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Instructional Uses of PhET Simulations for Learning DC Circuit Concepts in University Physics

Javiera Gamonal-Pérez, Universidad Andres Bello

Javiera Gamonal-Pérez holds a Bachelor's degree in Science with a mention in Astronomy and a Master's degree in Science with a mention in Physics, both from the University of Chile. Since graduation, she has taught introductory physics courses for engineering students at several universities across Chile. In 2022, she joined Universidad Andrés Bello, where she continues to focus on physics education for early-level engineering students. Her teaching emphasizes innovation through active methodologies and student-centered learning, fostering engagement and deeper understanding in foundational physics courses

Prof. Angeles Dominguez, Universidad Andres Bello, Chile; Tecnologico de Monterrey, Mexico

Angeles Dominguez is an adjunct researcher at the Institute for the Future of Education at Tecnologico de Monterrey, Mexico. She also collaborates with the School of Engineering at the Universidad Andres Bello in Santiago, Chile. Angeles holds a bachelor's degree in physics engineering from Tecnologico de Monterrey and a doctoral degree in Mathematics Education from Syracuse University, NY. Dr. Dominguez is a member of the Researchers' National System in Mexico (SNI-2) and has been a visiting researcher at Syracuse University, UT-Austin, and Universidad Andres Bello. Her main research areas are interdisciplinary education, teaching methods, faculty development, and gender issues in STEM education. She actively participates in several national and international mathematics, engineering, and science education projects.

Prof. Genaro Zavala, Tecnologico de Monterrey, Monterrey, Mexico; Universidad Andres Bello, Santiago, Chile

Genaro Zavala is the leader of the Socially Oriented Interdisciplinary STEM Education Research Group of the Institute for the Future of Education at Tecnologico de Monterrey. He collaborates with the Faculty of Engineering, Universidad Andres Bello in Chile. He is National Researcher Level 2 in Mexico. His research lines are interdisciplinary STEM education, social oriented education, conceptual understanding, active learning, assessment tools, and faculty development. Dr. Zavala was appointed to the editorial board of the PRPER (2015-18). In the AAPT, he was a vice-presidential candidate, member of the Committee on Research in Physics Education, member and chair of the International Education Committee, and elected member of Leadership Organizing Physics Education Research Council .

CARLOS PINEIDA, Universidad Andres Bello

I am a physics professor at UNAB, I have more than 20 years of experience teaching physics to engineering students among other careers.

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Abstract

Interactive simulations are widely used to support conceptual learning in introductory physics, yet their impact depends strongly on how they are integrated into instruction. This study investigates the PhET Circuit Construction Kit: DC simulation when implemented in two instructional contexts in an Electricity and Magnetism course at a large private university in Chile: (i) an inquiry-based activity from the PhET community repository, adapted and translated by the authors, and (ii) traditional lecture-based instruction using an instructor-projected simulation. Eight course sections taught by seven instructors participated (196 enrolled); 152 students completed a 10-item pre-test, 125 completed the post-test, and 81 completed both. Learning was assessed using a Spanish translation/adaptation of selected items from the DIRECT instrument, covering current (3 items), voltage (3), power (3), and circuit visual representations (1). We computed normalized gain ⟨g⟩ with error propagation and examined item-level response distributions grouped by simulation use versus non-use. Results show consistently low overall gains across sections, with modest differences by modality. Item-level analyses reveal mixed patterns: sections without simulations achieved medium gains on several items, while simulation-supported sections showed low or even negative gains on some concepts. At the same time, simulations appeared to reduce specific misconceptions (e.g., "charge is absorbed in the bulb") and to support performance on a pictorial circuit-completion item, but were associated with increased selection of "progressive loss" voltage reasoning in a series-circuit item when explicit instructional guidance was limited. These findings suggest that simulations are not sufficient by themselves; they are most productive when paired with structured prompts and debriefing that connect simulation observations to scientifically accurate models and to symbolic circuit representations.

Keywords: PhET simulations, DC electric circuits, Conceptual understanding, Electricity and Magnetism, Higher education, Educational innovation

Introduction

Introductory physics instruction often struggles to move beyond traditional models that emphasize content coverage and lecture-based methodologies. Such approaches can encourage students to memorize equations rather than build explanatory models that connect physical principles to observable phenomena. This challenge is especially visible in direct-current (DC) circuits, where decades of research have documented persistent misconceptions about current, voltage, and resistance, even after formal instruction [1]. Recent work continues to show that even "simple" circuit conceptions remain difficult for many learners, underscoring the need for instructional designs that explicitly promote conceptual understanding rather than procedural plug-and-chug [2].

In response, Information and Communication Technologies (ICT) have been increasingly adopted to support more interactive and conceptually oriented learning experiences. Among these tools, PhET (Physics Education Technology) simulations are widely recognized as interactive and accessible resources that can support conceptual comprehension and help bridge classroom theory and laboratory practice [3-4]. Grounded in a constructivist perspective, PhET simulations foster learning through exploration, prediction, and direct manipulation of models, aligning with active learning and inquiry-oriented approaches reported in the physics education literature [5-7]. However, prior studies also suggest that the learning benefits of simulations depend on how they are integrated into instruction and on the pedagogical supports that accompany them.

Related work has begun to examine how established instructional strategies can be strengthened through technology integration in circuits learning environments. For example, Quezada-Espinoza and colleagues adapted RealTime Physics activities using different instructional technologies, including PhET, to support learning in a circuits laboratory, highlighting both the promise and the practical considerations of implementing technology-enhanced instruction [8]. Building on this line of research, the present study examines how the PhET Circuit Construction Kit: DC simulation (2025) functions under two contrasting instructional contexts in an Electricity and Magnetism course: (i) an active learning implementation based on a PhET activity [9], translated and adapted by the authors, and (ii) a more traditional lecture-based implementation in which the simulation is used as a visual support during instruction. Our goal is to characterize how these instructional choices relate to students' conceptual development, as reflected in learning gains and item-level response patterns on a circuits concept test.

The remainder of the paper is organized as follows. Section II describes the instructional context, study design, and analytic approach. Section III presents the results from the assessment instrument, including overall gains and item-level patterns. Section IV concludes with implications for instruction and directions for future research in introductory physics education.

Research Methodology

To investigate the impact of PhET simulations within active learning contexts, the study involved a total of N = 196 engineering students enrolled in a fourth-semester Electricity and Magnetism course at a Latin American university. These students had already completed a basic general physics program comprising three prior courses.

The participants were distributed across eight course sections taught by seven different instructors. For research purposes, the sections were organized into two groups according to class schedule: Group 1 comprised three sections taught during the first morning block at 8:30 a.m., which generally had lower student participation due to the early schedule. In particular, the experimental section in Group 1 enrolled far fewer students than in the other sections. By contrast, Group 2 included five courses scheduled for 12:10 p.m., each with approximately 30 students. As Group 2 was larger and more populated, it provided stronger statistical power, thereby supporting more robust conclusions and comparisons across the instructional modalities. Within each schedule group, three instructional modalities were implemented. A total of two sections followed an experimental approach (EXP), engaging in face-to-face instruction with an activity guide adapted from the PhET community [9], together with the Circuit Construction Kit: DC simulation [10]. The control condition was divided into two formats: one received traditional lecture-based instruction with a projected in-class simulation (SIM), while the other received lecture-based instruction without a simulation (NOSIM). All sections addressed the same circuits and conceptual content, differing only in instructional methodology. Table 1 summarizes the number of students per section in each study group.

Table 1. Student distribution by Group and instructional modality.

	Instructional modality	N° Pre-test	N° Post-test
Group 1	EXP	10	8
	SIM	19	14
	NOSIM	13	16
	Total G1	**42**	**38**
Group 2	EXP	23	23
	SIM	29	29
	NOSIM	58	35
	Total G2	**110**	**87**
Study	**Total study**	**152**	**125**

Student learning outcomes were evaluated using a 10-item multiple-choice test, adapted and translated into Spanish from the DIRECT (Determining and Interpreting Resistive Electric Circuit Concepts Test) [1]. The instrument comprised three items on current, three on voltage, three on power, and one on visual representation. The 10 test items were selected by an expert panel to ensure alignment with the Electricity and Magnetism course content students are studying.

The test was administered as a pre-test at the beginning of the unit and as a post-test at the end, each lasting 15 minutes. In total, 152 students completed the pre-test, 125 completed the post-test, and 81 students completed both assessments. The discrepancy in sample sizes reflects the fact that the tests were conducted on different days, resulting in varying classroom attendance; consequently, only 81 students confirmed participation in both sessions. The complete test instrument and the inquiry-based activity guide are provided in the appendices.

Data analysis involved calculating the normalized gain ⟨g⟩ and its associated uncertainty using error propagation, accounting for statistical fluctuations in mean pre- and post-test scores [11]. Additionally, the distribution of responses to selected items was examined to explore how PhET simulations might have influenced students' conceptual models.

