Circuits in Action, Grounded in Discovery

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Abstract

This Evidence-Based Practice Paper describes an inter-university introductory circuits lesson designed to immerse students in foundational electrical engineering concepts through active learning. The module integrates flipped classroom preparation, discovery-based learning, hypothesis testing, think-pair-share, collaborative problem solving, and hands-on experimentation to support conceptual understanding of voltage, current, resistance, and basic circuit analysis. Before class, students engage with curated multimedia materials and guided readings to build foundational knowledge. In-class activities emphasize peer interaction, practical circuit construction, simulation-based exploration, and iterative testing of predictions. The lesson also introduces students to engineering career pathways by highlighting contributors in electrical engineering whose backgrounds reflect the demographics of the student population. This paper outlines the pedagogical framework and instructional tools used in the module and examines patterns in student perceptions of the active learning strategies employed. Students identified hands-on circuit construction and simulation activities as the most effective learning tools. These findings suggest that the module provides a scalable foundation for strengthening early engineering learning and supporting design-oriented problem solving in introductory STEM courses.

Introduction

First- and second-year STEM students often struggle with core electrical concepts, like voltage, current, resistance, circuits, and Ohm's Law. When presented mainly through traditional methods like lectures and equations, these topics can seem abstract, leading to misconceptions and disengagement. Research shows that evidence-based instructional practices (EBIPs) such as flipped classrooms, real experimentation, virtual experimentation, team-based learning, and other active learning pedagogies significantly improve conceptual understanding and retention in STEM education [17-18]. Not all active learning approaches yield the same results. Selecting the most effective strategies and incorporating multiple representations enhance both the acquisition and the deepening of conceptual understanding.

Common Instructional Framework

Across two institutions, Rutgers University and North Carolina Agricultural and Technical State University (NC A&T), the module was structured around a shared instructional framework grounded in evidence-based practices [1–3]. The framework integrates (1) flipped pre-class exposure to foundational concepts, (2) just-in-time sequencing that introduces simulations and hands-on experimentation immediately following conceptual instruction, (3) prediction-before-testing through hypothesis formation, (4) collaborative think–pair–share discussion, (5) structured reflection connecting observations to theory, and (6) exposure to engineering role models aligned with student demographics. While implementation details varied by institution, these core elements were consistent across contexts.

Research Purpose and Questions

The purpose of this Evidence-Based Practice study is to examine how a just-in-time, multi-modal instructional framework influences early-year students' learning experiences in introductory circuits courses across two institutional contexts. Specifically, this study investigates the following research questions: 1) RQ1: How do students perceive the effectiveness of hands-on experimentation, simulation-based exploration, and structured reflection in supporting their learning and engagement? 2) RQ2: What evidence of early design behaviors (e.g., hypothesis formation, testing, and justification) emerges through team-based experimental activities?

This practice paper highlights an inter-university collaboration between NC A&T and Rutgers, both of which are committed to broadening participation in STEM and serve student populations that are predominantly historically underrepresented in the field. NC A&T, a public HBCU, participates through its Department of Electrical Engineering. Rutgers University participates through its Women in Science and Engineering (WiSE) program at Douglass Residential College, the historic women's college at Rutgers that welcomes all students. Among more than 1,200 STEM students affiliated with Douglass, 99 percent are women. Examining the implementation of the instructional sequence across these two institutional contexts provides insight into how a common pedagogical framework can be adapted to different student populations and course goals.

This project introduces a multi-class circuits module that integrates several evidence-based instructional practices while maintaining academic rigor. The module combines a flipped course structure, hands-on experimentation, electricity simulations, team-based learning, and authentic role-model spotlights. Students engage in hypothesis-driven exploration of foundational electrical concepts and connect theoretical ideas to real-world applications. By featuring role models whose backgrounds reflect the student population and embedding active learning throughout, the module seeks to deepen conceptual understanding, strengthen STEM identity, and prepare students for advanced STEM coursework [4–16].

Methodology

The instructional design follows a similar structure at both universities, despite some differences in the courses. Although the two courses differ in their goals and the order of activities, both provide introductory electrical circuits modules that incorporate active learning techniques, as shown in Table 1. Each course uses a flipped classroom model in which students engage with foundational concepts before class, reserving class time for hands-on activities and collaborative problem solving. Students draw on knowledge from multimedia reference materials and circuit simulation tools to inform their experimentation. This iterative structure, which blends out-of-class conceptual preparation with increasingly complex in-class experiments, promotes active engagement, peer collaboration, and progressively deeper understanding of electrical circuit principles. The two courses are outlined as follows:

NC A&T - Introduction to Problem Solving Course: At NC A&T's Department of Electrical and Computer Engineering, first-year students enroll in an introductory problem-solving course during the fall semester as a required entry point to the ECE major. This course prepares students for the subsequent Electric Circuits I course by emphasizing foundational problem-solving skills and conceptual reasoning related to basic electrical principles. Students therefore gain early familiarity with circuits concepts before engaging in formal circuit analysis in the follow-on course. In Fall 2025, the course enrolled 74 students, including 67 first-year students who represent a typical early-stage Electrical and Computer Engineering student population. All 74 students agreed to participate in this study. The electricity module at NC A&T spanned six in-person class meetings. Students worked in teams of three to design and present a hypothesis-driven experiment, providing evidence of conceptual understanding and collaborative problem solving. Although the module did not include a full design project, the activity sequence supported early design behaviors such as hypothesis formation, variable selection, testing, and justification, establishing a foundation for open-ended design tasks in later coursework.

Rutgers University - Introduction to Scientific Research Course: At Rutgers, the women in STEM program houses a long-standing research initiative that serves up to 100 students each year. A central component of this program is the required Introduction to Scientific Research course, which introduces students to the foundations of research, lab safety certification, hands-on STEM workshops, and five hours per week of laboratory shadowing with faculty. The workshops expose students to a range of STEM topics that build the scientific literacy needed for effective research, including a module on electricity. In Spring 2026, 74 students across two sections enrolled in the course. These students represented a variety of STEM majors and were primarily in their sophomore year. More than half will not take a formal electricity course as part of their majors, making this module the first and possibly only university-level exposure many will have to the topic. The electricity module at Rutgers was delivered across two in-person class meetings. Out of 74 students, 46 students agreed to participate in this research study.

Table 1: Module Comparison

Module Elements	**NC A&T**	**Rutgers**
# Sections	1	2
Enrollment	74	74 (~40 per section)
Class Year	1st yr (67) 2nd yr (7)	1st yr (5) 2nd yr (48) 3rd yr (19) 4th yr (2)
Student Major	ECE	ECE (2), other Engg (10), CS (13), Sciences (49)
# Class Meetings	6	2
In class groups	3	2
Instruction Format	flipped classroom	flipped classroom
Circuit Simulation	PhET	PhET + TinkerCAD
Circuit Type	series and parallel	series
Circuit Components	wires, bulb, battery, paper clip, switch, pencil	wires, bulb, battery, switch, Arduino
Calculations	Ohm's Law, algebraic problem-solving	Coding modifications
Assessment Types	circuit construction, algebraic problem-solving homework, quizzes	Circuit simulations, homework (pre-labs): quizzes, post lab discussions

The circuit simulation tools allow students to explore concepts independently and visualize ideas that are typically abstract. Virtual experimentation reinforces conceptual understanding by enabling students to test parameters, observe system behavior, and develop intuition before working with physical components. Simulations also help students generate theoretical predictions that can be compared with standard calculations and hands-on experimental results during class. In the classroom, students work collaboratively in small groups on hands-on activities. Instructional strategies include think-pair-share, hypothesis testing, small-group problem solving, and guided circuit construction.

Each university also incorporates stylistic elements designed to enhance engagement. These include framing each activity in a real-life context, highlighting a contributor to the field of electricity whose background aligns with the institution's student population, and selecting lesson titles that resonate with college-age learners. Embedding real-world context strengthens conceptual understanding because students are more likely to grasp the purpose of new content when it connects to familiar experiences. Situating circuit concepts within everyday scenarios helps students relate abstract ideas to their own lives, which supports retention and later retrieval. Humanizing the field further increases motivation and belonging. Featuring an individual contributor helps make the discipline feel accessible and supports identity development among learners. A sample lesson outline for each university is provided in Table 2. Complete module lessons are provided in the Appendix.

Table 2: Lesson Plan Samples

Element	**NC A&T**	**Rutgers**
Lesson Title	Bulb Your Enthusiasm – Circuits Intro and Hypothesis Writing	In Your Electric Era: Build a Simple Circuit
Pre Lecture	Define Voltage, Current, Resistance, Ohm's Law.	Understanding Electrical Circuits reading; Build simple circuits using PhET simulation, Understanding Electrical Circuits Quiz
Instructor Intro 10min	Who is Henry Sampson? Review definitions	Lecture (concept review, review of circuit simulations, contextualized problem setting) review the woman in STEM highlight: Kim Moore (KDM Engineering).
Classwork	In groups: light a bulb with battery and wires. Think-pair-share: Think about what constitutes a pathway for charges that forms a "loop" (i.e. closed circuit), write a hypothesis of what constitutes a closed circuit. A few volunteers share their hypothesis. Individually, use PhET simulation software to recreate the bulb/wire/battery and test their hypothesis	In pairs: light an LED with a battery, wires and a switch Complete analogy: electric circuit/people running on a track Class discussion questions for Think-Pair-Share: individually answer questions in writing, compare with partner, ask for volunteers to share: 1. Why is it important for a circuit to be closed for current to flow? How does this principle apply to real-world devices like smartphones or household appliances? 2. How does adding a switch improve the functionality of a circuit? Can you

		think of examples where switches are essential in everyday life? 3. What would happen if the polarity of an LED is reversed in a DC circuit?
Homework	Build various circuits with bulbs/resistors on PhET. Submit Reflection on class activities	Reading: Understanding Electrical Circuits Circuit simulations using PhET. Research the highlighted woman in STEM. Quiz - Understanding Electrical Circuits

