Circuit Diagrams Vs. Physical Circuits: *The Effect of Representational Forms During Assessment*

Kayla DesPortes, Aditya Anupam, Neeti Pathak and Betsy DiSalvo
Georgia Institute of Technology
Atlanta, GA USA
ksdesportes@gatech.edu, aanupam3@gatech.edu, pathak.neetin@gatech.edu, and bdisalvo@cc.gatech.edu

***Abstract*—Assessment of students' conceptual knowledge is a difficult task in all fields including electrical engineering. Recently, electrical engineering assessments have tried to isolate various types of knowledge through expert reviewed and validated tests or concept inventories, which attempt to cover the foundational concepts within a particular domain. While these tests have been fundamental in uncovering how students understand important concepts within specialties, they are traditionally administered on a static 2D interface without providing the students with tangible examples to think with or about. We report on a qualitative laboratory study to understand how different tools can change the possibilities and limitations of thinking with circuits. Specifically, we administer two versions of an assessment targeting concepts in direct current (DC) circuits in which students talked through their reasoning. One version represents the circuits as conventional symbolic diagrams, and the other version represents the circuits using physical circuit components connected with wires and solder. The participants conveyed several misconceptions within both forms with an even spread across each assessment. However, students exhibited the misconception of *sequential reasoning* more prevalently in the physical circuit assessment than the diagram assessment.**

Keywords—electronics education; Circuits; Assessment; Think-aloud

I. Introduction

"The use of tools limitlessly broadens the range of activities within which the new psychological functions may operate" [1, p. 55].

Tools have the ability to extend both our physical as well as our mental capabilities. Vygotsky, emphasized the *unity* between tools and human behavior, focusing attention specifically to the tools and artifacts that learners use to think. He regarded *tools* as an external means of mediating activity between humans and objects, which then had internal representations that humans manipulated through *symbols*. He claimed that it was through this mutual shaping of the internal and external worlds that humans build their conceptual models [1]. Since the time Vygotsky's work was first published, many researchers have explored the possibilities afforded through various representational forms in education. From simulations [2], to virtual reality [3], to augmented reality [4], the possibilities for representations in educational tools has exponentiated with the advancement of technology.

While previous research has shed light on what it means to teach and learn with certain representations, there is little research investigating how students think with and about various representations during assessment. Within a qualitative laboratory study, we administered a test to target fundamental concepts within direct current (DC) circuits. We used a subset of questions from the DIRECT (Determining and Interpreting Resistive Electric Circuit Concepts Test) version 1.0, developed by Engelhardt and Beichner, only using questions involving circuit diagrams. We administered two versions of the test: in one test we used circuit diagrams (as was done in the original) and in the second test we transformed the diagrams to physical circuits using actual circuit components with the batteries removed. We administered both versions of the test to 11 novice students who adhered to a think-aloud protocol voicing their thoughts as they traversed the questions. The think-aloud protocol enables an investigation into the nuances within student understanding of the representational forms, which would been hidden in a purely quantitative analysis. The participants were recorded through video and audio devices during the study. We focused our investigation on the following questions:

1. *Do students' understanding of DC circuits change based on the representational form of the assessment?*
2. *Do students articulate different misconceptions based on the representational form of the assessment?*

The analysis of the data indicated some similarities and some differences between the representations. Although there were not large differences in overall performance between the two forms, the findings from this study emphasize the importance of using circuit diagrams and physical circuits within electronics education. While a typical electrical engineering classroom involves using various representations of circuits, this is not always true of many of the courses for non-majors. Courses for non-majors may not have a laboratory section, which would give students experience with the physical representations that could bring their misconceptions to light. Conversely, classes which adopt themes from the maker movement [5], [6] do not always teach students circuit diagrams, which could prove useful for scaffolding some of the complexities found in the physical forms. This study suggests that as these educational interventions gain popularity and circuitry finds its way into more classrooms, it is important for their curriculum to include the circuit diagrams as a complement to the physical circuitry and vice versa.

II. Motivation and Background

Electronics education often involves representing fundamental concepts through use of various forms: *symbolic diagrams* are an industry standard and have the abstraction necessary to simplify circuit components while students learn the complexities behind how electricity works [7]–[9]; *mathematical equations* provide a way to represent the fundamental concepts with numerical outcomes; *physical circuits* give students the opportunity to build and observe real-world applications of the concepts [4], [10]; and even the *language* used to articulate the fundamental concepts can be important to how students understand electricity [11]. Even with all these representations, which were intended to make it easier to think about electricity and circuits, students still have difficulty understanding and reasoning correctly about the fundamental concepts [2], [11]–[14].

