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Circuit-First Approach to Improve Engagement and Retention

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Abstract

In many engineering physics programs with low enrollments, *General Physics* courses are offered only once per academic year. In addition, incoming students often exhibit wide variation in mathematics preparation, and many are unable to enroll in *Calculus* during their first semester. Consequently, completion of the *Calculus–General Physics* sequence may be delayed until the junior year, postponing access to core engineering courses. Such delays can undermine student motivation, as mathematics is often perceived as abstract and disconnected from engineering practice, and may ultimately contribute to increased student attrition.

To address this challenge, our program implemented a **Circuit-First approach**, placing *Circuit Analysis I* in the second semester of the freshman year so that it can run in parallel with *General Physics*. To support students with relatively weak mathematical preparation, an introductory mathematics course is offered in the first semester, covering the foundational concepts and skills needed for *Circuit Analysis*. This curricular restructuring provides students with early exposure to engineering concepts and applications, even when their mathematical preparation is incomplete. While the approach offers clear benefits in terms of student engagement and engineering identity formation, it also introduces challenges related to student readiness, conceptual understanding, problem-solving skills, and laboratory proficiency.

This paper examines these challenges through instructional experiences and observations of student performance, describes targeted pedagogical strategies developed to support first-year learners, and reflects on the overall impact of the **Circuit-First approach**. The results provide practical insights for engineering programs seeking to mitigate curricular bottlenecks, improve student retention, and strengthen early connections to engineering practice.

1. Introduction

Engineering Physics programs, particularly those with relatively small enrollments, often face structural and curricular constraints that significantly affect student progression and retention. In many such programs, the *General Physics* sequence is offered only once per academic year and is tightly coupled to the *Calculus* sequence. As a result, *General Physics I* is typically scheduled in the second semester of the freshman year, assuming that students enroll in *Calculus I* during their first semester.

At institutions with broad access or high acceptance rates, however, incoming students arrive with widely varying levels of mathematics preparation. A substantial fraction of first-year students are not *Calculus*-ready and must begin with precalculus or other remedial mathematics courses. For these students, enrollment in *General Physics I* is delayed until the sophomore year, effectively postponing completion of the *Calculus–General Physics* sequence until well into their academic programs. This delay, in turn, restricts access to the engineering courses that depend on the physics sequence and slows overall progress toward degree completion.

This misalignment has broader implications for student engagement and retention. During their first two years, many engineering students encounter little direct exposure to engineering coursework, while spending a disproportionate amount of time in mathematics classes that are often perceived as abstract, highly theoretical, or disconnected from engineering practice. The lack of early engineering context can erode student motivation, weaken the development of an engineering identity, and increase the likelihood of attrition—a phenomenon commonly described as the "leaky pipeline" in engineering education [1–4].

To address these challenges, our program implemented a revised curricular sequence that introduces *Circuit Analysis I* in the second semester of the freshman year, allowing it to run in parallel with *General Physics*. This *Circuit-First Approach* is intended to provide early, discipline-relevant engineering experiences even for students whose progress in mathematics and physics is delayed. This paper presents the motivation for this curricular change, examines the instructional and pedagogical challenges encountered when offering a rigorous engineering course at the freshman level, and discusses lessons learned that may inform similar efforts in other engineering programs.

2. Challenges of Circuit-First Approach

Beginning in Spring 2023, the prerequisite of *General Physics* was removed for *Circuit Analysis*, thereby opening the course to freshman students. This change was motivated by enrollment patterns observed prior to the curricular revision, which highlighted significant delays in student progression. For example, the Spring 2022 roster for *Circuit Analysis I* illustrates the severity of the issue. Of the seventeen students enrolled, six were senior students with more than 90 earned credit hours, nine were junior students with over 60 credit hours, and only two were sophomores.

Circuit Analysis I is typically the first required course in the electrical engineering sequence and serves as a gateway to numerous upper-level engineering courses [5]. When students are unable to enroll in this course until their junior or senior year, progression through the remainder of the curriculum is substantially delayed. As a consequence, many students face extended time-to-degree, with graduation often requiring five or more years. These enrollment data underscore how prerequisite structures tied to *Calculus* and *General Physics* sequences can unintentionally create bottlenecks that impede timely student advancement and contribute to attrition.

The curricular shift also revealed several instructional and learning challenges associated with introducing *Circuit Analysis* at the freshman level. Compared to their more advanced peers, first-year students often lack the required capability that can meet the expectations and cognitive demands of sophomore-level engineering coursework. While *Circuit Analysis* is grounded in a small set of fundamental principles—most notably Ohm's law and Kirchhoff's voltage and current laws—the network of concepts, representations, and analytical techniques that builds upon these foundations can be difficult for novice learners to navigate.