Gain Function

The average normalized gain $\langle g \rangle$ has become a widely accepted standard measure to assess the effectiveness of instructional methods in fostering conceptual understanding. This parameter, essential for consistent comparisons across student populations with varying levels of prior knowledge, is defined as the ratio between the actual average gain of the class ⟨G⟩ and the maximum possible average gain $\langle G \rangle_{max}$.

$$\langle g \rangle = \frac{\langle G \rangle}{\langle G \rangle_{max}} = \frac{\%\langle S_f \rangle - \%\langle S_i \rangle}{100\% - \%\langle S_i \rangle}$$

where $\%\langle S_f \rangle$ denote the average post-test and pre-test scores, respectively. Normalized gain is a robust measure of course effectiveness in promoting conceptual learning, as it exhibits minimal correlation with initial scores, thereby reducing bias when comparing groups with different levels of prior preparation [11].

When reporting normalized gain, it is important to account for statistical fluctuations or random errors $D\hat{g}$, using conventional error propagation. Random error for pre-test (Dy) and post-test (Dx) scores were defined as the standard error of the mean, i.e., the standard deviation divided by the square root of the number of measurements (N). Assuming independence of errors, error propagation combines the partial derivatives of the normalized gain function $\hat{g} = (x - C)/(C - y)$, where C is the number of items, with Dx and Dy to obtain:

$$D\hat{g} = \sqrt{\left(\frac{\partial \hat{g}}{\partial x} Dx\right)^2 + \left(\frac{\partial \hat{g}}{\partial y} Dy\right)^2}$$

Beyond statistical fluctuations, variability across courses may also reflect systematic errors and differences in pedagogical implementation. Courses were classified according to normalized gain [11] (see Table 2):

Table 2. Classification of courses according to the gain obtained.

High gain	**Medium gain**	**Low gain**
$0.7 \le g$	$0.3 \le g < 0.7$	$g < 0.3$

Variation in Alternatives

Response analysis extended beyond identifying correct answers to examine how students' conceptions evolved between successive assessments. To this end, variation metrics were employed to quantify the impact of instructional interventions. Absolute variation was defined as the change in the number of students selecting a given alternative:

$$\Delta = \frac{Post - Pre}{Pre} \times 100$$

This measure captures persistence or shifts in the number of students endorsing a particular conception. However, it may be limited when group sizes differ between pre- and post-tests, as it does not reflect relative proportions. To address this, we also computed percentage variation:

$$\Delta_{\%} = \frac{\frac{Post}{N_{post}} - \frac{Pre}{N_{pre}}}{\frac{Pre}{N_{pre}}} \times 100$$

This indicator highlights changes in the relative incidence of a conception within the group, even when the absolute number of students remains constant.

Results

The test questions are grouped by the content they assess, as detailed in Table 3. The results are organized into two groups, corresponding to the two class schedules described in the methodology.

Table 3. Classification of pre- and post-test questions applied in the experiments.

Content	Current	Voltage	Power	Visual representation
Item numbers	1, 4, 7	2, 6, 10	3, 8, 9	5

The gains for each question type and for the complete test are shown in Figures 1 and 2. All sections exhibited consistently low normalized gains when considering the test as a whole. Analysis by content domain revealed differences between sections, although all remained within the low-gain range. A modest advantage was observed for simulation-based instruction in the item assessing visual representation of circuits in Group 1; however, this finding has limited statistical significance, as it derives from a very small course of approximately 10 students compared with the larger sections included in the study.

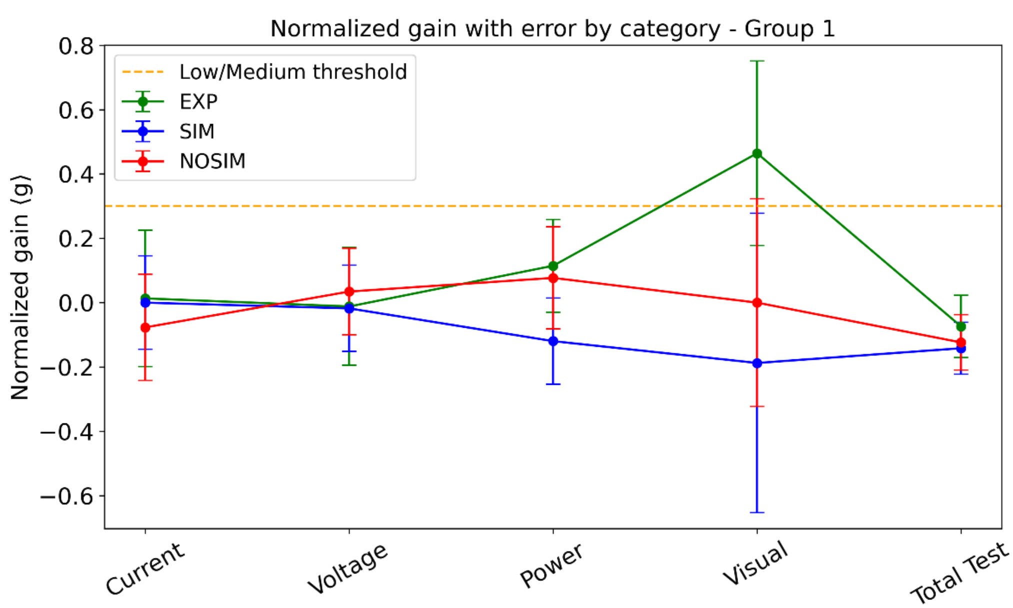

Figure 1. Average normalized gain ⟨g⟩ with associated error by question category and for the complete test, comparing experimental courses with simulation (EXP), traditional courses with simulation (SIM), and traditional courses without simulation (NOSIM) in Group 1.

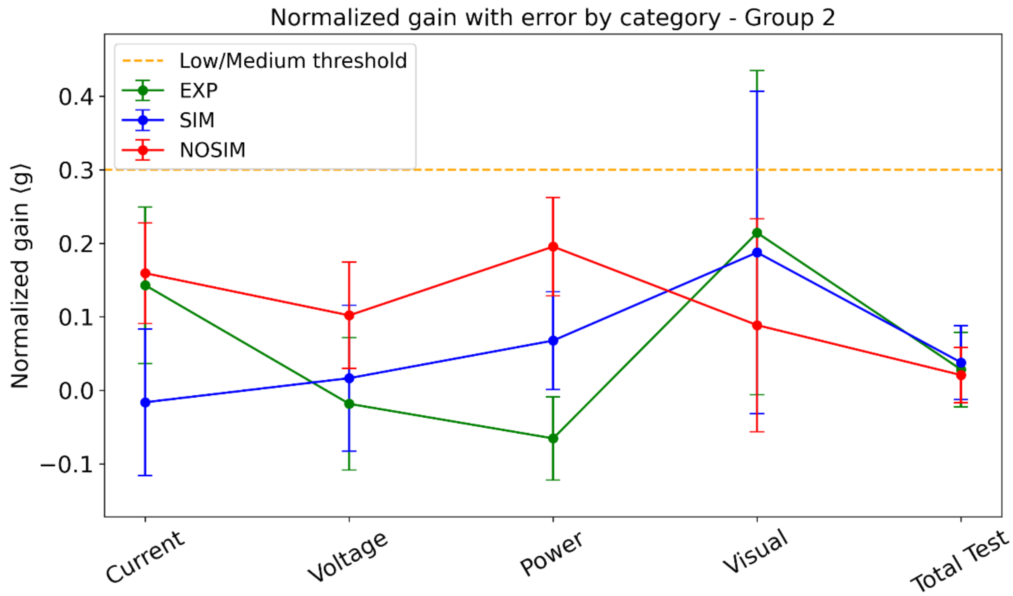

Figure 2. Average normalized gain ⟨g⟩ with associated error by content category and for the complete test, comparing experimental courses with simulation (EXP), traditional lecture courses with simulation (SIM), and traditional lecture courses without (NOSIM) in Group 2.

The gain by individual question is presented in Figures 3 and 4. Item-level analysis revealed that the sections without simulation achieved medium gains on Items 2, 3 and 7, in contrast to the consistently low gains observed in the sections with simulation. The most pronounced effect was observed in Item 2, which will be examined in detail later to analyze the distribution of student responses across alternatives. However, some items even displayed negative gains, suggesting regression in conceptual understanding for particular topics. Moreover, the associated errors are relatively large, particularly in Group 1. This is explained by the smaller number of course sections in that group and, more specifically, by the experimental section, which was considerably smaller (approximately 10 students) than the other sections, which averaged around 40 students. These limitations highlight that more reliable comparisons could be achieved with larger sample sizes (N), where statistical fluctuations would be reduced and methodological effects more clearly distinguished. Selected items will be examined in detail to explore how the distribution of student responses varied with the use of simulations, independent of instructional methodology.

