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Co-STARS: a Community of Students Through Augmented Reality Systems

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1. Introduction

Electrical and computer engineering courses, like many of their counterparts in science, technology, engineering, and math (STEM) fields, face challenges in improving the student understanding of the subject matter. Some of these challenges include connecting the abstract concepts that are covered in the classroom to real-life applications and systems; engaging the students in the learning process and easing the burden of long, abstract lectures; working with tangible objects such as circuits, development boards, electronic parts, etc. while presenting the topics for the first time to students; and enhancing the soft skills, such as communication and team working while delivering the engineering concepts.

To address some of the challenges, many approaches involve a type of active learning, which aims to engage the students in their learning experience rather than being the silent audience in the classroom. Flipped, problem-based, and collaborative learning are examples of active learning pedagogy that aim to increase the students' engagement in their education experiences, knowledge retention, and information applications. These pedagogy approaches also enhance the students' critical thinking, investigation, verbal communication, and teamworking skills (e.g., [1]—[4]).

Whereas these active-learning pedagogical methods and approaches have addressed many of the challenges in STEM educations, they may not have been able to address *additional* challenges that are unique to electrical and computer engineering (ECE) courses. That is, while ECE courses can benefit from the active-learning pedagogical approaches, they face challenges in illustrating fundamental concepts to students due to the intrinsic abstract nature of such concepts (e.g., illustrating currents in circuits). Students may not be able to fully envision or visualize fundamental concepts or the cause-and-effect relationship between the concepts. Textbook figures and diagrams and in-class drawings can only depict a static view of the equations and lack the lucidity of portraying the cause and effect dynamically (challenge #1).

Furthermore, the complexity of the mathematical solutions behind ECE concepts can further exacerbate the ability of portraying the dynamic interactions among concepts or components in an electrical system. For instance, in a resistor-inductor-capacitor (RLC) circuit, differential equations are used to arrive at the steady-state solution, and multiple drawings of different states can only be done at coarse-grained steps to illustrate the dynamics. Hands-on laboratories can aid in illustrating theoretical concepts by working with physical components and measuring tools (e.g., building small circuits and using oscilloscopes). However, these laboratories tend to be carried out in a subsequent semester after the students have finished with the theoretical foundations. There is a need to provide dynamic illustrations at a fine granularity to students while theoretical concepts are discussed in the classroom (challenge #2).

Based on our observations of challenges 1 and 2 in ECE courses, we proposed Co-STARS, a Community of Students Through Augmented Reality Systems. Co-STARS aims to address the

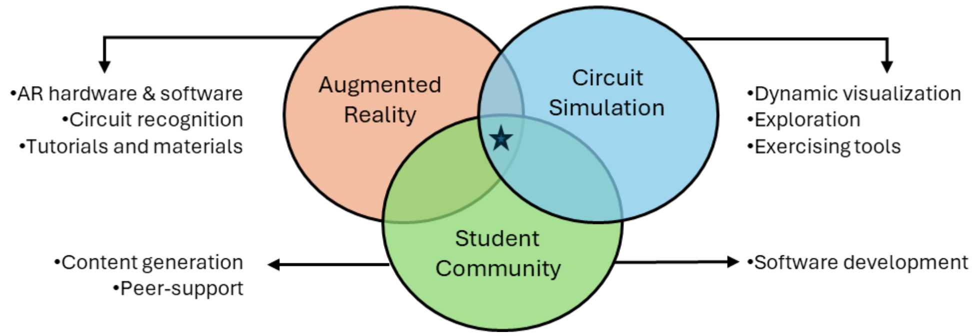


Figure 1. CO-START foundation, based on the intersection of augmented reality, circuit simulation, and student community.

shortcomings of static illustrations of abstract concepts using dynamic simulations while maintaining student engagement in the learning process. We piloted Co-STARS in our Circuit Analysis Theory class, which has abstract concepts and complex mathematics [5]. The pilot was well received by the students. The positive reception was validated by the amount of content creation and positive feedback received.

2. Co-STARS

Our framework has three aspects: augmented reality, circuit simulation and student community. The intersection of these three aspects provides the students with the opportunity to engage, contribute, and practice circuit analysis theory.

