey trends and course-level performance context presented earlier, this suggests that simulation may have helped support learning even when physical instrumentation was limited.

5.2 Design Implications for Sustainable Remote Labs

These findings suggest that successful remote laboratories depend less on duplicating campus equipment and more on strong curriculum design, explicit scaffolding, and reliable logistical support.

First, logistics should be treated as part of the pedagogical infrastructure. The anomaly observed in Summer 2025 demonstrates that delayed kit delivery can significantly affect students' perceptions of accessibility and workload manageability. For sustainable remote laboratories, kits should be in students' hands before the first experiment begins, with inventory confirmation to reduce compressed timelines and uneven learning conditions.

Second, early-stage friction can be reduced through targeted instructional scaffolding. Short micro-tutorials addressing common measurement tasks, grounding practices, and wiring errors may mitigate recurring difficulties that disproportionately affect novice learners in remote environments. Similar implementation considerations have also been discussed in broader online and continuing engineering education contexts, where structured scaffolding and support mechanisms have been shown to be particularly important when laboratory-style instruction moves outside traditional physical spaces [19].

Third, flexibility in synchronous engagement appears particularly important for summer offerings. Milestone-based check-ins may preserve accountability while accommodating diverse student schedules.

Finally, instrumentation constraints should be addressed strategically rather than comprehensively. Although the absence of oscilloscopes limited direct waveform visualization, the combination of simulation and targeted measurements appeared sufficient for the intended learning context. Optional low-cost instrumentation add-ons may be considered where specific objectives require them, while balancing cost and equity concerns.

5.3 Limitations and Future Work

This study reports a case study from a single institution and one foundational circuits course, which limits generalizability. Although inclusion of four offerings across two academic years strengthens interpretation, cohort populations likely differed across terms in preparation, motivation, transfer status, scheduling constraints, and student demographics. Additionally, the present analysis does not fully separate effects attributable to curriculum redesign from effects associated with delivery modality. Some observed differences may reflect logistical constraints, cohort differences, accelerated summer pacing, or individual versus paired laboratory structures, rather than remote delivery alone.

The assessment relies primarily on self-reported survey data supplemented by descriptive course-level outcomes rather than direct post-course performance measures designed for causal comparison. These data provide useful insight into student perceptions and instructional trade-offs, but they do not establish learning equivalence across modalities.

Future work will incorporate common practical assessments, rubric-based artifact analysis, and longitudinal tracking in subsequent courses to better evaluate how remote laboratory experiences influence retention and transfer of hands-on skills.

6 Conclusion

This paper examined the adaptation of a foundational Circuits I laboratory from a traditional ten-week in-person format to a condensed six-week fully online course incorporating remote laboratory activities. Through intentional redesign of laboratory structure, hardware infrastructure, and instructional support, the remote laboratories supported core learning objectives while operating under significant logistical and temporal constraints.

Multi-term survey results suggest broadly similar student perceptions of theory understanding and safety confidence across instructional modalities. Although modest declines were observed in perceived instructor accessibility and iteration speed in the remote format, qualitative feedback suggests these trade-offs were accompanied by meaningful pedagogical shifts, including increased ownership of hands-on work, greater independence in troubleshooting, and stronger reliance on simulation as a predictive engineering tool.

Within the context of this case study, the findings suggest that carefully designed remote laboratories can provide a feasible option for supporting hands-on learning in online summer offerings. Additional work is needed to determine how broadly these findings generalize across institutions, student populations, and laboratory contexts. Rather than viewing remote laboratories solely as an emergency accommodation, this work suggests they may serve as a complementary instructional modality worthy of continued investigation, particularly for contexts where flexibility and access are important considerations.

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