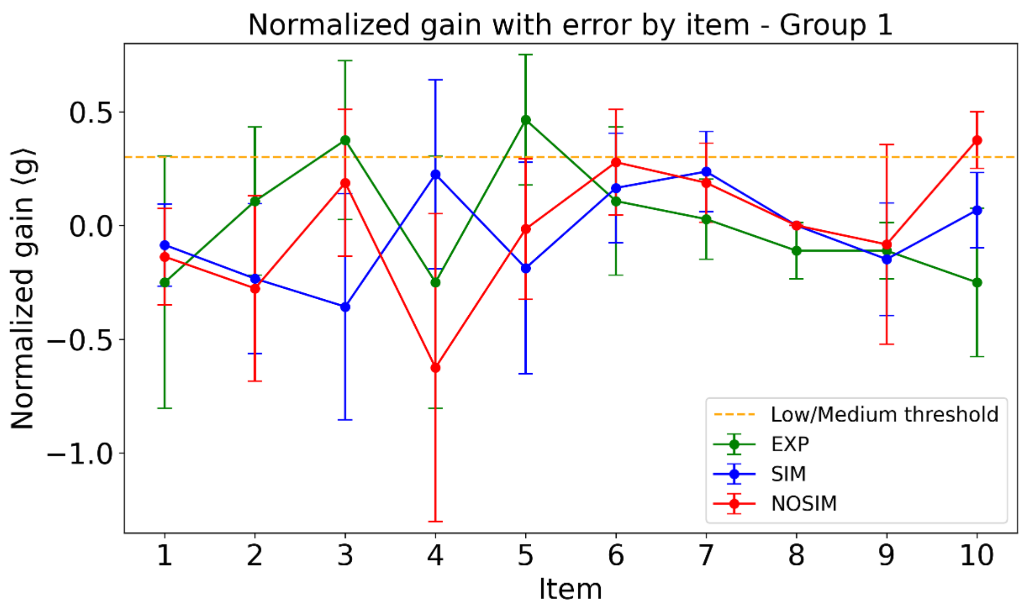

Figure 3. Average normalized gain ⟨g⟩ with associated error by item, comparing experimental courses with simulation (EXP), traditional lecture courses with simulation (SIM), and traditional lecture courses without simulation (NOSIM) in Group 1.

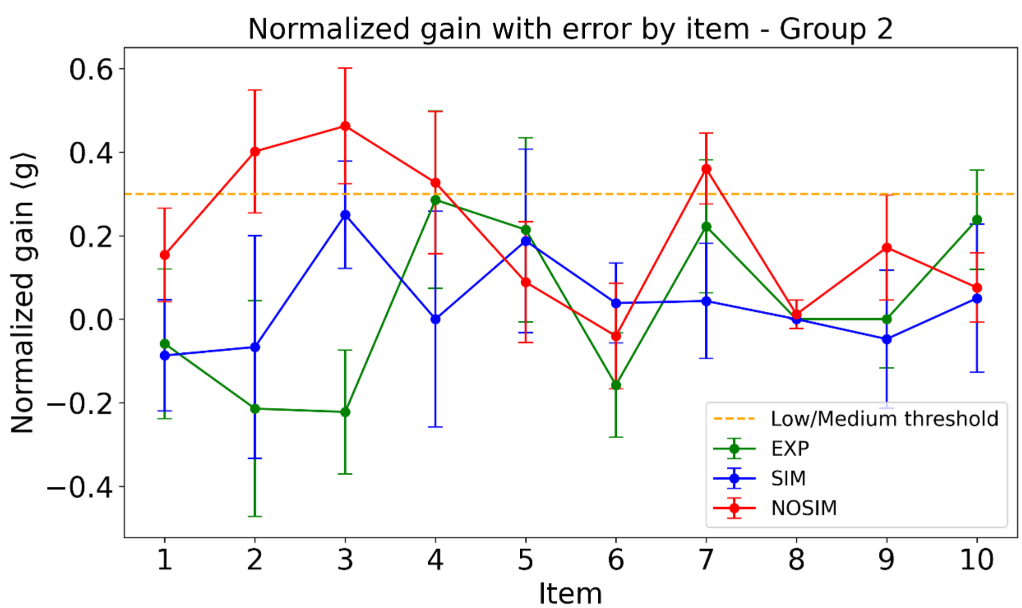

Figure 4. Average normalized gain ⟨g⟩ with associated error by item, comparing experimental courses with simulation (EXP), traditional lecture courses with simulation (SIM), and traditional lecture courses without simulation (NOSIM) in Group 2.

In the following subsections, we present item-level analyses for a selected set of test questions. The results are organized exclusively by simulation use versus non-use, without distinguishing between active and lecture-based instruction. This choice was made because all sections exhibited similarly low normalized gains at the overall-test level, making aggregate comparisons less informative for understanding where improvement occurred (or did not). Item-level analysis is a well-established strategy to deepen interpretation when overall gains mask meaningful conceptual patterns, as it can reveal the specific mental models and misconceptions students are bringing to particular topics; this approach has been used successfully in our prior work to uncover learning mechanisms beyond global score shifts (e.g., [12]). Accordingly, by focusing on how response distributions change with or without simulations, we can examine whether simulation-supported instruction is associated with shifts away from common incorrect models and toward the scientifically correct one. For this reason, we analyze in detail only those items that are especially diagnostic of students' underlying reasoning, or that exhibit the most noticeable differences in gain patterns across simulation conditions.

Item 1 Analysis

Item 1 targets students' understanding of charge conservation in a simple circuit with a light bulb. The question asks whether electric charges are "consumed" when the bulb produces light, and it probes the explanatory model students use to justify their choice. The correct answer (option E) states that charge is conserved: charges are not used up in the filament; instead, as charges move through the filament they undergo interactions (often described in the item as "friction"/resistance-related effects) that transfer energy, which appears as thermal energy and light, while the charges themselves continue to circulate in the closed circuit. Common incorrect responses reflect alternative conceptions such as treating charge like a fuel that is consumed to produce heating/light, claiming that charges are converted into photons and therefore lost, or assuming charges are absorbed/trapped by the filament; a frequent "nearly correct" pattern is to acknowledge conservation but still describe heat/light as a transformation of charge rather than a transformation of energy.

Figure 5 presents the distribution of answers students choose in the pre-test and post-test. The number represents the number of students who chose that option, and the percentage is calculated based on the number of students who were present in the pre-test or the post-test. Table 4 presents the percentage change in students' choices for item 1 from pre-test to post-test.