Figure 1 displays a summary of our framework aspects. The augmented reality (AR) system consists of AR headsets and an AR application (hardware and software), and is responsible for integrating circuit recognition, simulations, and tutorials. The circuit simulations aim to alleviate the burden of abstract concepts on students and increase their engagement in the classroom. It is used in our lecture to display dynamic visualization of the example-circuits to our students and serves as a tool for exploration and exercises. The student community represents the students' responsibilities and engagement in the learning process—student engagement in content creation, peer-supporting (tutoring), and system development.

To allow the framework flexibility, the circuit simulations and student community contents are not hard coded into the AR system. Rather, the AR system is designed for future compatibility, with respect to generated content and simulations. That is, the AR system is designed with an interface that allows it to accept new content, generated by students, faculty, or the Co-STARS community—the system itself does not contain hard-coded material, nor requires many changes to adopt newly-generated content.

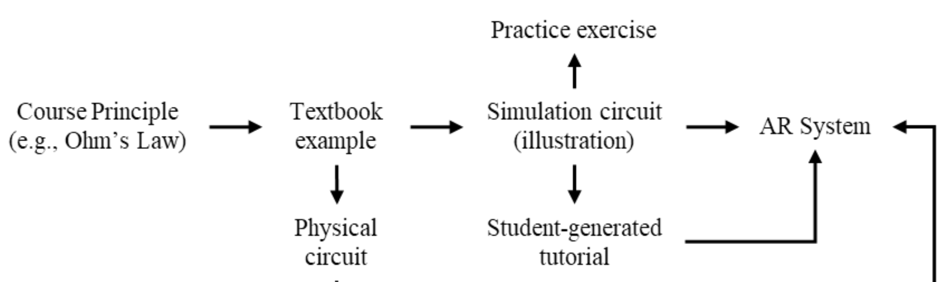


Figure 2. Instructional design flow in Co-STARS framework.

Figure 2 displays an instructional design flow for our framework. Starting with a principle that is covered in our class, we examine the content in the textbook and select, design a physical circuit (on a printed-circuit-board), and simulate the circuit in software. The simulation of the circuit is used to illustrate the concept to students during classroom exercises. Based on this simulation, the students are tasked to solve exercises and generate tutorial material. During subsequent activities, the AR system is used to engage the students once more in learning about the principle. The students will wear an AR headset and launch the application to inspect the circuit, run the simulation, and launch/select tutorial material as needed.

3. Circuit Simulations

Using simulation and emulation software is a well-known method to study, evaluate, and explore systems before the systems are sent for fabrication. In education, such software is used to illustrate to students the interactions among circuit components, enhance students' understanding of the abstract concepts involved in a circuit, and provide hands-on experience on circuit design and exploration. There is a myriad of such software that ranges from open source to professional and proprietary, with various levels of complexity, hardware/operating system requirements, accuracy and easiness.

Consequently, there are tradeoffs one must consider before selecting the software to be used for the intended purpose. For instance, while a professional-grade software (e.g., [6]) can simulate a circuit accurately, it may require a steep learning curve to master and may not be intuitive, and consequently is not suitable for undergraduate students who are still learning the basics of circuits, nor suitable for in-class activities. Therefore, to select software that is appropriate for our framework, we considered the following factors:

(1) Interoperability: interoperability of the simulation software allows students to run simulations on their personal devices, regardless of the devices' hardware and operating systems specifications.
(2) Ease of use: to alleviate the burden of steep learning-curve, the software must be usable without requiring lengthy setup processes, dependencies, libraries, scripting, or compilations.
(3) User Experience (UX): our UX metric focused on intuitiveness and graphical user interface (GUI) easiness. For our intended purposes, intuitiveness is the ability to drag-and-drop circuit components and click-and-play simulation runs; and GUI easiness entitled descriptive components (buttons, menus, circuit elements, etc.) and common functionalities (open, save, export, functions, etc.).
(4) Cost: expensive software may hinder the student's ability to obtain a license for personal use. To alleviate the cost burden on students, the software license must be affordable or free (e.g., open source)

We narrowed down our search and experimented with the following three software programs: OpenSce [7], EveryCircuit [8], and Falstad [9]. EveryCircuit and Falstad met our factors the most, however, EveryCircuit was our choice for its interoperability (e.g., running inside a Chrome browser without dependencies) and user-friendly GUI.