The preceding description of the courses, activity structure, and active learning techniques establishes the pedagogical foundation of this module. To understand how these design choices influenced student learning, we next describe the assessments and artifacts that provided insight into students' conceptual understanding and skill development.

Assessment Instruments and Artifacts

To evaluate how students engaged with the module and the extent to which they achieved the intended learning outcomes, a series of assessments were implemented that aligned with the instructional design described above. These assessments captured both conceptual understanding and practical application, offering multiple points of evidence across the multi-class sequence. In addition to formal measures, we also examined student-generated artifacts that provided insight into their reasoning processes, problem-solving approaches, and interaction with the active learning components of the lesson, outlined in Table 3.

Table 3: Assessment Instrument Comparison

Assessment Element	**NC A&T**	**Rutgers**
In-class observations	In-class quiz assessing definitions of voltage, current and resistance as well as Ohm's Law. Assessment of series and parallel circuit configurations. Identification of minority engineer Henry Sampson.	Assessment of circuit simulations Identification of a notable woman in STEM whose work significantly relates to electricity or electrical systems. Building a simple circuit.
Homework submissions	PhET - circuit simulation screenshots, reflections). Students will use the PhET on-line simulator to build various circuits and submit one screenshot of each.	Reading: Simple Circuits Build simple circuit using PhET Research a notable woman in STEM whose work significantly

	They will record observations comparing bulb brightness, identifying which circuit is brightest and dimmest, and explaining why. Students will then reflect on how brightness relates to current flow and predict what will happen when current is measured with a volt-ohm meter in the next class. Students will write 2–3 sentences about Kim Moore, an electrical engineer at Lockheed Martin, and connect her work to engineering problem-solving. A 20 point rubric evaluates a PhET-based series and parallel circuits activity across four areas: correct construction and screenshots of required circuits, accurate observations and brightness comparisons, quality of written reflection explaining brightness behavior, and overall organization and clarity. Full credit requires clear evidence, correct reasoning, and thoughtful reflection; partial credit is given for incomplete, unclear, or partially correct work, and no credit for missing components. An optional bonus of up to 2 points is available for a brief, relevant written response.	relates to electricity or electrical systems Quiz on simple series circuits.
Algebra-based quizzes	Complete the data table comparing predicted (math) vs. simulated results for voltage and current as well as power.	N/A
Team hypothesis presentations	Hypothesis formation, circuit building, testing with digital multi-meter, and communication (oral group presentation) of the electric circuit kit just like real engineers. Culminates in a short peer-reviewed report and reflection.	N/A

Survey and Results

In addition to the described assessment measures and student artifacts, students were also asked to complete a brief survey approved under the Institutional Review Board (IRB) protocols at both participating institutions to capture their perceived experiences with the electricity module. The survey consisted of three questions designed to gather feedback on what aspects of the module supported their learning and how they envisioned applying these strategies in the future.

Survey - Students at both universities were asked 3 questions about their experience with the electricity module:

1. Which type of activity has helped you learn the most effectively? (Multiple choice)
   - Simulation
   - Group work
   - Hands-on circuit
   - Instructor demo
   - HW reflection
   - Text/reference material

2. What type of additional support would most help you in upcoming activities (Multiple Choice)
   - Calculations with math
   - More hands-on practice
   - Short video walk-throughs

3. Please enter your feedback about the electricity lesson and activities: (text response)

Results - The electricity modules were implemented at the respective universities in different semesters. NC A&T had a fall 2025 implementation, where Rutgers University had a spring 2026 implementation. Survey results are provided in Table 4.

Table 4: End of Year Survey Results Comparison

Result Element	**NC A&T**	**Rutgers**
N	**74**	**46**
Helped Most		
Simulation	44%	11%
Instructor demo	29%	4%
Hands-on circuit	14%	54%
HW reflection	8%	2%
Group work	5%	20%
Reference material	0%	9%
Future Help		
Hands-on work	30%	76%

Math Calculations	22%	7%
Short videos	20%	17%
Group Tutoring	15%	0%
No Additional Support	13%	0%

Overall, results from this study suggest that the multi-class, flipped, multi-modal module supports engagement and fosters early-stage design-oriented reasoning at both institutions and instructional settings.