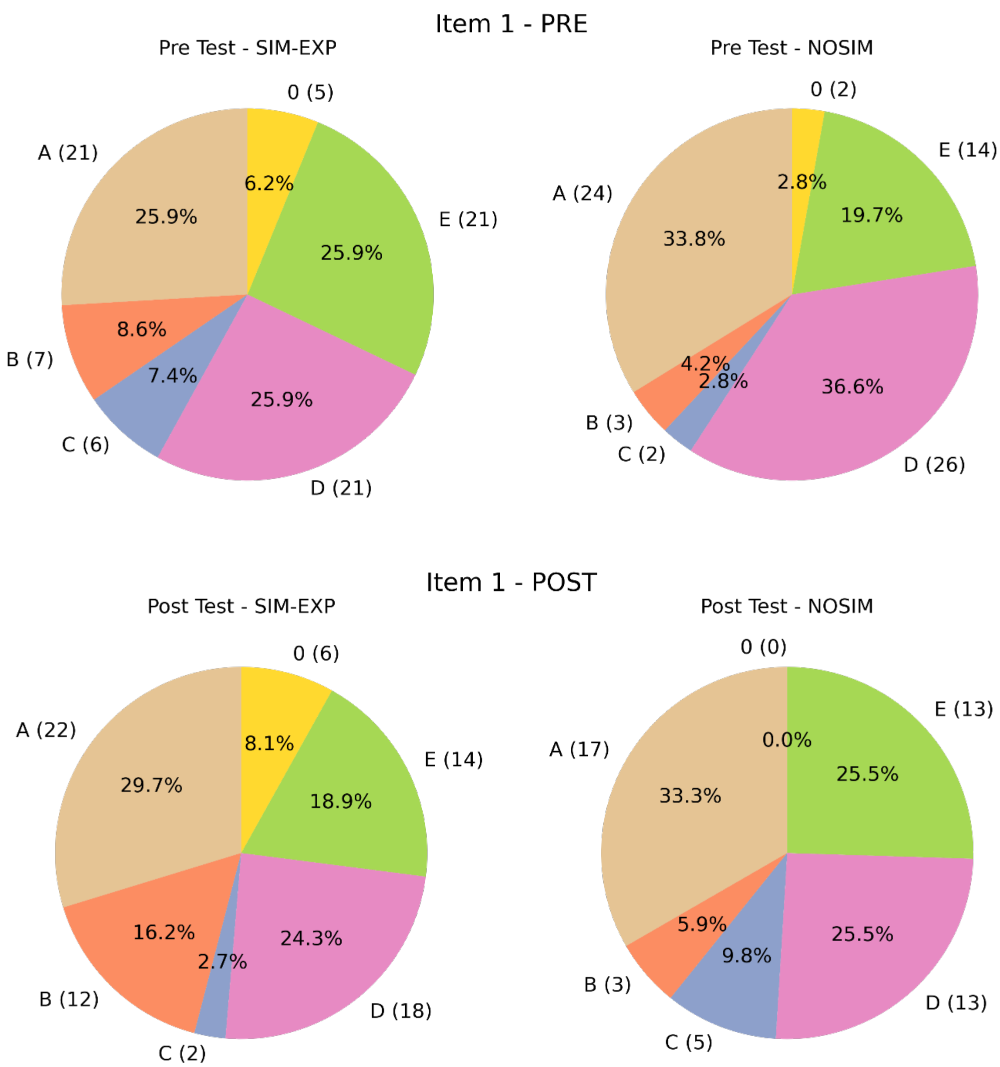

Figure 5. Distribution of alternatives chosen by students in the pre- and post-test for Item 1, grouped according only to the use of simulations.

Table 4. Percentage of relative change $\Delta_{\%}$ in the choice of alternatives for Item 1 in relation to the use of simulation; the correct alternative is highlighted.

Alternative	**$\Delta_{\%}$ SIM-EXP**	**$\Delta_{\%}$ NOSIM**
A	14.7%	-1.4%
B	87.6%	39.2%
C	-63.5%	248.0%
D	-6.2%	-30.4%
E	-27.0%	29.3%
0	31.4%	-100.0%

The analysis of Figure 5 and Table 4 for Item 1 reveals significant differences between sections that worked with simulations and those that did not. The correct alternative, corresponding to option E, shows favorable behavior in the NOSIM sections, with a relative variation of +29.3%. This indicates that the alternative's weight increases with the size of the group that completed the post-test. In contrast, in the SIM-EXP section (active and lecture-based methodology) a relative decrease of −27.0% is observed. This pattern is consistent with the possibility that, without explicit instructor mediation, students may develop or maintain non-normative interpretations despite simulation use.

In the SIM-EXP sections, the choice of alternatives A and B increased in relative measures, which may reflect that some students interpreted the electron visualization in ways consistent with ‘consumption’ or ‘transformation’ ideas. In contrast, the NOSIM shows a small decrease in alternative A and an increase in alternative B, which is consistent with a reduced selection of the ‘consumption by friction’ idea in the non-simulation sections, but confusion regarding photon emission persists.

Alternative C, which represents the idea that charges are absorbed by the filament, shows a decrease of −63.5% in the SIM-EXP sections. This pattern is consistent with a reduction in this misconception in the simulation sections, as it shows that electrons enter and exit the bulb without being lost. In contrast, in the sections without simulation, this alternative shows a significant increase of +248.0%. Alternative D, which also supports charge conservation but with a less precise explanation, decreases in both modalities, with a considerable drop in the NOSIM sections. This is concerning, as D also represents a partially correct response in terms of charge conservation.

Overall, these results indicate a mixed pattern: simulation use is associated with decreases in some incorrect ideas and increases in others if not accompanied by clear explanations of charge conservation. This underscores the need for careful instructional design that integrates simulation with instructor interventions or feedback moments to guide student interpretation, to reduce the risk that visual features of the simulation are interpreted in ways that support non-normative conceptions.

Examining Figures 3 and 4, focused on Item 1 of the test, it is observed that in Group 1, no significant differences in gain were recorded between sections. In contrast, in Group 2, the courses that worked without simulation also showed low gains, similar to those in the other sections, though slightly higher. This difference may reflect instructor intervention related to this concept (e.g., emphasis, pacing, or feedback), rather than the modality alone.

In summary, the results of Item 1 suggest that simulations, although they may induce misconceptions when used alone, may have didactic value when integrated with explicit instructor guidance. Thus, simulation should not be discarded but rather conceived as a complementary resource that, under careful pedagogical design, may support consolidation of the correct model and enrich the learning experience.

Item 2 Analysis

Item 2 probes students’ understanding of how potential difference (voltage) is distributed in a simple series circuit with two bulbs in series. The item asks students to rank (from greatest to smallest) the potential difference across three locations in the circuit: between points 1–2 (the power source) and across each bulb segment, 3–4 and 4–5. The correct answer is option E, which states that the largest potential difference is across the source (1–2) and that the two bulbs have equal voltage drops ($\Delta V_{3-4} = \Delta V_{4-5}$) because the bulbs are identical and connected in series; consequently, the battery voltage equals the sum of the two equal drops. Typical incorrect responses reflect a “progressive loss” model in which voltage is thought to be “used up” as charges move through the circuit, leading students to claim that the first bulb (closest to the positive terminal) has a larger drop than the second (option A) or the reverse ordering (option B). Other incorrect choices imply that the largest potential difference is not at the source (options C/D), suggesting that voltage depends primarily on position along the loop rather than on the source and element resistances.

Figure 6 presents the distribution of answers students choose in the pre-test and post-test. The number represents the number of students who chose that option, and the percentage is calculated based on the number of students who were present in the pre-test or the post-test. Table 5 presents the percentage change in students' choices for item 2 from pre-test to post-test.

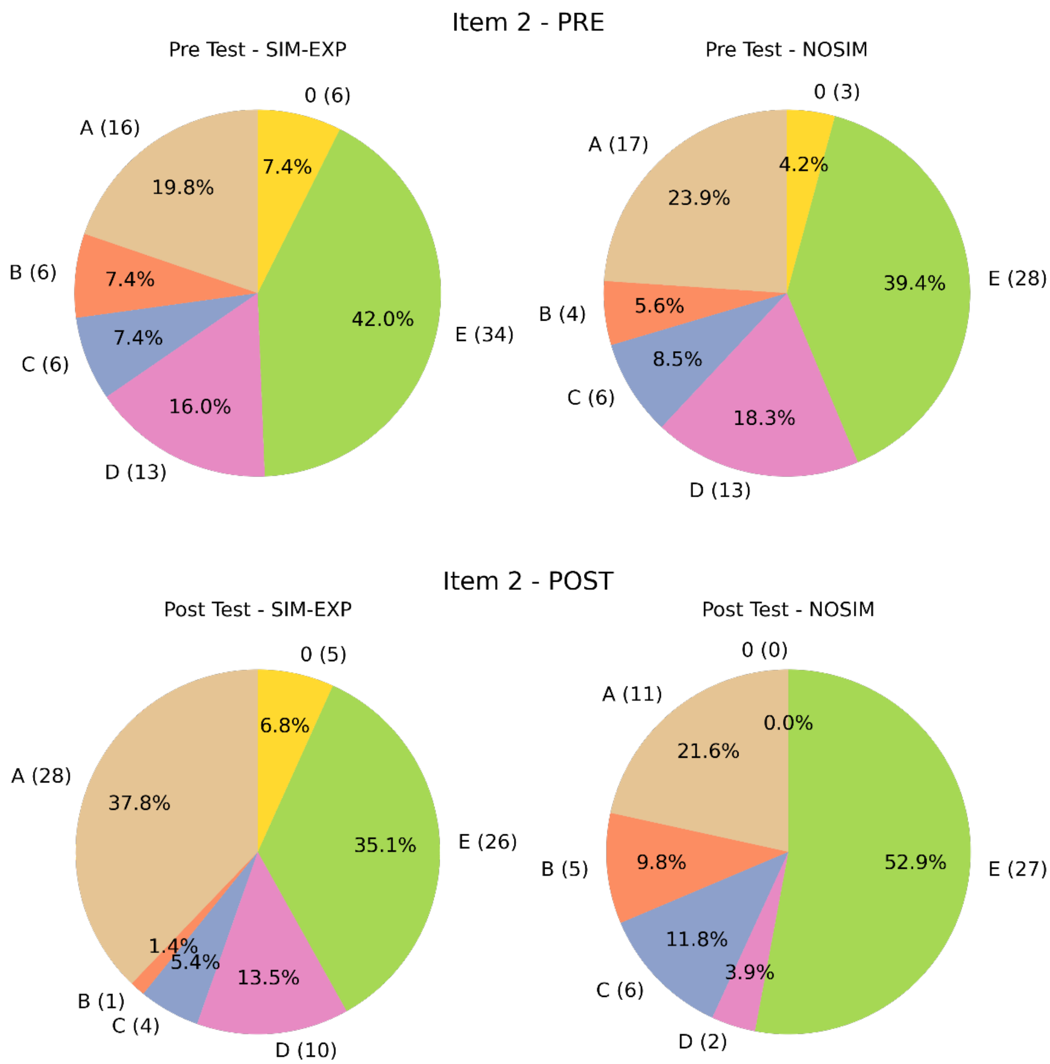

Figure 6. Distribution of alternatives chosen by students in the pre- and post-test for Item 2, grouped according only to the use of simulations.