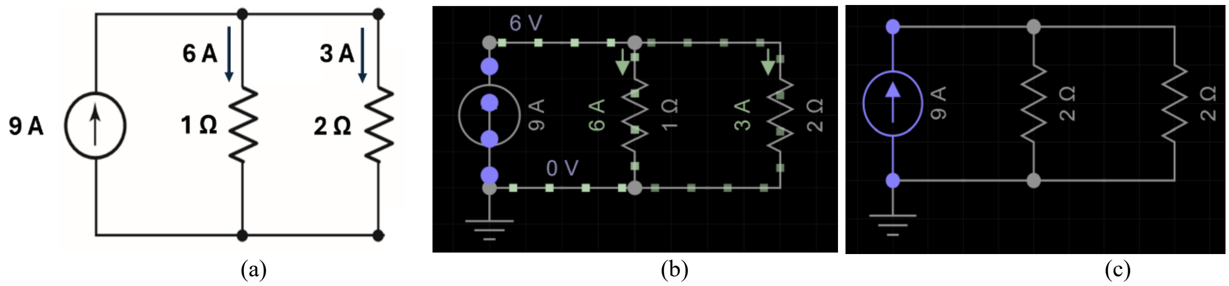


Figure 3. current division circuit in (a) static format, (b) capture of dynamic simulation, and (c) prepped for student exercise.

3.1. In-class Circuit Simulation Exercises

To encourage students to use simulation software in a classroom environment, we designed sample simulations, presented them as part of the lecture content, and designed exercises for students to complete using the simulation software. The sample simulations and the exercises are based on the textbook content that is used in our class.

Figure 3 is an example of our approach to illustrate concepts using simulation to the students. Figure 3 (a) displays an example of current division that is commonly used to illustrate the split of a current in two branches, wherein a 9 amps current is divided into 6 and 3 amps between the 1- and 2-ohm resistors, respectively. The example is static and discussed in theory with students. (b) is a capture of the dynamic simulation of the same example in EveryCircuit, showing the value of the current in each of the circuit's branches, the intensity of the current represented with the transparency of the current (the current in the 2-ohms resistor is more transparent), and the voltage at the top node (6 volts). (c) is the modified circuit the students must simulate to obtain the answer of the current values in the branches. Students must render the circuit on their electronic device (smartphone, tablet, or laptop), run the simulation, and answer a multiple-choice question about the current. The correct current value would be 4.5 amps in (c).

In a similar manner, we designed exercises for many basic concepts covered in our circuit analysis theory class. For instance, our exercises covered current division, voltage division, Ohm's law, and resistor combination principles. To alleviate the need to obtain a license from EveryCircuit, we designed the exercises such that the circuits are basic and can be executed on-the-fly, without requiring a registration or a license—they can be executed immediately and at *no cost*. Furthermore, the values of the constituent components of the circuits can be updated, and

Table 1. Summary of circuit simulations exercises for circuit analysis

Concept	Circuit/Sim.	In-Class Exercise	Assignment
Ohm's law	Current source and a resistor	Adjust resistor value, observe new voltage	Simulate a circuit with a voltage source and a resistor
Current division	Current source and 2 resistors in parallel	Equalize resistor values and observe current changes in branches	Simulate a similar circuit with 3 different current source values
Voltage division	Voltage source and 2 resistors in series	Equalize resistor values and observe voltage changes in loop	Simulate a similar circuit with 3 different voltage source values
Resistor combination	Voltage source with 2 resistors in parallel	Replace resistors with R_{eq}, observe current change	Simulate a circuit with 2 resistors in series with a current source

the changes in the effects/outcomes of the updates are displayed in real time. Table 1 displays a summary of the circuit simulation exercises for these basic concepts. Each concept has a circuit simulation description. The circuit simulation is prepared by the instructor to present during class. The in-class exercise is a modification to the simulation that was prepared by the instructor and obtaining the new value of concept of interest. The assignment is a simulation of a similar circuit with a simple alternation (e.g., a voltage source instead of a current source).