One recurring challenge observed was students' tendency to rely on "equation matching" approach, in which formulas are selected based on superficial resemblance to a problem rather than derived through systematic application of underlying principles. Additionally, many freshmen struggled to organize multi-step solutions, particularly when problems required the integration of conceptual understanding, mathematical reasoning, and circuit representation. These patterns suggest that early exposure to *Circuit Analysis* must be accompanied by more explicit scaffolding of engineering problem-solving strategies, including structured reasoning, principled model development, and clear solution pathways.

Laboratory sessions of *Circuit Analysis* presented additional challenges for first-year students. One common difficulty involved translating schematic diagrams into physical circuits. Many students struggled to map abstract symbols onto real components, particularly when connecting external sources such as voltage supplies or function generators. These challenges reflect limited prior experience with hardware-based representations of electrical systems.

Students also encountered difficulties in the proper use of measurement instruments. While voltage measurements were generally manageable, current measurements proved especially problematic, often due to improper circuit insertion. These errors frequently resulted in blown fuses, underscoring gaps in students' understanding of measurement principles and instrument operation.

Beyond these procedural and technical issues, a more subtle but significant challenge was the integration of theory and experiment. Many students approached laboratory activities by following step-by-step instructions without fully understanding the underlying purpose of each action or its connection to circuit theory. This tendency highlighted the need for instructional strategies that emphasize prediction, interpretation, and reflection, enabling students to view experiments not merely as tasks to be completed but as opportunities to test and reinforce analytical models.

3. Instructional Strategies

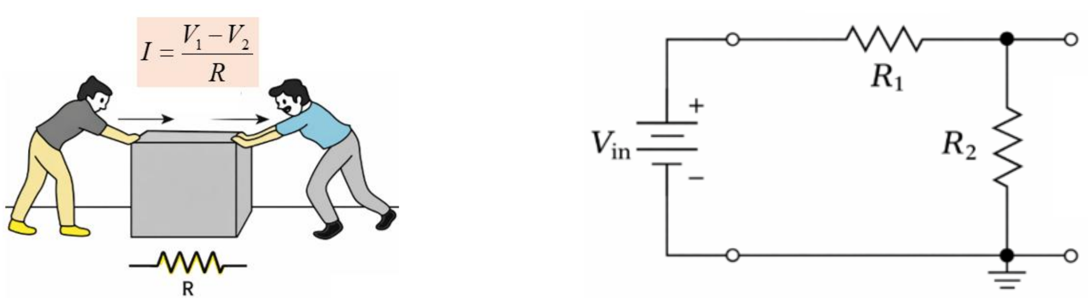
3.1 Understanding concepts and theorems

In response to these challenges, several instructional strategies were implemented, with particular emphasis on establishing a coherent conceptual framework for *Circuit Analysis*. Course content was organized around a hierarchical structure that can be represented as a "conceptual tree." The fundamental laws of *Circuit Analysis*—such as Ohm's law and Kirchhoff's laws—form the "trunk" of the tree, while analytical techniques, circuit configurations, and applications emerge as the "branches." This structure was made explicit during lectures to help students recognize how diverse topics originate from a small set of core principles.

From a complementary perspective, this framework was also presented as a *concept map* that illustrates the relationships among circuit elements, governing laws, and solution methods. Within this representation, problem solving is framed as navigating from a set of given parameters to a set of unknown quantities by following logically connected pathways, rather than searching for isolated equations. Frequent reference to the *conceptual map* through examples, analogies, and visual representations was used to reinforce structural understanding and help students develop a more integrated view of electric circuits.

Addressing student misconceptions is a critical component in teaching any course. One common misconception involves the definition of a *node* in an electric circuit. Students often interpret a node intuitively as a single physical junction where two or more wires meet, focusing only on its local, structural appearance. In *Circuit Analysis*, however, a *node* is defined as the entire wire network that are electrically connected by ideal conductors and therefore share the same electric potential. This conceptual understanding is essential for correctly identifying *series* and *parallel* elements, as well as for applying the method of *nodal analysis*.

Another frequently observed misconception concerns the interpretation of voltage in Ohm's law. Many students confuse *nodal voltage*—the electric potential of a node with respect to a reference—with the *bias voltage* (or voltage difference) across a circuit element. As a result, students may incorrectly substitute nodal voltages directly into Ohm's law. To address this issue, Fig. 1(a) is used as a conceptual aid to emphasize that current through an element is driven by the "difference in voltage between its two terminals", not by the absolute voltage at a single node. This visual representation helps reinforce the relational nature of voltage and supports more accurate understanding of Ohm's law.



(a) **(b)**

Fig. 1 (a) Mechanical model of Ohm's law, (b) voltage divider circuit.