Table 5. Percentage of absolute change Δ and relative change $\Delta_{\%}$ in the choice of alternatives for Item 2 in relation to the use of simulation; the correct alternative is highlighted.

Alternativa	$\Delta_{\%}$ SIM-EXP	$\Delta_{\%}$ NOSIM
A	91.6%	-9.9%
B	-81.8%	74.0%
C	-27.0%	39.2%
D	-15.8%	-78.6%
E	-16.3%	34.2%
0	-8.8%	-100.0%

Options C and D decreased in selection frequency among students who used the simulation, whereas only option D decreased among those who did not use it, suggesting differences in response patterns on this point. However, the most notable difference associated with simulation use is in the choice of options A, B, and E, which requires students to understand that the greater potential difference is across the battery. Options A and B show opposite results with both types of students. Students who used the simulation increased their choice of Option A and decreased their choice of Option B, whereas those who did not use the simulation behaved exactly the opposite. The distinction between these alternatives is that Option A implies that the bulb closest to the positive terminal of the power source has a greater potential difference than the subsequent bulb, whereas Option B assumes the same, but in the opposite circuit direction. Another difference is in the correct option E. Students who used the simulation relatively chose the correct answer less in the post-test, and students who did not use the simulation chose the correct answer more.

This pattern suggests that some students in the simulation sections may have favored an interpretation in which the first bulb produces a larger voltage drop than the second. Although Option B presents the bulbs in reverse order, its selection decreased, indicating that, in the mental models constructed by students, the order in which the bulbs are positioned relative to the positive terminal of the source in a series circuit is particularly important. This pattern could be related to how the simulation represents charge motion and current, which may cue 'progressive loss' interpretations for some students, since such an increase in confusion is not observed in the sections that worked without simulation. The same circuit was addressed in both active-learning activities and lecture-based classes. In the active-learning setting, students were asked to measure the potential difference at different points in the circuit on their own, meaning they decided whether to measure across both bulbs. In contrast, in the lecture-based classes, instructors explicitly emphasized that the potential difference across both bulbs is equal, either by measuring it directly in the simulation or by using visual representations of the circuit. This comparison suggests that when simulations are used within inquiry-based activities, explicit feedback is required to clarify this phenomenon and prevent the development of incorrect mental models. Without such guidance, students may fail to carry out the necessary measurements or to recognize the underlying voltage and current patterns on their own.

Item 5 Analysis

Item 5 assesses students' ability to interpret pictorial representations of a battery–bulb setup and to decide which of the four depicted configurations will cause the bulb to light. The item asks students to identify the circuit(s) that successfully complete a conducting path between the two battery terminals through the bulb (i.e., that connect both bulb terminals, the metal shell, and the bottom contact to opposite battery terminals). The correct answer is "Circuit 1 and 3" (option D), because only these two drawings show a closed loop in which the wire and bulb together provide a return path, allowing current to pass through the filament; in contrast, Circuits 2 and 4 leave the circuit open (only one bulb terminal is effectively connected), so the bulb will not light. Typical incorrect responses include selecting a single circuit (e.g., only Circuit 1 or only Circuit 3), choosing Circuit 2 based on the idea that physical contact between the bulb and the battery is sufficient, or choosing an option that includes Circuit 4, reflecting the misconception that a single wire connection can make the bulb light even without a complete return path.

Figure 7 presents the distribution of answers students choose in the pre-test and post-test. The number represents the number of students who chose that option, and the percentage is calculated based on the number of students who were present in the pre-test or the post-test. Table 6 presents the percentage change in students' choices for item 5 from pre-test to post-test.

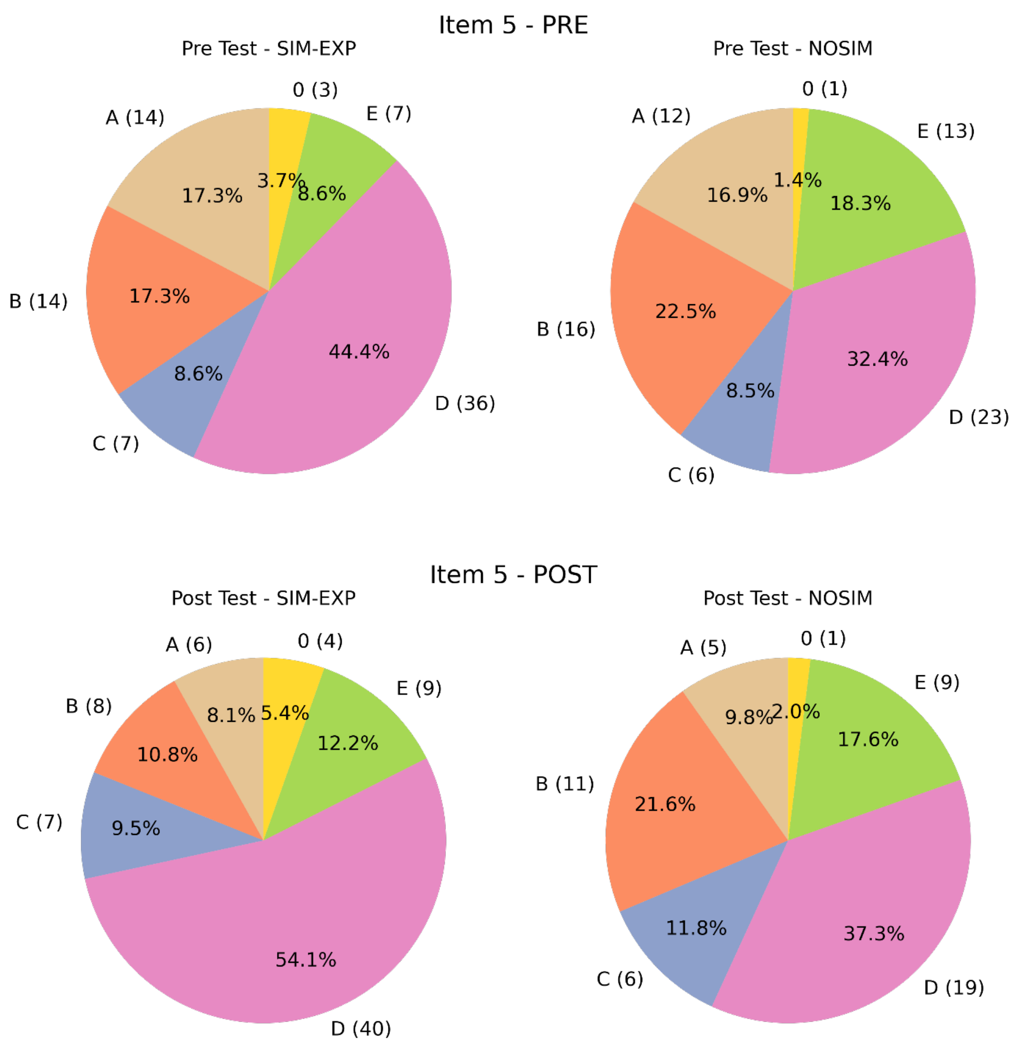

Figure 7. Distribution of alternatives chosen by students in the pre- and post-test for Item 5, grouped according to the use of simulations.

Table 6. Percentage change in the choice of alternatives for Item 5 in relation to the use of simulation; the correct alternative is highlighted.

Alternativa	$\Delta_{\%}$ SIM-EXP	$\Delta_{\%}$ NOSIM
A	-53.1%	-42.0%
B	-37.5%	-4.3%
C	9.5%	39.2%
D	21.6%	15.0%
E	40.7%	-3.6%
0	45.9%	39.2%

Item 5, analyzed in Figure 7 and Table 6, is associated with a larger increase in the correct option in the simulation sections, as it evaluates the visual representation of electrical circuits. Sections using simulation increased the incidence of the correct alternative in relative terms, whereas sections without simulation also showed a relative increase within their cohort, but less pronounced. Examining Figures 4 and 5, the gain associated with Item 5 in experimental section employing active methodology was higher in Group 1 and comparable in Group 2. This pattern suggests that both active and traditional approaches can support performance on this visual-representation item when simulation is used as part of instruction.