4. Augmented Reality for Circuit Analysis

In recent years, augmented reality (AR) has advanced to a level that allowed it to be used in entertainment, education, and engineering (e.g., [10], [11]). AR has bridged the gap between the physical, real environment and the virtual environment, enabling accessibility to add information onto existing, physical objects.

Several efforts aimed to use augmented reality in education (e.g., [11], [13], [14]). However, they have not used AR for courses in electrical and computer engineering specifically, due to the difficulty of creating AR applications that address the intrinsic challenges in ECE courses. Therefore, we aimed to create an AR application and use it with an AR headset (AR system) to address challenges in ECE education. We wanted to help students *envision the principles working in an actual circuit*, without having to use laboratory equipment. Consequently, the premise of our AR system is that the AR application can recognize a physical circuit with actual components (resistors and batteries), recognize the circuit's topography, and overlay simulations that match its topography.

There are a few headsets that come with support for development, including Microsoft's HoloLense [15] and Magic Leap [16]. For brevity, we skip the technical discussions of the AR headsets, and we acknowledge that both the HoloLense and Magic Leap headsets are comparable in terms of technological advancement and capabilities. However, there are non-technical advantages to using Magic Leap headsets at our institution, including cost; the headsets are available for students to check out from our library and use *at no cost*. Therefore, we aimed to develop our system with the Magic Leap headset.

4.1. AR Application Development

Overall, the AR software must present the student with a GUI that can be navigated easily to study a circuit and obtain the necessary information (simulations and tutorials) that supports the theory behind that circuit. To alleviate any networking complexity, the application would be hosted on the AR headset locally and can be ported to other AR devices as needed.

We developed our application in stages, such that each stage included a feature that would be used in our framework: starting with a version that displays a sandbox of our GUI, and ending with a stage that recognizes a circuit, displays tutorials, and overlays simulations. We developed the application using an agile development model and using the Unity engine [17] and the Magic Leap software packages. For each stage, we tested the application for correct execution and eliminated discovered bugs. For brevity, we excluded technical discussion of the backend development of the application from this paper. For circuit recognition, we used markers to enable the application to recognize a circuit and map it to the matching simulation.

4.2. Student Involvement in the Application Development

Developing the AR application requires design and coding skills that are not necessarily acquired by students who are taking our sophomore courses. However, there was an interest in supporting the development of the application by students who had completed the circuit analysis course in a prior semester. We engaged these students with the design of the sample circuits, testing of the application at various stages, and recording of the tutorials. The application was developed by graduate students at our institution.

5. Design of Tutorials

There are two types of tutorials, one for using the AR application and one for the circuits analysis concepts. For brevity, we focus our discussion on the tutorials for the circuit analysis concepts. The goal of the tutorials was to provide students with background information about the circuit under study, explanations of the results shown in the simulations, and references to textbook or class material that cover the concepts in the circuit. The tutorials were recorded offline, hosted on a local server, and were accessed by the AR application.

The tutorials aimed to assist the students understand the concepts included in the circuit. The tutorials broke down the concepts into steps that can be followed and later integrated into a holistic explanation of the circuit. For instance, a circuit that depicts current division would still employ Ohm’s law to calculate the voltage across resistor branches, and therefore the tutorial that accompanied that circuit would review Ohm’s law.

Furthermore, whereas this concept is straightforward, the composition of the tutorial must be crafted carefully to prevent repetition of in-class presentations (i.e., to avoid repeating the same explanation process, or using the same exact examples).

5.1. Student Engagement in Tutorial Creation

There were two tracks of tutorial creations, one to create content in tandem with the application development, and one to create content in the classroom setting. The overarching goal was to increase student engagement in content creation and therefore the learning process.

The application tutorials were developed as discussed in section 4.2. To engage the students in content creation in the classroom, we composed extra-credit exercises for students to complete. The exercises were to provide tutorials on one concept with an example, record the tutorial, and upload it to our course platform for other students to watch. Students were encouraged to use examples that match the circuits that were simulated in the classroom, but that was not a mandatory requirement.