At NC A&T, students overwhelmingly gravitated toward interactive digital tools, with the PhET simulation emerging as the most effective learning activity by a wide margin. Instructor demonstrations were a strong secondary support, while other activities played a much smaller role. Notably, hands-on circuit work ranked only third in effectiveness, yet it was the top request when students were asked what additional support they needed. One possible explanation is that because students worked in groups and shared materials, some may not have had enough time for individual exploration with the physical circuits. Students also expressed interest in additional worked examples, though at much lower levels. In terms of conceptual understanding, calculating total resistance stood out as the most challenging concept, more frequently cited than any other topic. Evidence of early design behaviors emerged through team hypothesis presentations. All teams generated predictions prior to experimentation, and approximately 65% demonstrated relational or mechanistic reasoning linking resistance, current, and brightness. Several teams revised initial claims after observing discrepancies, citing wiring errors or component variation.

In open-ended survey responses, students highlighted the value of combining simulations, hands-on circuit kits, and guided reflection. Students noted that this sequence helped them "see how the math connects to a real circuit instead of just numbers on paper," and that building and testing circuits "made me think about why the design worked and how I could improve it." These responses suggest not only increased engagement, but the emergence of design thinking, as students evaluated circuit behavior, connected theory to implementation, and considered iterative improvement.

At Rutgers, survey data indicated that hands-on engagement was perceived by far as the highest-impact instructional practice, followed by online simulations and demonstration videos. A small number of students suggested that clearer alignment between visual aids and written instructions, as well as the addition of a short video tutorial, would further support implementation. The students completed the circuit activities much more quickly than anticipated. Only a handful of students requested assistance, and the support needed was minimal. This outcome suggests that the pre-work was effective in preparing students and reinforcing their understanding of key circuit concepts. There were minimal challenges during the activity. The primary challenge was in the preparation phase designing clear, effective instructions and ensuring that the in-class activity closely mirrored the simulation. It was also important to intentionally incorporate references to the assigned readings so students could clearly connect theory to practice.

Open-ended student responses nevertheless reinforced the overall findings, emphasizing the role of active learning in supporting conceptual understanding, engagement, and persistence in this electricity module. Very clearly and succinctly, a student recounted which EPIB was the primary driver of her understanding - hands-on learning, “The physical lab helped me understand the subject matter the most.” Furthermore, another student highlights the benefits of concept acquisition through hands-on activities that include productive struggle, “I really liked our hands-on activity with the circuit; our circuit didn’t work at first, but I think the struggle really reinforces the lesson of the circuits.” Understanding the abstract topic of electricity is further described by this student’s impact statement, “I liked how we had to figure out how to maintain the correct current flow in order to light up the LED light, helping us have a better understanding overall in current flow.” The full set of open-ended responses is provided in Appendix 3.

Discussion

Student engagement and learning outcomes observed in this study suggest that combining multiple EPIBs including hands-on circuit construction with simulation-based exploration and structured reflection can effectively support early-year students’ understanding of foundational circuit concepts. Survey responses and student artifacts indicate that learners particularly valued activities that allowed them to test predictions and immediately observe circuit behavior, reinforcing the role of active experimentation in conceptual sense-making. The just-in-time sequencing of instructional components appears to be a key factor in student learning. Pre-class exposure to core concepts, followed by in-class prediction, testing, and reflection, enabled students to connect mathematical relationships from Ohm’s Law to observable physical behavior. This sequencing may have reduced cognitive overload and supported iterative refinement of student understanding during class activities. Although the module does not include a full design project, the instructional sequence supports early design behaviors such as hypothesis formation, variable selection, testing, and justification. These practices align with introductory design competencies and may serve as a foundation for more open-ended design experiences in subsequent engineering coursework.

Several limitations should be noted. The findings are based on a single course implementation at both universities. Additionally, the study uses descriptive analysis of student work and survey responses rather than a controlled experimental design. As a result, conclusions focus on observed patterns rather than causal claims. Future work may include analysis of assessment instruments, exploration of how the instructional framework can be extended to incorporate open-ended design challenges, and investigation of longer-term impacts on student performance and retention in subsequent courses.

Adoption Feasibility and Scalability

This section provides an overview of the instructional and logistical conditions that support successful adoption of the module. It reviews preparation, staffing, costs, and other factors that influence feasibility and scalability across different course environments.

Instructor prep time: Active learning implementations require a significant upfront investment in planning and lesson design. The amount of preparation needed varies based on the complexity of the activity and the instructor’s familiarity with active learning strategies. In this module, Author 2 from Rutgers brought extensive experience with active learning and had implemented a similar lesson in previous courses. This background aligned well with Author 1’s instructional goals and classroom approach at NC A&T, allowing for an efficient integration of the techniques. The curriculum at Rutgers is predominately active learning based, includes several hands-on activities, and includes supplies. Considerable time, planning, and money are spent every year on this course. For instructors who are newer to active learning, it is advisable to collaborate with colleagues who have experience in these methods or to seek support from resources such as a university's school of education, teaching and learning center, or an established community of practice.