In *Circuit Analysis I*, Thévenin's theorem consistently emerges as one of the most conceptually challenging topics for students. Difficulties arise not from the mathematical complexity of the theorem, but from the required shift in perspective when analyzing circuit behavior under different conditions. To support student understanding, the voltage divider circuit shown in Fig. 1(b) is used as a prototype to introduce and illustrate the core ideas of Thévenin equivalence.

Although the voltage divider is among the simplest resistor networks, it provides a powerful instructional example with applications extending to topics such as the transfer function of first-order filters in AC circuits. When determining the open-circuit Thévenin voltage, students correctly recognize that the two resistors are connected in series. However, confusion often arises when calculating the equivalent Thévenin resistance. After deactivating the independent voltage source, the same resistors must be analyzed from the output terminals, at which point they are electrically in parallel. This change in perspective is highly counterintuitive for many students and requires deliberate instructional emphasis.

Rather than relying on memorization, instruction focuses on guiding students to reason through the source-deactivation process and terminal-based viewpoint inherent in Thévenin's theorem. With repeated exposure and structured practice, students gradually develop a more flexible understanding of circuit equivalence and the conditions under which circuit topology must be reinterpreted.

3.2 Scaffolding problem-solving process

During Fall 2025, the author taught both *General Physics II* and *Circuit Analysis II*, providing an opportunity to compare differences in homework assignment structures and their influence on student problem-solving practices. At many universities, large enrollment in *Calculus* and *General Physics* courses necessitates the use of online homework systems. For example, WileyPLUS is used in author's institution for *General Physics*.

These systems offer clear logistical advantages. Automated grading significantly reduces instructor workload, and randomized numerical parameters require students to perform individualized calculations rather than rely directly on solution manuals. However, a critical limitation of such systems is that students are typically required to submit only final numerical answers. As a result, intermediate reasoning, modeling choices, and solution procedures remain largely invisible to instructors.

This assessment structure can inadvertently encourage a results-oriented approach to problem solving, in which students focus on obtaining the correct numerical answer rather than developing a coherent and transferable solution process. The absence of feedback on reasoning steps contrasts sharply with the expectations of engineering coursework, where structured analysis and justification are essential. This mismatch highlights the need for deliberate instructional strategies in *Circuit Analysis* courses to explicitly emphasize and assess problem-solving processes, particularly when students transition from physics and mathematics courses that rely heavily on automated homework systems.

To address the problem-solving challenges discussed above, homework assignments in *Circuit Analysis* were redesigned using a structured, multi-step format. This scaffolded approach is intended to shift students away from equation matching strategies and toward principled, systematic reasoning. By explicitly breaking problems into sequential tasks, instructors are able to assess not only final answers but also the intermediate reasoning processes that lead to those results.

Circuit transformations play a central role in this design, as they are widely used in the analysis of electrical networks. Students are required to draw transformed circuits at each relevant step, making their conceptual understanding explicit. For example, when applying Thévenin's or Norton's theorems, students must first construct and document the appropriate equivalent circuit before proceeding to numerical analysis. Similarly, when Kirchhoff's laws are employed, students are asked to formulate the governing equations as a distinct step prior to solving them.

This multi-step structured style reinforces the idea that *Circuit Analysis* is a process of model development and refinement rather than a direct search for equations. By making each stage of reasoning visible, the scaffolded homework design supports deeper conceptual understanding and promotes transferable problem-solving skills essential for subsequent engineering coursework. In addition, it can also effectively prevent students from copying from solution manuals.

3.3 Developing laboratory skills

Under the Circuit-First Approach, *Circuit Analysis I* is offered in parallel with *General Physics I*, which typically focuses on mechanics. As a result, many first-year students enter the course with little or no prior experience working with electrical circuits in a laboratory setting. Developing foundational laboratory skills thus became an essential component of the course design.

To support students during this transition, sample circuits assembled on breadboards were provided for demonstration in the initial laboratory assignments. These examples allowed students to focus on understanding circuit behavior and measurement techniques before assuming full responsibility for circuit construction. This approach is analogous to learning to read before learning to write, emphasizing the importance of guided exposure prior to independent practice.

In addition, brief instructor-led demonstrations were conducted at the beginning of each laboratory session to introduce measurement instruments and proper procedures for voltage and current measurements. For example, a "break-and-insert" approach was emphasized for current measurement: students first break the circuit to create an opening and then insert the ammeter to bridge the gap, which is shown in Fig. 2. This explicit two-step procedure helps students overcome the common tendency to place meter probes across a device, as is done in voltage measurements.

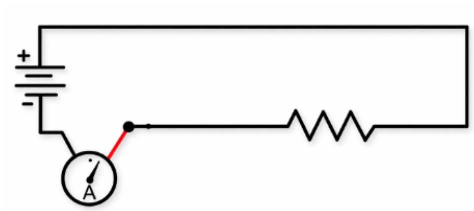


Fig. 2 Break-and-insert approach in current measurement.