6. Integration of Co-STARS

We designed physical circuits that resemble the examples in our in-class circuit simulation, executed the simulation for these circuits on EveryCircuit simulator, and curated and recorded tutorials that cover the topics involved in these circuits. Furthermore, to further enhance the students' understanding of the concepts, we *altered the circuit topography* and recorded the

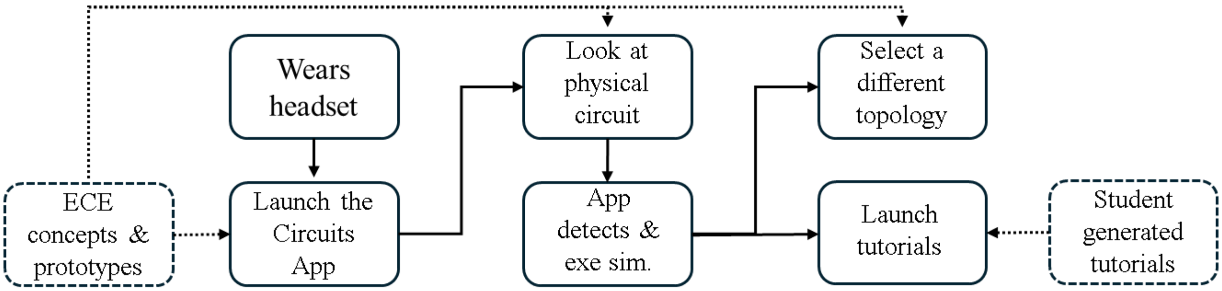
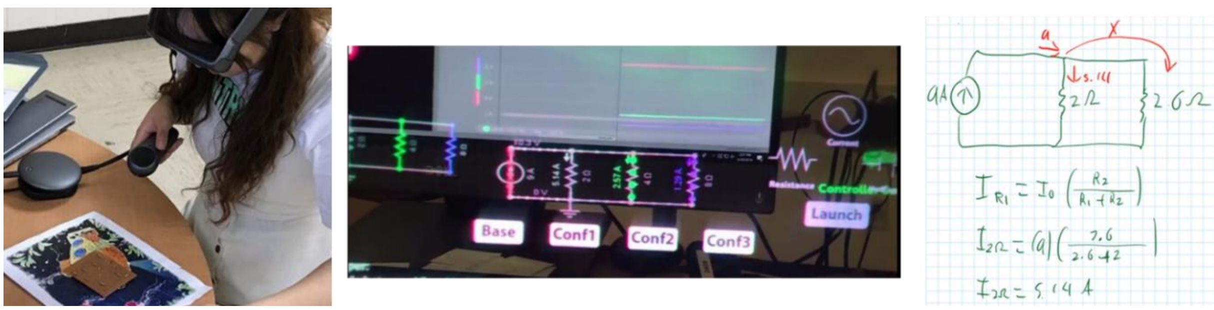


Figure 4. The Co-STARS framework. – AR application flow -- student engagement

simulation for each alteration. Students were able to use the AR system to inspect a circuit, run simulations, inspect alternate topography/configuration, and look up tutorials.



(a) (b) (c)

Figure 5. An example of using the AR system to study a circuit.

Figure 4 provides a holistic view of our Co-STARS framework and how it is utilized. The ECE concepts are based on those covered in a circuit analysis class. For each concept to be adopted in the framework, there must be a physical prototype (physical circuit). When a student wears the AR headset, he/she launches the Circuits application that we developed, and looks at the prototype through the AR headset. The application will detect the prototype and run the simulation that matches the circuit that was detected. The student will be presented with options to select a different topology/configuration/layout of the same circuit or run tutorials that explain the concepts related to the circuit being viewed.

The prototypes and the tutorials are open to students to participate in, increasing the student engagement in the framework. Furthermore, the student generated tutorials can be leveraged from the tutorial-creation exercises by the students and can be accessed by the AR application. However, for our pilot, the prototypes and student generated tutorials are completed separately from tutorial-creation exercises to avoid potential recording/file format compatibility issues.