Classroom Support: NC A&T implemented the module independently, with the instructor solely responsible for lesson delivery, facilitation of all hands-on activities, and grading of all student assessments to ensure consistency and careful evaluation. No teaching assistants or additional instructional support were used. Conducting the study in this "lone wolf" capacity was professionally rewarding but also demanding, as it required balancing instructional delivery, real-time troubleshooting, and careful assessment of oversight without additional facilitation support.

In contrast, Rutgers University incorporated upper-division undergraduate assistants who serve as near- peer mentors to help facilitate the hands-on components of the lesson. In each section of the course, there are a total of 8 near-peer mentors, 4 per section who are each assigned 12 mentees. These mentors have the following responsibilities and receive a $1000 stipend during the semester:

- Assist with implementation of the course lesson plans.
- Serve as peer mentors and program support throughout the course.
- Attend weekly training and meetings with the program director.

These additional supports proved valuable in ensuring that students received timely guidance, particularly during the more complex stages of circuit construction and troubleshooting. While not strictly necessary, having extra facilitators can enhance the student experience by providing more individualized support throughout the activity.

Additional Costs: Implementing active learning can introduce additional costs, especially when hands-on materials or consumable supplies are required. Both universities in this study experienced expenses associated with the electricity module. At the same time, many active learning strategies can be implemented at little or no cost. Little or no-cost examples include problem-based learning, case-based learning, collaborative learning, think-pair-share, and flipped classroom approaches. It is important to consider budgetary constraints when designing or revising curriculum and to select active learning methods that align with available resources.

Scalability: Hands-on or real experimentation can be scaled effectively when instructor efforts, budgetary constraints, and classroom support are considered. In this study, both universities operated medium-sized classes, with NC A&T approaching the threshold of a large class. These conditions suggest that the module is workable beyond small settings and provide a positive outlook for instructors who wish to incorporate active learning into their own courses.

Is this feasible for other institutions? Yes, this example demonstrates that the module can be adapted across a variety of instructional contexts, and we hope it serves as a practical resource for faculty who wish to enhance their teaching through active learning. Instructors may choose to adopt the complete lesson, which is provided in the appendix, or they may draw inspiration from selected components as they design their own course reforms. The structure of the activities, the accessibility of the materials, and the flexibility in facilitation approaches make this module well suited for institutions with different class sizes, student populations, and instructional goals. Our intention is that this work not only offers a ready-to-use model but also sparks new ideas that instructors can tailor to meet the needs of their programs and students.

In summary, this project demonstrates that early exposure to hands-on circuit work, paired with intentional sequencing and active learning strategies, can meaningfully support students' conceptual understanding. The findings offer a practical instructional model that can be adapted for a range of introductory engineering contexts. Continued research will help clarify how these approaches can be expanded and sustained to strengthen foundational learning for diverse student populations.

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APPENDIX

Appendix #1 - NC A&T Lesson Plan

This 6-class module introduces students to electric circuits using a combination of hands-on activities, instructor demonstrations (including projected multimeter measurements), optional short instructional video supports, visual observation, use of multimeters, and simulations (PhET software).

Class 1 – "Bulb Your Enthusiasm" - Circuits Intro and Hypothesis Writing

- Pre-Lecture: Define Voltage, Current, Resistance, Ohm's Law.
- Instructor Intro (10min): Who is Henry Sampson? Review definitions
- Classwork: Students work in groups to light a bulb with battery and wires. Think-pair-share: Think about what constitutes a pathway for charges that forms a "loop" (i.e. closed circuit). In pairs, write a hypothesis of what constitutes a closed circuit. A few volunteers share their hypothesis. Individually, use PhET simulation software to recreate the bulb/wire/battery and test their hypothesis
- HW: make various circuits with bulbs/resistors on PhET. Submit Reflection on class activities

Class 2 – "Glow Up" - Resistance and Brightness

- Instructor Intro (10min): What is LuminAid. Summary of resistance and brightness.
- Classwork: Groups build circuits with different resistors/bulbs. Students observe bulb brightness and record using visual scale. Use a multimeter to measure. The instructor demonstrated proper probe placement and live voltage/current readings using a Zoom/document camera projected to the class Compare with PhET values done for HW. Create a table of predicted vs actual values. Provide rationale for any differences.
- HW: Read series circuit info. Use PhET to create various serial circuits. Who is Kim Moore and contributions to engineering (2-3 sentences)?
- Optional instructor-recorded review videos were posted on the LMS for reinforcement; viewing was not graded.