It is noteworthy that the choice of alternative E varied across sections. Sections using simulation increased their preference for this option, including Circuit 4, which prevents the bulb from lighting. In contrast, sections without simulation correctly identified that Circuit 4 would not produce light in the bulb. This outcome is unexpected, as one might expect simulation use to support recognition that an open circuit prevents current flow. Both experimental and control sections explicitly addressed this content in Part 1 of the activity. This conception of the open circuit is revisited in Item 10, analyzed below. One plausible interpretation is that some students had difficulty transferring what they did in the simulation to the symbolic representation used in the test item, or that the activity did not sufficiently emphasize that transfer.

Item 10 Analysis

Item 10 assesses students' understanding of electric potential in an open circuit. The diagram shows a 12 V battery, two resistive elements (bulbs/resistors), and an open switch between them; students are asked to determine the potential difference between points A and B. The correct answer is 12 V (option D): because the switch is open, no current flows, so there is no voltage drop across either resistor ($\Delta V = IR = 0$). As a result, point A remains at the potential of one battery terminal, and point B remains at the potential of the other terminal, so the full battery voltage appears across the open gap, making it 12V. Common incorrect responses include choosing 0 V (treating "open circuit" as "no voltage anywhere"), or selecting 6 V or 3 V by incorrectly applying a voltage-division idea as if current were flowing and the resistors were dropping the battery voltage, even when the circuit is not closed.

Figure 8 presents the distribution of answers students choose in the pre-test and post-test. The number represents the number of students who chose that option, and the percentage is calculated based on the number of students who were present in the pre-test or the post-test. Table 7 presents the percentage change in students' choices for item 10 from pre-test to post-test.

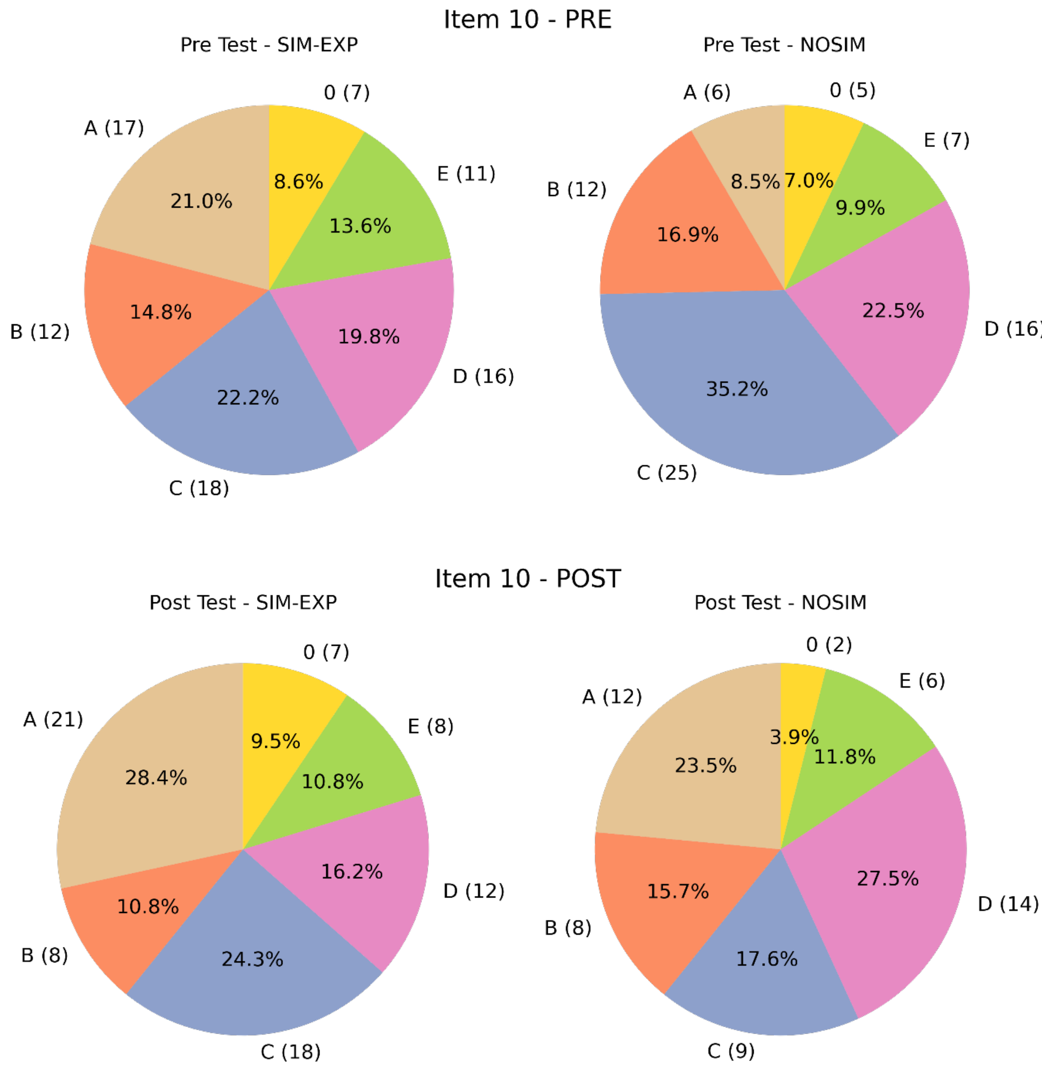

Figure 8. Distribution of alternatives chosen by students in the pre- and post-test for Item 10, grouped according to the use of simulations.

Table 7. Percentage change in the choice of alternatives for Item 10 in relation to the use of simulation; the correct alternative is highlighted.

Alternativa	$\Delta_{\%}$SIM-EXP	$\Delta_{\%}$NOSIM
A	35.2%	178.4%
B	-27.0%	-7.2%
C	9.5%	-49.9%
D	-17.9%	21.8%
E	-20.4%	19.3%
0	9.5%	-44.3%

In Item 10, as shown in Figure 8 and Table 7, both modalities increased the proportion of students selecting the correct option that an open switch prevents current flow; consequently, there is no voltage drop across the resistive elements ($\Delta V = IR = 0$), while the full battery voltage appears across the open gap. However, it is noteworthy that the sections that work without simulation show a much larger increase in the correct alternative, identified as option D. In contrast, option A, which is zero volts, shows a great increase for students who did not use the simulation compared to a still increase, but less, for students who used the simulation.

It is important to note that alternative C is the correct response for a closed circuit. The choice of this alternative remains relatively constant in the simulation sections, whereas in the non-simulation sections, its selection decreases substantially. This pattern is consistent with a larger increase in correct responses in the non-simulation sections for this item, reaching the same conclusion reported in the analysis of Item 5.

Conclusions

Across eight course sections (taught by seven instructors) in an Electricity and Magnetism course, we compared three instructional modalities: an inquiry-based activity using the PhET Circuit Construction Kit: DC simulation (EXP), a lecture-based approach with an instructor-projected simulation (SIM), and a lecture-based approach without simulations (NOSIM). Overall, normalized gains on the 10-item DIRECT-based test were consistently low across sections, and differences among modalities were modest. Although the visual-representation category showed a small advantage in one simulation-supported section, this observation should be interpreted cautiously because it is driven by a very small section (≈10 students). Item-level gains further indicate that no single modality produced a uniformly higher gain profile across concepts; in several items, the NOSIM condition reached medium gains while simulation-supported sections remained in the low-gain range.

A closer look at response distributions indicates that simulation use was associated with different patterns across items, which may reflect how students interpreted what they observed. For example, in Item 1, simulation sections showed a reduction in the response that treats charge as “absorbed” in the filament, but this shift did not consistently translate into higher selection of the fully correct conservation model. In Item 2, simulation sections shifted toward an ordering consistent with a "progressive loss" view of voltage in series circuits, while non-simulation sections increased the proportion of correct responses. By contrast, Item 5 (a pictorial circuit-completion task) exhibited a clearer increase in correct responses in the simulation sections, consistent with the affordances of interactive visualization for circuit topology. Taken together, these results suggest that simulation exposure alone was not consistently associated with higher conceptual gains; instead, the potential value of simulations likely depends on the presence of instructional supports that connect simulation behaviors to scientifically accurate models and to symbolic/schematic representations.

This study has limitations typical of quasi-experimental classroom research. First, because the eight sections were taught by different instructors, variations in pacing, emphasis, and enactment of the activity/simulation could have influenced outcomes beyond the nominal modality. Second, the design groups sections by schedule (Group 1 vs. Group 2), and Group 1 includes a notably small experimental section, which increases uncertainty and reduces comparability. Third, participation differed across administrations (pre-test N = 152; post-test N = 125; matched N = 81), reflecting attendance variation across testing days; although we report relative variations to mitigate unequal group sizes, differences in who was present can still affect observed shifts in item distributions and gains. Finally, results rely on a short multiple-choice instrument (adapted/translated), which limits inferences about students' underlying reasoning and may not fully capture learning outcomes emphasized in inquiry-based simulation work.