Laboratory preparation was further reinforced through lecture–lab coordination. Key concepts and objectives of each laboratory assignment were introduced and discussed in lecture prior to the lab session, helping students establish connections between theoretical analysis and experimental implementation. Together, these strategies provided structured support for novice learners while gradually building confidence and competence in circuit experimentation.

NI Multisim was incorporated as an integral instructional tool in *Circuit Analysis* to support both conceptual understanding and laboratory preparation. The software provides a wide range of virtual instruments and circuit components, allowing students to simulate realistic circuit behavior under controlled conditions. After guided practice, most students were able to construct and analyze a variety of circuits using the simulation environment.

In the laboratory assignments, students were required to complete circuit simulations prior to conducting the experiments. These simulations served as a reference model and guided expectations for experimental outcomes. When significant discrepancies arose between simulated and measured results, students were prompted to reexamine their circuit construction, measurement techniques, and assumptions to identify potential sources of error. This simulation–experiment comparison encouraged reflective troubleshooting and reinforced the connection between theoretical models and real-world circuit behavior.

4. Discussion

The Circuit-First Approach has produced mixed but encouraging outcomes. Student feedback indicates increased motivation and a stronger sense of engineering identity, particularly as students begin to recognize how foundational coursework in mathematics and physics supports engineering applications. Early exposure to discipline-specific engineering content appears to promote engagement and may contribute to improved retention, especially among students who might otherwise experience delayed entry into the engineering curriculum.

Additional insight into the relationship between *General Physics* and *Circuit Analysis* was obtained when the author taught both *General Physics II* and *Circuit Analysis II* during Fall

2025. An informal student survey examined perceptions of taking the two courses concurrently, and a majority of respondents indicated that the parallel enrollment was beneficial. Notably, many students reported that the knowledge and problem-solving skills developed in *Circuit Analysis II* were more helpful for understanding topics in *General Physics II* than the reverse. One possible explanation is the difference in instructional pacing between these two courses. In *General Physics II*, AC circuit topics—including capacitors, inductors, and transformers—are typically covered within a limited time frame of approximately two weeks. In contrast, *Circuit Analysis II* provides a full-semester, in-depth treatment of these topics, allowing students to develop a more robust conceptual framework and analytical skill set that transfers effectively to the physics context. Therefore, many people questioned the necessity of completing *General Physics* series before taking engineering courses [6-8].

Although AC circuits are generally considered more complex than DC circuits, many students reported that *Circuit Analysis I* was more challenging than *Circuit Analysis II*. One possible explanation is the strong conceptual continuity between the two courses. Most fundamental theorems introduced in DC *Circuit Analysis*—such as Kirchhoff's laws, Thévenin and Norton theorems, and nodal and mesh analysis—remain applicable in AC circuits, with the primary modification being the extension from real-valued quantities to complex-valued phasor representations. This continuity allows students to build upon an established analytical framework rather than learning entirely new methods.

In addition, by the time students enroll in *Circuit Analysis II*, they are generally more comfortable with laboratory instruments and experimental procedures, reducing the cognitive load associated with hands-on work. In contrast, *Circuit Analysis I* requires students to simultaneously develop new conceptual understanding and foundational laboratory skills. These observations suggest a potential curricular refinement: Relocating *Op-Amp circuits* or *second order transient circuits* from *Circuit Analysis I* to *Circuit Analysis II*. Such a shift could provide students with additional time to consolidate core concepts and laboratory competencies before engaging with time-domain analysis, thereby improving overall learning and reducing perceived difficulty in the introductory course.

5. Summary

This paper presents a **Circuit-First approach** implemented in an Engineering Physics program to address curricular delays caused by variations in mathematics readiness and rigid physics prerequisites. In programs with low enrollments and once-per-year offering of *General Physics*, students who are not calculus-ready often experience delayed access to both physics and engineering courses, resulting in extended time to degree and increased risk of attrition. By introducing *Circuit Analysis I* in the second semester of the freshman year and offering it in parallel with *General Physics*, the revised sequence provides early exposure to engineering concepts even for students whose mathematics preparation is delayed.

This paper examines instructional challenges associated with offering *Circuit Analysis* at the freshman level, including conceptual overload, misconceptions, equation-focused problem solving, and limited laboratory experience. To address these issues, several targeted strategies were implemented, including explicit conceptual frameworks, scaffolded homework assignments, coordinated lecture–laboratory instruction, and simulation-supported experimentation. Preliminary observations and informal student feedback suggest increased student engagement, stronger development of engineering identity, and improved transfer of learning between *Circuit Analysis* and *General Physics*. These results indicate that early, well-supported engineering coursework can help mitigate curricular bottlenecks and improve student persistence.

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