Class 3 – "Current Crush" - Series Circuits

- Instructor: Summary on Series (5min). Ask for volunteer to describe Kim Moore.
- Classwork: Build series circuit physically, use multimeter, record. Compare to PhET. Create a table of simulated vs actual and rationale for differences.
- Instructor: Solve various Ohm's law problems (series)
- HW Series calculations. Read parallel circuit info. Use PhET to create various parallel circuits.

Class 4 – "It's Getting Amped in Here" - Parallel Circuits

- Instructor: Summary on Parallel Circuits. Who is Jeremy Blum, Shaper Tools OR Austin Weisberger, SWERV
- Classwork: Build parallel, use multimeter, record. Compare to PhET. Create a table of simulated vs actual and rationale for differences. Complete the track-electricity analogy

- Instructor: Solve parallel circuit equations. Review presentation and peer grading
- Homework: Hypothesis, setup, observations, and conclusion. Reflect on simulation vs. real-world results and learning. Include one highlighted EE Contributor who has contributed to the field of EE and write 2-3 sentences, and include in presentation. What you liked the most from this circuits lesson. Will be peer graded, provide rubric to class. Solve both series and parallel problems.

Class 5 – Parallel Circuits & Electrical Power

- Instructor: The instructor will briefly review voltage, current, and electrical power in parallel circuits and demonstrate proper use of a VOM for measuring circuit quantities.
- Classwork: Teams construct series and parallel bulb circuits, measure voltage and current using a VOM, and calculate electrical power. Recreate in a PhET, and submit a short reflection explaining how power relates to observed brightness.
- Students will document circuit configurations by identifying component values and computing equivalent resistance for series–parallel arrangements. They will calculate branch currents, element voltages, and electrical power using Ohm's Law and power relationships, and organize these results in tables comparing calculated values to simulated results. Students will capture screenshots of PhET simulations and include images showing measured or simulated voltage and current readings. Each submission will include a brief written reflection explaining how the calculated and simulated results align and how electrical power relates to observed bulb brightness.

Class 6 – Series and Parallel Brightness – PhET Simulation & Reflection

- Classwork: Students will use a PhET circuit simulation to construct series and parallel bulb circuits and predict relative bulb brightness prior to calculation. For each circuit, students will record qualitative observations of relative bulb brightness, identify the brightest and dimmest configurations, and explain observed differences in brightness. Students will also respond to reflection questions connecting brightness to current flow and will document predictions regarding how measured current is expected to change when physical measurements are taken in the subsequent class session.
- Teams present (5min each). Peer graded using rubric
- HW: Each student submits a 1 page report (include a highlighted EE contributor).

Sample Data Collection Table

Students will fill out a table similar to the one below:

Circuit Setup	Resistor (Ω)	Voltage (V)	Brightness (1–5)	Predicted Current (mA)	Measured Current (mA)

Expanded Experimental Scenarios and Data Tables

All activities will be conducted in teams of 2–3 students. Each team will be responsible for forming hypotheses, building circuits, recording data, and presenting their findings.

Scenario 1: Current or Brightness vs Resistance (Fixed Voltage)

Objective: To observe how increasing resistance affects current and bulb brightness while keeping voltage constant.
Prompt: Form a hypothesis such as: 'If resistance increases, current will decrease, and the bulb will appear dimmer.'
Each team will keep voltage constant (e.g., 3V) and change resistor values. They will estimate brightness and optionally measure current.

Resistance (Ω)	Voltage (V)	Brightness (1–5)	Measured Current (mA)	Predicted Current (mA = V/R)

Scenario 2: Current or Brightness vs Voltage (Fixed Resistance)
Objective: To explore how increasing battery voltage affects current and brightness using a fixed resistor.
Prompt: Form a hypothesis such as: 'If voltage increases, current will increase, and the bulb will be brighter.'
Each team will keep the resistor fixed (e.g., 100Ω) and vary the battery voltage.

Voltage (V)	Resistance (Ω)	Brightness (1–5)	Measured Current (mA)	Predicted Current (mA = V/R)

Reflection Questions
Each team should reflect on the following questions in their report or final presentation:
1. How well did your experimental results align with your hypothesis?
2. What differences did you observe between simulated and real circuit behavior?
3. Were there any sources of error or unexpected results in your measurements?
4. How did using bulb brightness instead of measuring current affect what you thought about the circuit??
5. What did this experiment help you understand about Ohm’s Law in real-world circuits?

Appendix #2 - Rutgers Lesson Plan

This two-class module introduces students to electric circuits using multiple learning pedagogies including: a traditional reference material review, assessment of basic circuit concepts, circuit simulation tools, hands-on assembly, real life contextualization, visual observation. It is designed to help students form and test hypotheses, apply Ohm's Law, and interpret both qualitative and quantitative data.

