Exploring student reasoning about circuits using reasoning chain construction tasks

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Physics education research has a long tradition of analyzing and supporting student conceptual understanding of specific physics topics, with electric circuits being no exception. This research seeks to explore a new methodology for how students formally reason with circuits concepts. This new methodology places emphasis on the process of linking concepts and observations together into a logical chain of reasoning using *reasoning chain construction tasks*, previously reported on in the literature. Additionally, this study builds upon previous research on students' comprehension of circuits and aims to explore how reasoning chain construction tasks can help illuminate students' use of conceptual ideas before and after receiving instruction. As such, this research contributes to the broader field of physics education by offering additional insight into student reasoning patterns, providing educators and researchers with more tools to inform instructional strategies and curriculum design in electric circuits education.

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I. INTRODUCTION

Physics courses foster problem-solving and critical thinking skills that are useful across various academic disciplines; furthermore, physics courses are often required for students in various majors. Physics remains a challenging subject as students have difficulty applying fundamental principles and productively utilizing existing knowledge, which can sometimes impede their ability to construct cohesive, logical arguments to explain or predict phenomena [1, 2].

Physics education researchers have created numerous teaching materials that focus on student's understanding of physics, and which have demonstrated efficacy in enhancing students' learning and comprehension within the subject [1, 3]. Many of these materials employ a structured progression of questions to guide students through qualitative chains of reasoning [4,2]. A useful tool for studying qualitative inferential reasoning chains is the *reasoning chain construction task*, which prompts students to utilize provided statements to construct a logical argument supporting a particular conclusion [5, 6]. This has offered valuable insight into how students' reason and pointed towards possible interventions that could help students learn to deal with strong intuitive, but unproductive, ideas [5].

The literature identifies numerous difficulties arising from students' incomplete conceptualizations of circuits and Ohm's law [7, 8, 9]. Research indicates that many students lack a clear understanding of fundamental electric circuit concepts like voltage, resistance, and current. When Ohm's law is introduced before understanding its underlying concepts, students may struggle to grasp the qualitative and quantitative relationships when problem solving [7, 8, 9, 10].

The topic of circuits has also been studied through the lens of the *resources framework*. This lens, among other things, focuses on the idea that often-times, students have productive ideas (called *resources* in the resources framework [11, 12]) with which to reason about physics concepts. One way to frame the process of instruction is to guide students in building on those resources and reorganizing associative cognitive networks of these resources so that they are used in a more context appropriate way [11, 12, 13]. While we do not undertake to draw firm connections to cognitive resources in this work, we do draw inspiration from the resources framework to develop a reasoning chain construction task in the context of circuits to investigate how student ideas about circuits are used to form reasoning chains both before and after physics instruction.

Overall, this research aims to enhance instructional strategies by exploring how students connect ideas into logical chains of reasoning and investigating how reasoning chain construction tasks might describe patterns in student reasoning and resource use before and after circuit instruction.

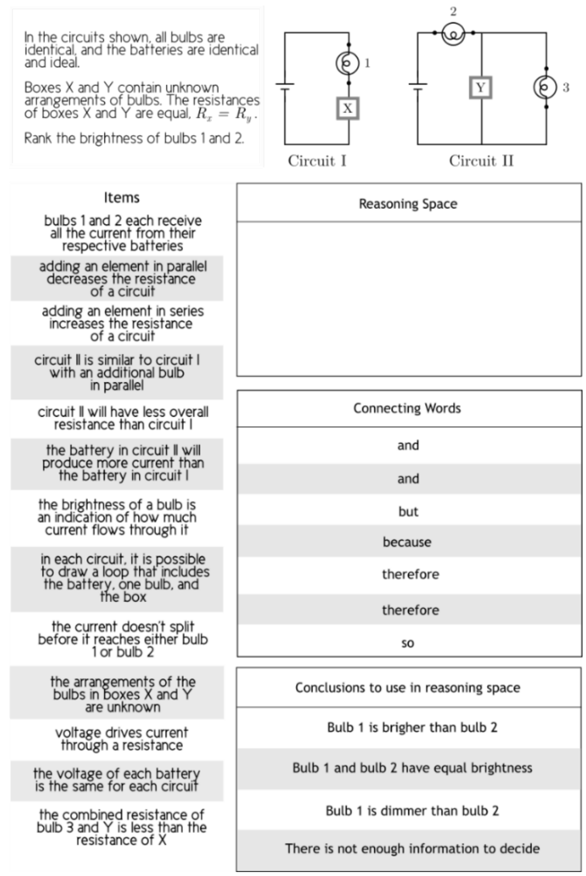

FIG. 1. The reasoning chain construction task used in this study, including the prompt, reasoning elements, connecting words, and conclusion. Students can move the elements in the "Items" column, "Connecting Words" box, or "Conclusions" box into the "Reasoning Space" and rearrange them into a line of reasoning. The task prompt was drawn from Ref 4.