Figure 5 depicts an example of what the student experiences while using Co-STARS. (a) A student wears the headset, launches the AR application we developed for CO-STARS, and looks at the circuit through the headset. (b) the application automatically detects the circuit and performs the following: displays a pre-recorded simulation of the circuit in its base/original layout; displays three soft buttons to select one of the three alternative layouts of the circuit (conf 1, conf 2, and conf 3); displays a button to launch a tutorial of concepts covered in the circuit. If a student selects one of the configurations, the application displays a pre-recorded simulation of the circuit of that configuration. If the student selects the tutorial, the application launches a pre-

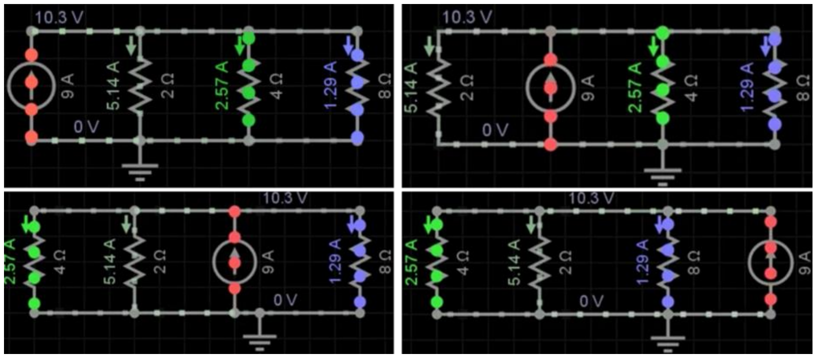


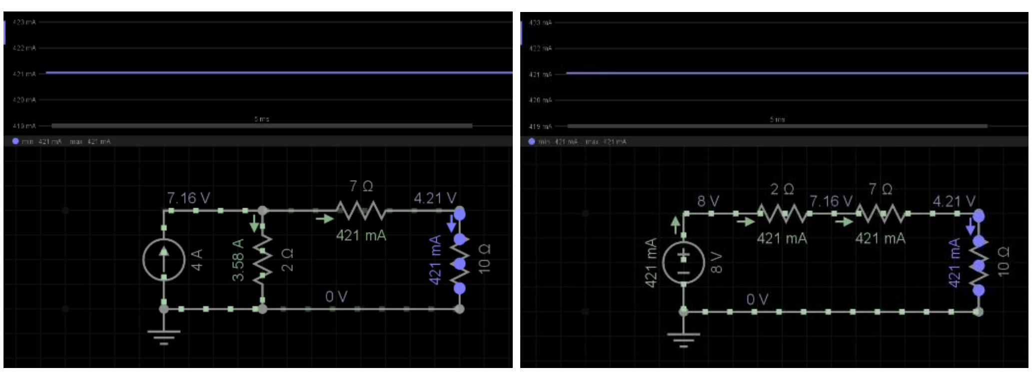
Figure 6. Four layouts/configurations of the circuit

recorded tutorial on a concept used in the circuit. (c) is a screenshot of the video-tutorial combining resistors in parallel and calculating the current through the 2-ohm resistor.

The example in Figure 5 is about current through resistors in parallel. The current through the 2-ohm resistor is 5.14A. The tutorial walks the student through the resistor combination and current division steps to arrive at the same current value of the 2-ohm resistor. For clarity, we depicted the base circuit and the simulation of each layout in Figure 6.

For the same circuit in Figure 5, the configuration options are shown in Figure 6. Top-left is the base circuit with the current source on the left-most branch of the circuit. Configurations 1 through 3 represent the three configurations/topologies/layouts of the same circuit, moving the current source one branch to the right, respectively. Configurations 1 through 3 are displayed in the top-right, bottom-left, and bottom-right diagrams. We note that Figure 6 is a static picture of the simulations the student views inside the AR application. However, the student sees dynamic simulations (as videos) that repeat in a loop, with the flow of the currents and the voltage values displayed. We also note that the dark background is transparent in the AR headset.

Figure 7 is another example of simulation of a circuit that consists of three resistors and a power source. In (a) the 2-ohm resistor is connected in parallel with the 4-amps current source, that can



(a) (b)

Figure 7. Source transformation simulation, using three resistors and one power source. (a) 2-ohm resistor in parallel with 4A current source, transformed to (b) a 2-ohm resistor in series with an 8V voltage source

be transformed to (b) a 2-ohm resistor in series with an 8-volt voltage source. Given the AR application detects a physical circuit that has this layout, the AR application provides the students with the simulation of the base layout (a) or the simulation alternate layout (b), along with the option to view a tutorial on source transformation. The student can view the simulation running and confirm the current through the 10-ohm resistor is the same in both layouts (421 mA). The value of the current is written over the resistor and displayed along the x-axis above the circuit.