Lesson 1 In Your Electric Era: Build a Simple Circuit
Pre-lab: reading, build simple circuit using PHET then complete a short quiz
Reading: **Understanding Electrical Circuits**
Practice: Build simple circuits using circuit simulations on PHET

1. Visit the Circuit Simulation: https://phet.colorado.edu/
    a. Simulations > Physics > Electricity-Magnetism-Circuits > Circuits Construction Kit DC- Virtual Lab> click the play button
2. Build the following circuits to **<u>light a bulb</u>** (be sure to add the flow or direction of current using arrows, *See 'show current' on the right-hand side and select *conventional* for arrows.

Take a screenshot of the configurations and bring to class

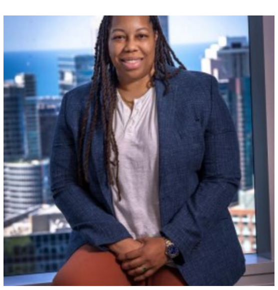
a. Using one battery, one wire
b. Using one battery and one paper clip, one wire
c. Using one battery and one pencil, one wire
d. Using two wires, one battery and a switch

Review: **Understanding Electrical Circuits Quiz**

1. Define voltage, resistance, and electrical current
2. What is an electrical circuit and what happens when a circuit is open?
3. In a DC circuit, how does current flow?
4. What is an open circuit versus a closed circuit?
5. What is the role of a switch in a circuit?

In class activity:

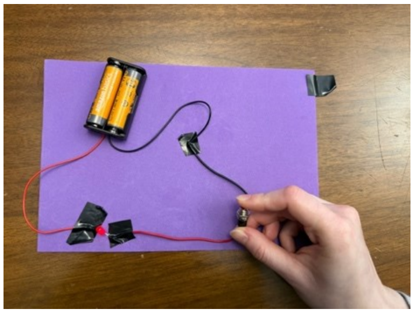
KDM Engineering is conducting environmental field assessments at a remediation site where technicians must monitor equipment zones during testing. To improve safety, the engineering team needs a simple, low-cost visual indicator system that clearly shows when a testing circuit is active. Your task is to design a prototype safety indicator using an LED, battery, wires, a switch.



Woman in STEM Highlight
Kimberly D. Moore is the founder and president of **KDM Engineering**, a Chicago-based firm specializing in power, gas, and telecom distribution design. A South Side Chicago native and NIU electrical engineering alum, she founded KDM in 2008 and rebuilt it after a recession-driven pause, growing it to 100+ employees. Moore is also the founder of **Calculated**

Genius, a nonprofit supporting underrepresented youth in STEM, and serves on several community and industry boards.

Your task is to design a prototype safety indicator using an LED, battery, wires, and switch.



Lecture and review circuit simulations, go over parts of the kit

Building a simple circuit: students work in pairs to build a simple circuit: light an LED with a battery, wires and a switch. On the paper board, draw arrows to show the flow/direction of current.

Discussion:

- Why is it important for a circuit to be closed for current to flow? How does this principle apply to real-world devices like smartphones or household appliances?
- How does adding a switch improve the functionality of a circuit? Can you think of examples where switches are essential in everyday life?
- What would happen if the polarity of an LED is reversed in a DC circuit?

Lesson 2 In Your Electric Era: Bring Your Circuit to Life with Arduino

Pre-lab: reading, build simple circuit and program an Arduino to turn an LED on/off using TinkerCAD, research and identify a notable woman in STEM whose work significantly relates to electricity or electrical systems then complete a short quiz.

Reading: **Arduinos and Simple Circuits**

Practice: build simple circuit and program an Arduino to turn an LED on/off using circuit simulations on TinkerCAD.

After completing the reading:

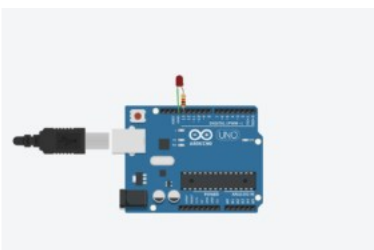
1. Visit the Circuit Simulation: TinkerCAD > Enter the log-in code which is your **NetID**
2. Click on classes > select ISR class > click on the Blink LED Activity > click copy and tinker
    a. Select an **LED**, make the **LED** any color other than red by clicking on the **LED** and selecting the down arrow on the color field
    b. Select a **resistor**, drag it to the workspace (change the resistance to **220 W** (ohms).
    c. Attach the cathode end of the **LED** to the port labeled **GND** on the **Arduino**, by clicking on the end of the cathode wire and dragging the wire to the port

    d. Attach the **resistor** to the anode end of the **LED**
    e. Add the **resistor** to the port labeled **13** on the **Arduino**
    f. **START** simulation > **LED** will **BLINK** as well as the **L** (onboard built- in LED) on the **Arduino board**
3. Reviewing the CODE (click on the code button)
    a. Select from the drop down: **blocks and text**
    b. You can now see the code used to make the LED blink
    c. Now let's make the LED to blink faster
        i. In the blocks, change the value to from 1 to 0.5
    d. **START** simulation
    e. Observe the change in speed of blinking
    f. **STOP** the simulation

Review: **Understanding Arduinos and Simple Circuits Quiz**

1. What is an Arduino? Provide a complete definition
2. Describe the role of an Arduino in physical computing.
3. What role do voltage, current, and resistance play in an Arduino circuit?
4. Why is a resistor important when connecting an LED to an Arduino
5. What does physical computing involve?