II. METHODOLOGY

All student participants were enrolled in an on-sequence calculus-based physics 2 courses at a predominately white, land-grant research institution in the northeastern United States. Students completed the tasks for participation credit as part of weekly homework and/or exam reviews. The tasks were conducted online using a "Pick/Group/Rank" question format through Qualtrics software [14].

This study utilized reasoning chain construction tasks, or *chaining tasks*, which prioritizes the process of linking concepts and observations to form a coherent chain of reasoning [5,6]. In these tasks, students must select and arrange from a set of true statements or "reasoning elements," to form a sequence of logical steps to justify their answer to a physics question. An example reasoning chain construction task is shown in Figure 1. In addition to

Reasoning Elements	Category of Knowledge
Bulbs 1 and 2 each receive all the current from their respective batteries	**Current (C1)**
Adding an element in parallel decreases the resistance of a circuit	**Junctions (J1)**
Adding an element in series increases the resistance of a circuit	**Junctions (J2)**
Circuit II is similar to Circuit I with an additional bulb in parallel	**Junctions (J3)**
Circuit II will have less overall resistance than Circuit I	**Resistance (R1)**
The battery in Circuit II will produce more current that the battery in Circuit I	**Current (C2)**
The brightness of a bulb is an indication of how much current flows through it	**Current (C3)**
In each circuit, it is possible to draw a loop that includes the battery, one bulb, and the box	**Junctions (J4)**
The current doesn't split before it reaches either bulb 1 or bulb 2	**Junctions (J5)**
The arrangements of the bulbs in boxes X and Y are unknown	**Junctions (J6)**
Voltage drives current through a resistance	**Voltage (V1)**
The voltage of the battery is the same for each circuit	**Voltage (V2)**
The combined resistance of bulb 3 and Y is less than the resistance of X	**Resistance (R2)**

FIG. 2. Main ideas and associated reasoning elements for the task shown in Figure 1. These elements were categorized as belonging to a specific knowledge domain and a given a letter-number code for ease of analysis.

the reasoning elements, students were provided with connecting words ("but," "and," "so," "because") to clarify their argument. Blank tiles were also available for students to incorporate their own reasoning elements if needed.

In this study, we employed 3 physics circuit questions framed as chaining tasks. However, we focus our analysis on just one of these questions (shown in Figure 1), though analysis of the other questions is also of interest and will be pursued in another article. Many of the statements provided to students were designed to resemble ideas about circuits from the literature [4, 6, 7, 9] and to evaluate students' application of Ohm's Law principles and their related associations. The same 3 questions were completed by students prior to instruction on circuits (which was roughly half-way through the 16-week course) and on a final exam review assignment.

To assess students' usage of conceptual ideas, we coded each element (shown in Figure 2) with a specific category of knowledge: ideas about current, ideas about voltage, ideas about resistance, and ideas about circuit connections/junctions. We assume that students may struggle with deciding when to employ a specific idea to use in problem-solving tasks. However, after instruction, it is expected that students would be more successful at prioritizing relevant and productive ideas to apply when solving these problems. Therefore, we wanted to test the frequency of conceptual idea usage pre- and post-instruction to identify how student reasoning patterns shift as a result of instruction. We propose that chaining tasks are an efficient way to accomplish this.

III. RESULTS AND DISCUSSION

Generally, performance on this task improved after instruction. The distribution of final answers to this task are shown in Table 1. To determine the statistical significance of changes in students' responses before and after instruction, we employed a chi-square test and used Cramer's V for a measure of the effect size. There was a statistically significant increase in correct answer choices after instruction when conducting a Chi-squared test on a 2x2 contingency table comprised of correct vs. incorrect counts ($p = .00$, $V = 0.35$).

Answer Choice	Before Instruction (N=207)	After Instruction (N = 236)
Bulb 1 is brighter	27%	14%
Bulb 1 is dimmer (correct)	**13%**	**44%**
Equal brightness	34%	18%
Not enough information	1%	1%
No final answer selected	25%	23%

Table 1: Distribution of answer choices on the task shown in Figure 1 before and instruction. The correct answer is highlighted in boldface.