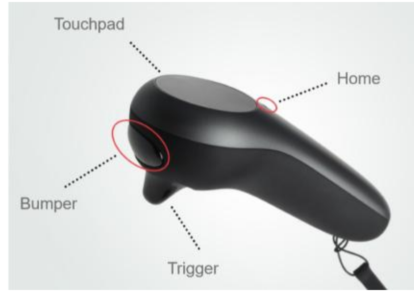


Figure 8. AR controller

To navigate the application in the headset, the student uses a physical controller, shown in Figure 8. The controller has three physical buttons and a touchpad. To keep the application simple, we designed the Home button to take the student to the AR home screen, and the Trigger button to select the options. While the application is running, the controller produces a beam that is visible within the headset. The student can make a selection by pointing the beam onto the virtual button (e.g., Base in Figure 5) and click the trigger. When the trigger is clicked, the AR application plays the simulation of the circuit layout that the student selected or launches the tutorial video.

Consequently, using Co-STARS to practice ECE concepts enables students to envision the dynamics of a physical circuit in the AR environment, explore different circuit topologies or layouts, and review material that pertains to the circuit presented.

7. Student Reception and Discussion

We evaluated the reception of our framework by measuring the student engagement and feedback received about participating in the content creation or application development. For the content creation, we quantified the number of students elected to submit the extra-credit exercises (section 5.1). 31 out of 39 students, or 79% of the students completed the content creation exercises. 52% of these students had already gotten a grade of an A- or better without completing the extra credit assignments, which indicates students' engagement in these activities are not necessarily grade-driven but enthusiasm-driven. Additionally, students were enthusiastic about making their recording, and used movie effects, white boards, and/or drawing software to polish their videos. These were not requirements for the exercises, but rather a sign of engagement in the learning activities.

Furthermore, we used the results of the course evaluation to assess the students' reception of the approaches we use in the classroom. Table 2 summarizes the results of three relative questions in these evaluations, taken by students of two sections—71% and 80% of students completed the evaluations for these two sections, respectively.

Table 2. Summary of student feedback in course evaluation

Metric	Strongly Agree		Agree		Neutral		D/SD	
	Sec. 1	Sec. 2	Sec. 1	Sec. 2	Sec. 1	Sec. 2	Sec. 1	Sec. 2
My ability to communicate about this subject has been enhanced.	71%	58%	23%	25%	6%	17%	0%	0%
I learned to think critically about this subject	71%	67%	18%	25%	12%	8%	0%	0%
This course has been a valuable learning experience	59%	67%	35%	25%	0%	8%	6%	0%

Overall, students had a very positive communication outcome in the class, with 71% and 58% strongly agreed, and 23% and 25% agreed, for sections 1 and 2, respectively. No students indicated disagree or strongly disagree in that category. Similarly, 71% and 18% strongly agreed, and 67% and 25% agreed, for sections 1 and 2, respectively, that their critical thinking skills have improved in the class. Finally, 59% and 35% strongly agreed, and 67% and 25% agreed, for sections 1 and 2, respectively, that the class has been a valuable learning experience for them. Only 6% of students from section 1 disagreed. There were no comments related to this number.

For the AR development engagement, we received the following feedback from the student who assisted with the tutorials that went into the AR application, "… *we are able to cross the barrier between learning and understanding via AR …. Through this project, we are not only just teaching them [students], but we are providing the students with a unique experience by using the latest technology available*." Similarly, we received positive feedback regarding the video tutorial that was given to students, as one student indicated "*I liked the video tutorials [instructor] provided. It was so helpful because I could play it anytime and as many times as I would like*".

There was a small learning curve to using the AR headset. Students needed to learn how to wear the headset correctly and use the AR hand-held controller in conjunction with wearing the headset. Subsequently, the students needed to learn how to navigate to the AR application and launch it. Otherwise, students were enthusiastic about trying the new technology. We attribute the enthusiasm of using the AR systems to the AR's intrinsic advanced electrical and computer engineering concepts and the gamification aspect of the AR headset. Although there was no scoring system in our AR application, the application exhibited an environment similar to a mobile game: downloading an application to the headset, interacting with the augmented reality, exploring the environment with virtual buttons, testing hand-held controllers, exploring alternative configurations and observing the outcomes, etc. Our attribution is aligned with research that supports the gamification and augmented reality positive impact on learning in higher education [18], [19], [20].