For instruction, these findings suggest embedding simulations within structured prediction–test–explain cycles and following them with brief debriefs that foreground the most error-prone ideas identified here (e.g., charge conservation, voltage drops in series, and open-circuit reasoning about potential difference), explicitly asking students to map simulation observations onto circuit schematics and measurement conventions. In particular, activities should include checkpoints that prompt students to compare voltage drops across both bulbs in series and to explain why the full battery voltage appears across an open switch when no current flows. For future research, we recommend designs that reduce confounds and strengthen inference (e.g., larger and more balanced sections, higher matched pre/post participation, documentation of implementation fidelity across instructors, and inclusion of short written explanations or interviews). These additions would help clarify when simulations are associated with shifts away from common incorrect models versus shifts toward alternative non-normative interpretations, and whether observed difficulties stem from conceptual understanding or transfer to symbolic representations.

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Appendices

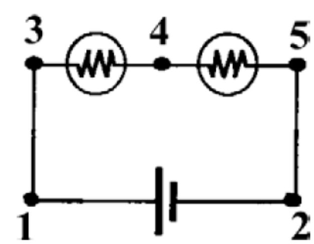
A. Pre/Post Test

1) Are charges used up in the production of light in a light bulb?

   A) Yes, charge is used up. Charges moving through the filament produce "friction" which heats up the filament and produces light.
   B) Yes, charge is used up. Charges are emitted as photons and are lost.
   C) Yes, charge is used up. Charges are absorbed by the filament and are lost.
   D) No, charge is conserved. Charges are simply converted to another form such as heat and light.
   E) No, charge is conserved. Charges moving through the filament produce "friction" which heats up the filament and produces light.

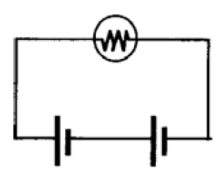
2) Rank the potential difference between points 1 and 2, points 3 and 4, and points 4 and 5 in the circuit shown below from HIGHEST to LOWEST.

   A) 1 and 2; 3 and 4; 4 and 5
   B) 1 and 2; 4 and 5; 3 and 4
   C) 3 and 4; 4 and 5; 1 and 2
   D) 3 and 4 = 4 and 5; 1 and 2
   E) 1 and 2; 3 and 4 = 4 and 5

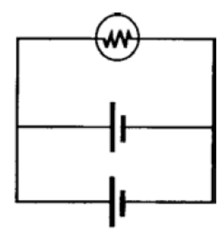


3) Compare the brightness of the bulb in circuit 1 with that in circuit 2. Which bulb is BRIGHTER?

   A) Bulb in circuit 1 because two batteries in series provide less voltaje
   B) Bulb in circuit 1 because two batteries in series provide more voltage.
   C) Bulb in circuit 2 because two batteries in parallel provide less voltage.
   D) Bulb in circuit 2 because two batteries in parallel provide more voltage.
   E) Neither, they are the same.



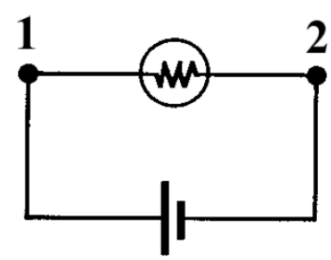
Circuito 1



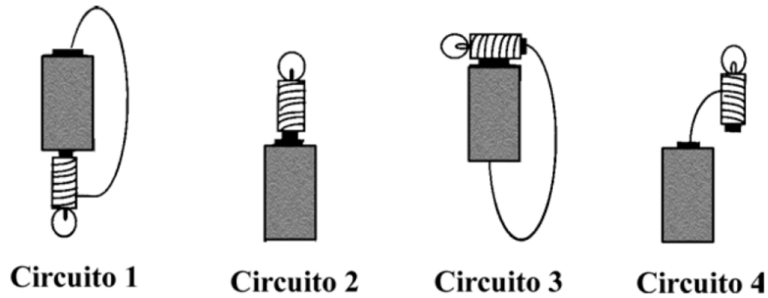
Circuito 2

4) Compare the current at point 1 with the current at point 2. At which point is the current LARGEST?

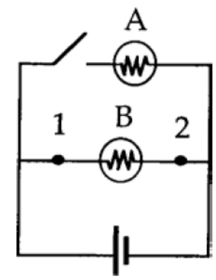
   A) Point 1
   B) Point 2
   C) Neither, they are the same. Current travels in one direction around the circuit.
   D) Neither, they are the same. Currents travel in two directions around the circuit.



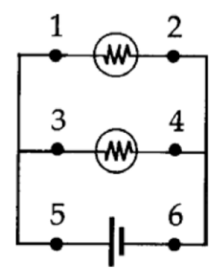
5) Which circuit(s) will light the bulb? (The other object represents a battery.)
   A) Circuit 1
   B) Circuit 2
   C) Circuit 3
   D) Circuit 1 and 3
   E) Circuit 1, 3 and 4



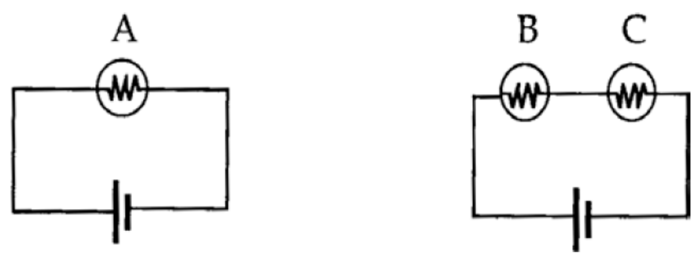
6) What happens to the potential difference between points 1 and 2 when the switch is closed?
   A) Quadruples (4 times).
   B) Doubles.
   C) Stays the same.
   D) Reduces by half.
   E) Reduces by one quarter (1/4).



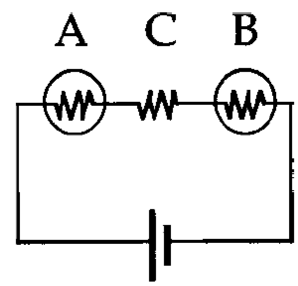
7) Rank the currents at points 1, 2, 3, 4, 5, and 6 from HIGHEST to LOWEST.
   A) 5, 3, 1, 2, 4, 6
   B) 5, 3, 1, 4, 2, 6
   C) 5 = 6, 3 = 4, 1 = 2
   D) 5 = 6, 1 = 2 = 3 = 4
   E) 1 = 2 = 3 = 4 = 5 = 6



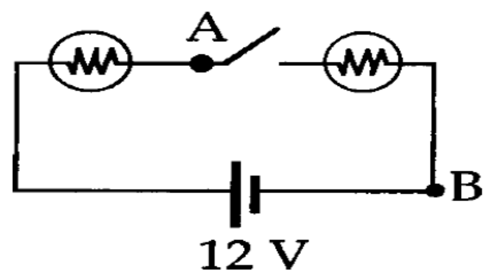
8) Compare the brightness of bulb A with bulb B. Bulb A is _____ bright as bulb B.
   A) Four times as
   B) Twice as
   C) Equally
   D) Half as
   E) One fourth (1/4) as



9) If you increase the resistance C, what happens to the brightness of bulbs A and B?
   A) A stays the same, B dims.
   B) A dims, B stays the same
   C) A and B increase.
   D) A and B decrease.
   E) A and B remain the same.



10) What is the potential difference between points A and B?
   A) 0 V
   B) 3 V
   C) 6 V
   D) 12 V
   E) None of the above.

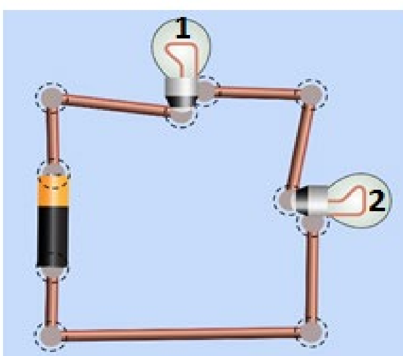


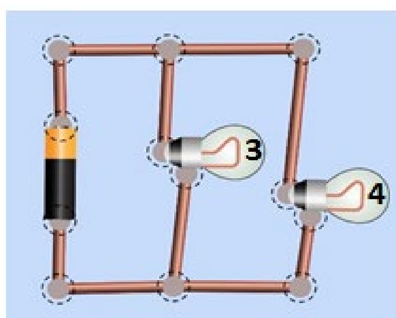
11) **Adapted PhET activity (translated and modified by the authors)**

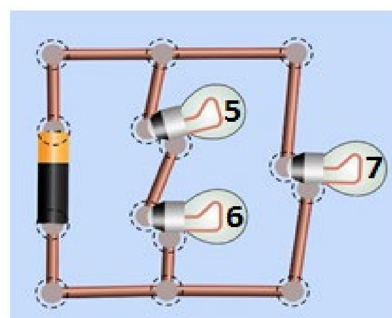
Part 1: Prediction Questions - comparing circuits

Consider the pictures of each of these circuits, then answer the questions below. Answer the prediction questions before you build these circuits:

Series Circuit **Parallel Circuit** **Complex Circuit**







1) From the circuits above, predict which bulb (or bulbs) will be the brightest. Why do you think that?
2) Current is the flow of charge (measured in coulombs/sec = amps) in a circuit. Describe how you think current will flow in the different types of circuits above.