One representative student response for the correct answer is given below.

"bulbs 1 and 2 each receive all the current from their respective batteries / and / adding an element in parallel decreases the resistance of a circuit / circuit II is similar to Circuit I with an additional bulb in parallel / so / Bulb 1 is dimmer than bulb 2."

A representative student response for an incorrect answer is follows.

"bulb 1 and bulb 2 have equal brightness / because / bulbs 1 and 2 each receive all the current from their respective batteries / and / circuit II will have less overall resistance than circuit I / but / in each circuit, it is possible to draw a loop that includes the battery, one bulb, and the box".

Note how both examples utilize element C1 but arrive at different conclusions. One aim of this study is to examine the subset of elements that is shared between incorrect and correct answer responses, and then to examine elements that appear to differentiate the two. We show below how our methodology accomplishes this in an efficient way.

Students' responses were analyzed to assess their utilization of specific reasoning elements, as presented in Figure 3. After matching the data and excluding students who did not complete both versions of the *chaining tasks*, our sample consisted of 172 students, about 73% of the course enrollment. Responses where no final answer selection was given (even if there were other elements in the reasoning space) were removed to focus on unambiguous data to ensure quality in our analysis. For each category, we quantified the frequency of each reasoning element among correct and incorrect responses on the pre- and post-instruction task. To determine the significance of shifts between these groups, we performed Fisher's exact tests on the entire (13x2) contingency table and examined residuals. Elements with residuals of greater than ± -1.5 were subjected to individual Fisher's exact tests, using a Bonferroni-corrected p-value (the lowest threshold of which was $p = 0.01$ corresponding to 5 elements being tested). This approach allowed us to pinpoint meaningful changes in students' reasoning strategies throughout the instructional process. Elements that showed a significant difference between comparison groups are indicated with an asterix in Figure 3.

As can be seen in Figure 3.a, after instruction, the element C1 is used equally in both correct and incorrect answers post-instruction. Elements J1, J3, R1, V2, C2, and C1 or J5 constitute a correct and mostly complete line of reasoning on this problem. In Figure 3.a, we see many of these six elements present in the correct answers after instruction, but only some of them (J1, R1, and J5) are statistically different in frequency of use compared to the incorrect answers ($p=0.00$, 0.00, and 0.01, respectively).

Element J1 and R1 explain that the overall resistance of circuit II will decrease, and it appears that this idea is the main differentiator between correct and incorrect answer choices. Elements C1 and J5 are equivalent statements, with J5 being both an additional detail explaining the mechanism behind element C1 as well as utilizing more concrete language. Element J5 was used less frequently among correct answers, while element C1 was used equally among correct and incorrect answers. It could be that the content of element J5 might reinforce the incorrect answer "equal brightness" for students that still have a sequential view of current in circuits. While we can't tell the reason behind a difference with our data alone, our methodology *did* reveal a difference, and we feel this is an advantage of using reasoning chain construction tasks.

Figure 3.b shows element usage for only those students who answered incorrectly before instruction but answered correctly after instruction. Among this population, we see a rise in J1, R1, and C2 element usage which are core elements consistent with the correct answer ($p=0.00$, 0.00, and 0.00, respectively). This data suggests that the main idea gained from instruction in this population was that the current of the battery will respond to the overall resistance of the circuit. The element J5 trended towards a decrease usage after instruction for this population but this shift wasn't statistically significant, while element C1 remained stable in usage.

The pre-instruction and post-instruction comparison for students who answered incorrectly before and after instruction is shown in Figure 3.c. There was no overall statistical shift in this distribution, but there are some interesting trends. The elements J4 trends towards decreased use after instruction for this group. From the personal observations of the authors, students typically think about "drawing loops" as a way to begin understanding circuits, and then often switch to more formal representations of series, parallel, and equivalent resistance. Perhaps this decrease is indicative of a shift from concrete to abstract mental representations of circuits. This observation does not appear to be documented in the literature, so more research would have to be done on this. However, element J5 also trends upward in usage, along with element C3. If additional data collection makes this trend significant statistically, it could be pointing towards ideas that reinforce an incorrect answer.

The pre-instruction and post-instruction comparison for students who answered correctly before and after instruction (not shown) was also lacking in statistical significance, *i.e.,* students in that population showed no change in the frequency of element usage. We had hoped and expected that student's usage of ideas would shift even for those who did not shift their final answers as their knowledge and thinking was refined through instruction, but our methodology did not reveal such a shift.