In class activity



Lecture and review circuit simulations, go over parts of the kit (Arduino photo).

Build simple circuit and program an Arduino to turn an LED on/off. Students work in pairs to make an LED blink using an Arduino, resistor, two wires and an LED

Discussion:

1. Why are Arduinos considered essential tools for learning physical computing?
2. Why is it important to include a resistor when connecting an LED to an Arduino?
3. Describe a real-world application of physical computing using Arduino.

Appendix #3: Rutgers Open Ended Survey Question

Please enter your feedback about the electricity lesson and activities.
I think that it gave me better understanding of basic circuits and its components.
I enjoyed making the circuit since it makes the theory really connect to what circuits are in reality, making it easier to understand the concept
I liked how we had to figure out on how to maintain the correct current flow in order to light up the LED light helping us have a better understanding overall in current flow.
It was very fun! I appreciated the simulation beforehand but actually working with it in person helped me understand current flow more
I enjoyed the electricity lesson and activities, everything was detailed and easy to follow.
I thought this activity was redundant and less interesting than the hands-on version. If anything, it would make sense to do this one first as prep for the in-person one.
It was very fun and interactive, the directions were very simple to follow along!
It was good, but I prefer group work in class to learn because it is more interactive.
The activity was very helpful to apply the learning
I really liked our hands on activity with the circuit, our circuit didn't work at first but I think the struggle really reinforces the lesson of the circuits.
I thought it was helpful, and I really enjoyed having a group to work with.
The lesson gave me a good reminder of the basics of circuits and helped us to build the circuit. The instructions and diagrams in the instruction helped us build the circuit quickly and successfully.
It was a bit difficult getting the lightbulb to work, but with our table we were able to connect the wires efficiently.
I liked it but wish we could have watched a Youtube video about circuits beforehand to summarize everything we learned through the readings + simulation.
Some of the written instructions were confusing or had mistakes/typos, and the visual provided did not match the instructions. Granted, it did not make a difference, but it would've been good for them to match. The online activities were good!
The simulation was a great way to apply the knowledge, instead of simply reading about it.
The instructions were a little unclear, ie the graphic did not match what was written. The activity itself was simple and straightforward.

Really great. Asked Dr.Jo and figured it out.
I thought the study was simple and understandable overall the only part I found a bit strange was part 2 where we had to connect the concepts to a running track.
It was fun!
The lessons are nice and give good practice for understanding electricity and seeing how it works.
Liked its hands on
It was difficult to ensure all the parts were interacting with each other.
N/A
It was very interactive and I learned a lot. It was very fun and engaging
It was fun and simple to do
-
I felt that the instructions were thorough and easy to comprehend.
This was too basic of a lesson for the education level that we are at. I wish there were short videos to demonstrate connecting the modules.
This was a fun lab, it was a little frustrating at first because the connectivity of the wire was difficult.
It was a fun simple activity that introduced and well illustrated basic principles of electrical circuits.
It was nice to compare our circuit with another group to identify our mistakes. Having a video that we can watch to prepare for the practical aspect of the assignment would allow for a smoother time in interpreting the directions as the pictures sometimes do not entirely always correlate accurately with the instructions which can cause confusion.
I think this was a very interesting lab.
I think it was difficult to make sure all the parts were right but overall very fun and I enjoyed doing the lesson!
I really enjoyed the hands on approach as it made visualizing the circuit a lot easier.
It was pretty fun, although I didn't really understand the analogy in the worksheet where you relate an electric circuit to people running on a track, specifically the series and parallel part. I understand what circuits in series and parallel are, but I don't know what it is in track terms.
I liked how it pushed me to think critically.
The physical lab helped me understand the subject matter the most.
Overall, the lesson was easy to understand, but I think that a video walkthrough of sorts would have aided my understanding of how to produce a functional LED.
It was nice being hands on with this experiment , Directions were a little confusing, but having the outcome is fun it's like a puzzle

It was helpful for learning although I did have significant experience with circuits
The wires were hard to connect to each other
I liked the electricity lesson and activities as it was easy to comprehend. All the definitions in the reading were comprehensive and I liked the hands-on activity as I'm able to make connections.
N/A
It was an interesting activity and I liked working with circuits.
I enjoyed the lesson.