Part 2: Explore the simulation

A) Visit the PhET circuit construction kit simulation: https://tinyurl.com/ALHS-cir, and choose **Intro**

B) Explore the simulation

- Build a circuit: figure out how to make a light bulb light up, then make any circuit you want.
- Figure out how to measure current and voltage.

Questions:

1) Imagine you're an engineer making a string of battery powered holiday lights. If a bulb burns out current cannot flow through that bulb any longer (like if the wire at the bulb has been cut). Figure out how to hook up 2 light bulbs and a battery so that when one bulb burns out (or is disconnected) the other stays lit.
2) You instead want to make sure the battery for your string of lights will last as long as possible. A battery will last longer if it powers a circuit with low current. How could you hook up a battery and 2 light bulbs so the **least amount of current** flows through the battery? Use the measurement tools in the simulation to check your design.

Part 3: Measuring Current and Voltage

Instructions: Your goal in this part is to **come up with rule to describes how patterns of current and voltage in a circuit relate to the structure of the circuit** (how the battery and light bulbs are connected).

To do this, you will need to measure current and voltage in multiple places on several different circuits.

<table>
<tr><th colspan="2">Examples:</th></tr>
<tr><th>Measuring Current</th><th>Measuring Voltage</th></tr>
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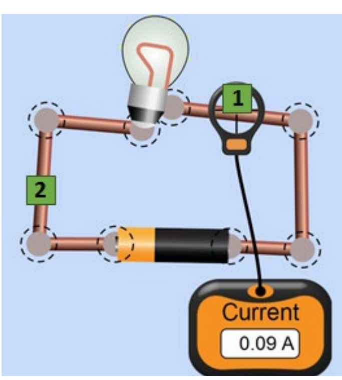
"Current" is the flow of charge, measured in Amps (Coulombs/s). An ammeter measures the current past a single point in the circuit.



The current flowing through point 1 can be written as: $I_1 = 0.09$ A.

</td><td>

"Voltage" is a measure of the difference in electric potential between two points. The voltmeter measures this difference by placing the two leads (pronounced "leeds") at two different points.

The voltage between points A and B can be written as $V_{AB} = 9$ V.

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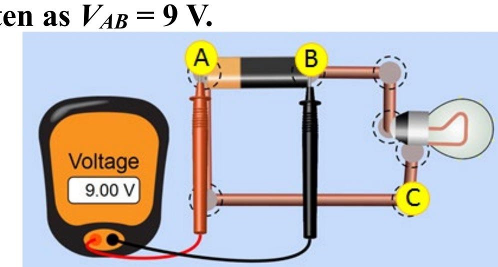

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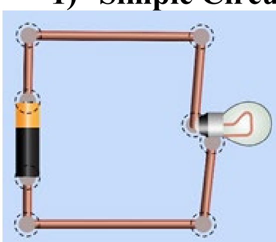
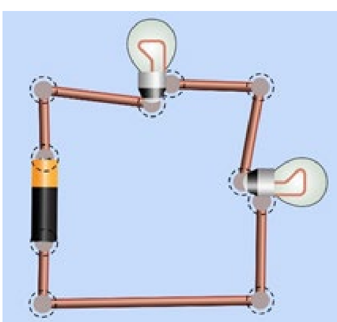
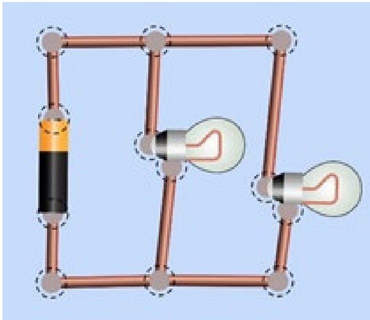
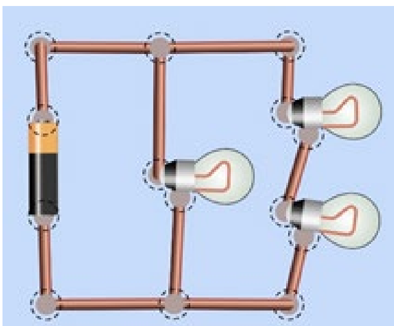
</table>

Use the table below to record your measurements and patterns you notice. You decide where will be the most useful places to take measurements, and how many to take. Use the diagram to label the places you pick.

Circuit Label the places where you decide to measure current and voltage. Try several places.	**Current Measurements (Amps)**	**Voltage Measurements (Volts)** .	**What patterns do you notice?** ● Where is the current the same? Where is it different? ● Where does the voltage change? Where doesn't it change? ● How do the different circuits compare?
1) **Simple Circuit**  **Label on the picture the places where you measure (See examples above).**	**Example:** I_1 = ______ A ____________ ____________ ____________ ____________	**Example:** V_{AB} = ______ V. ____________ ____________ ____________ ____________	
2) **Series Circuit** 	____________ ____________ ____________ ____________ ____________ ____________ ____________	____________ ____________ ____________ ____________ ____________ ____________ ____________	
3) **Parallel Circuit**	____________ ____________ ____________ ____________ ____________ ____________ ____________	____________ ____________ ____________ ____________ ____________ ____________ ____________	

			
4) **Complex circuit** 	____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________	____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________	

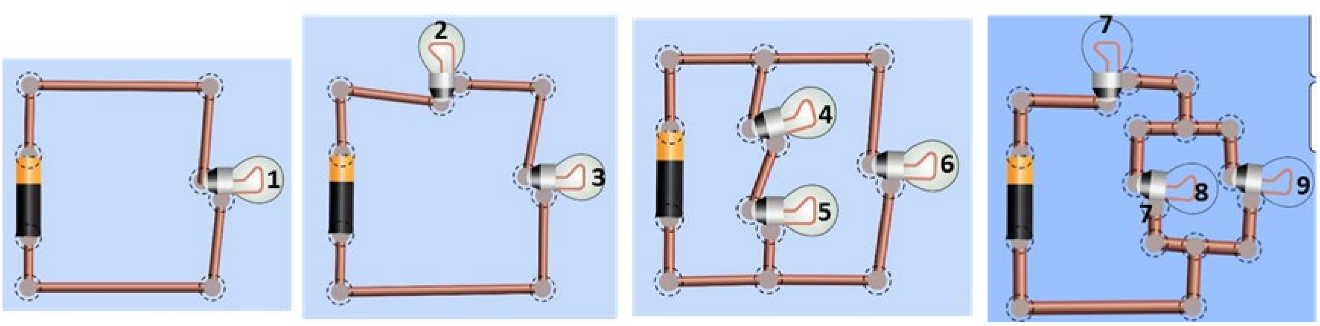
Summary (your rule):

1 Compare the patterns you see in a series circuit to the ones you see in parallel and complex circuits. Try to establish the rules about voltage and current for each type of circuit.

For example, “In a series circuit, I see that the current ….., whereas in a parallel circuit I see… ”.

Part 4: Brightness and y Power.

1) From your rules above, sort (or list) the light bulbs in these circuits from brightest to dimmest (i.e greatest current to least current). Some bulbs might be the same brightness.



Complete the first column of the table with your predicted brightness order.

Circuit	Predicted order from brightest to dimmest	Corrected order
Simple		
Series		
Mixed A		
Mixed B		

2) After making your brightness order, build some of the circuits to check your answers and complete the third column of the table with the correct order, if necessary.
    - Did your rules allow you to correctly order the brightness of the bulbs?
    - If the answer is yes, explain the order you obtained using your rules.
    - If the answer is no, describe what changes you could make to improve your rules.
    - For this, you can use the concept of **electric power**, which is directly related to the brightness of a bulb. Power is calculated with voltage and current:

$$\boldsymbol{P = V \cdot I}$$

3) Complete the following sentences:
    - If several bulbs are connected in a circuit where the current is constant, then the bulb subjected to __________ voltage will have __________ power and will be __________ brighter than the others.
    - If several bulbs are connected in a circuit where the voltage is constant, then the bulb that receives __________ current will have __________ power and will be __________ brighter than the others.
    - In a series circuit, all the bulbs share the same __________. Therefore, the brightness of each one will mainly depend on __________.
    - In a parallel circuit, all the bulbs are subjected to the same __________. Therefore, the brightness of each one will mainly depend on __________.
4) Determine how much the brightness of the bulb in the simple circuit increases in relation to the series circuit.