Whereas engagement and enthusiasm were observed in our pilot, statistical and quantitative analysis are needed to measure the immediate impact of using our framework on the student assessment scores. These studies would require instructional designs that involve control and treatment groups to measure the difference in the assessment outcomes of the two groups. Research with similar AR setup (i.e., overlaying information on physical objects), has demonstrated statistically significant improvements in student assessment outcomes in civil engineering [21] and physics [22] courses. Additionally, research has also shown that students favored videos as the medium of creation when they were asked to generate peer tutorials in organic chemistry courses [23]. Given these supportive research conclusions, we conjecture that Co-STARS will have a similar positive impact on student assessment outcomes.

8. Adaptation and Scalability

To adapt the framework into course modules, instructional design of the topics must balance between instructor-lead presentations and student-generated outcomes. As we demonstrated examples in Table 1, each concept required a simulation, an in-class exercise, and an assignment exercise. To adopt the concept in the framework, a physical circuit must also be built and marked for the AR application to recognize. This approach is similar to a flipped learning setup, in which students review material before attending class and solve exercises during the lecture, wherein the simulations are part of the pre-lecture material, and using the AR headsets constitutes the post-lecture activities. Therefore, we speculate that instructors who are integrating active- or flipped-learning modules into their circuit analysis courses can find our framework suitable for their teaching style. However, suiting the framework for a circuits analysis course requires expertise to set up the headsets (e.g., downloading the application, authenticating the headset, connecting the headset to the wireless network, etc.), general knowledge of working with AR systems (using the physical controllers, buttons, virtual beams, etc.), and physical circuit construction. These requirements can be easily mitigated, however, given the support material available online.

Additionally, we believe that our framework could be extended to multi-institutional collaboration in future iterations. Ideally, institutions could benefit from sharing the content generated in the framework, such that students would have access to a plethora of tutorials recorded by their peers at other institutions, and instructors cross-checking physical circuits completed by instructors at other institutions. However, from a technical perspective, broadening Co-STARS framework requires an infrastructure that supports the authentication of users outside of the institution; technical expertise to produce and maintain a production-level AR application (e.g., application is distributed on the Magic Leap Hub); and an accessible repository of the tutorial and simulation videos for the circuit modules. These challenges can be alleviated by leveraging institution-sponsored cloud storage services, and/or open-source secure authentication mechanisms (e.g., Open-Source Secure Shell (SSH)). A logical next step for our framework, for instance, can focus on measuring the feasibility of using Open SSH to scale the access permissions to users outside the institution; and evaluate the overhead associated with accessing our framework.

Finally, whereas the availability of the headsets we used contributed to our pilot success, accessibility to the headsets at other institutions or to individual students could be limited due to the high costs of the headsets. However, we believe that augmented reality is still a relatively young technology, and that not only will the cost of headsets lessen as more AR companies and research aim to produce more affordable headsets (e.g., [24]), but also the development will be less technically challenging as more software libraries are being developed and supported.

9. Conclusion

We presented a framework for enhancing the learning of circuit analysis by students. The framework integrates simulation, augmented reality, and tutorials to help students visualize and understand abstract circuit analysis concepts. Our framework aimed to bridge the gap between physical circuits and abstract concepts that are taught in circuit theory classes and engage the students in their learning experiences through content creation and experimentation via the AR system. Students received the content creation and system development very positively and our findings aligned with research about using AR in higher education. Adopting the framework in the curriculum and broadening its audience is feasible, however with challenges. Nonetheless, we believe that these challenges will abate due to the continuous drive in the market and research to reduce the cost of the headsets and increase software development support.

Future research will conduct quantitative and statistical analysis of the impact of the framework on student assessment scores and study the similarity and differences between our framework and state-of-the-art research in AR for higher education. Furthermore, to broaden the participation in our framework, future work will also evaluate the feasibility of using open-source tools and a network infrastructure to authenticate users to our framework and measure the performance overhead associated with scalability.

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