IV. CONCLUSIONS

While there is much to comment on with regards to the information shown in Figure 3, we wish to start by commenting on the data this methodology affords. Using reasoning chain construction tasks, we were able to quickly gather information about specific ideas that students are employing to reason through a circuits problem. We were also able to easily compare the frequency of idea use on the task prior to and after relevant instruction. Thus, reasoning chain construction tasks can provide detailed information about student reasoning and can reveal insights into shifts in those reasoning patterns over the course of instruction.

Overall, this study investigates how chaining tasks can show patterns in idea usage before and after circuit instruction. As students develop a better conceptual grasp of the Ohm's Law triad, we suspect that they become more likely to select the appropriate elements to explain phenomena, and more particularly to decide when it's not useful to use these elements. We saw some evidence of this refined selection process on this task, but more research can be done to design tasks that can target this change during instruction more fully. For instance, some research has

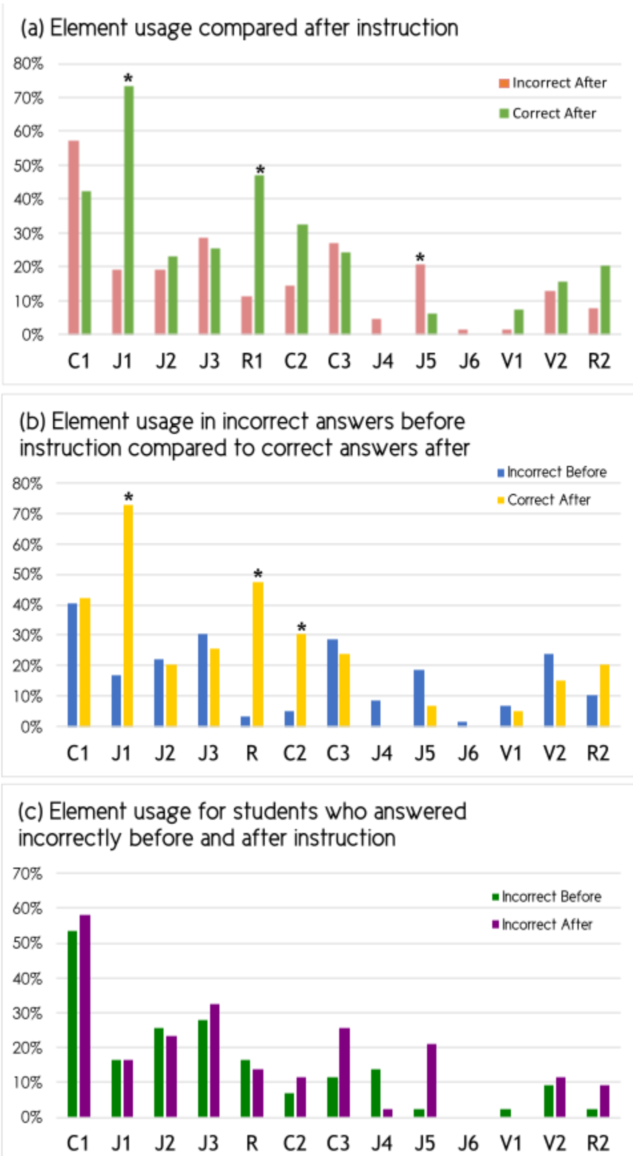

Figure 3: A comparison of the frequency of element use (using the element codes shown in Figure 2) (a) in responses that contained the incorrect answer choice and correct answer choice, (b) in incorrect responses before and after instruction, and (c) in correct responses before and after instruction. An asterix indicates a statistically significant difference (based on the results a 2x2 chi-square test).

identified specific cognitive resources that students use when solving circuits tasks and developed tutorials to aid students in recognizing the contexts in which each resource is productive to use or non-productive [9]. Reasoning chain construction tasks might be able to effectively measure increased selectivity in resource use by analyzing results across *multiple* circuits tasks, provided that the elements given to the student align with the resources commonly cued by circuits tasks.

This research has utilized a novel methodology, emphasizing reasoning chain construction tasks, to explore student conceptual understanding in electric circuits. Through analysis of the frequency of element use, there are notable shifts in student use of Ohm's Law principles and connections/junctions while reasoning about circuits. Reasoning chain construction tasks seem to be capable and useful at designing educational tools that support and measure the development of lines of qualitative reasoning during instruction.

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