One important aspect of learning in the classroom, is for the teacher to be able to identify student misconceptions so they can rectify their students' conceptual models [15]. The literature contains several examples of assessments that researchers and educators have administered in an attempt to understand the misconceptions that students harbor (ex. [13], [14], [16], [17]). While some teachers have integrated assessments which allow for students to work with several representations, such as Viegas' lab based assessments [10], many educators default to 2D symbolic circuit diagrams. However, we know that representational form can impact how students think.

In a series of experimental studies [7]–[9], researchers demonstrated the importance of using symbolic abstract circuit diagrams when teaching electronics. Using a worked example curriculum, Moreno et al. gained an understanding of whether teaching circuits in a contextualized manner—using real-world pictures of components in the circuit diagrams and cover stories—leads to better student perceptions and performance. From a theory standpoint, they present conflicting hypotheses. Contextualized learning theory, suggest that situating the learning within familiar contexts will make learning easier. The conflicting theory presented, cognitive load theory, suggest that abstract representations will remove extraneous information and concepts needed to enable students to learn more easily in a simplified environment. Their findings show that students perform better in the abstracted group on the near transfer problems supporting the cognitive load hypothesis in this context [8]. Two consecutive studies also show that the abstracted version of the curriculum led to higher transfer than students who were being taught in a contextualized manner [7], [9]. These studies have important implications for how we integrate representational forms into education. However, while these studies demonstrate clear differences in performance, they do not offer qualitative explanations to understand how students were thinking during the examination, or provide insight into the various misconceptions that might have been associated with the different representations. This information could be pertinent to understanding when it makes sense to use the symbolic form of a circuit or a more realistic form of a circuit. Moreno et al.'s work was important first step in identifying differences, and our work serves to supplement the understanding of differences between representations.

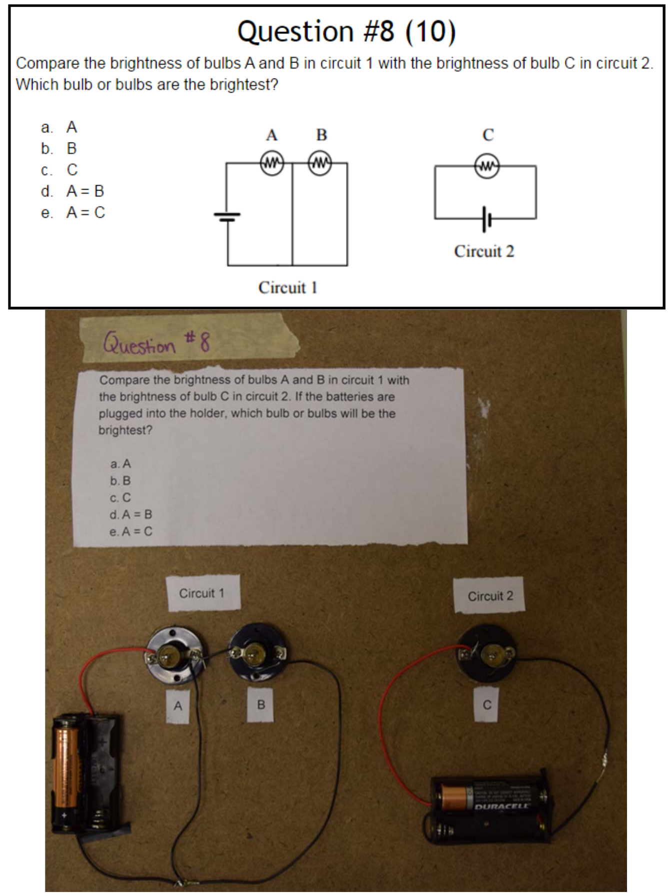


Figure 1. Question 8 diagram (*top*) version and physical (*bottom*) version

III. Methods

A. DIRECT Assessment

The researchers administered two shortened versions of the DIRECT (Determining and Interpreting Resistive Electric Circuit Concepts Test) version 1.0 assessment developed by Engelhardt and Beichner. The test was designed to target the fundamental concepts when teaching direct current circuits covering instructional objectives consisting of: physical aspects of circuits, energy, current, and potential difference [16]. DIRECT was chosen over conventional concept inventories, such [18] and [19], as those are normally reserved for use at the end of rigorous electronics courses. The original DIRECT test consisted of 29 multiple choice questions and was administered to 1135 high school and college students to validate the reliability and consistency of what the questions measured. Engelhardt and Beichner also conducted 28 student interviews on 10 of the 29 questions to identify misconceptions and ensure their alignment with the objectives [16].

The investigation presented in this paper was focused on qualitatively analyzing student reasoning when presented with a circuit diagram or a physical circuit. Researchers created two versions of DIRECT using 20 of the 29 questions in the original: a symbolic diagram test, and a physical circuit test. They chose only the questions from the original test that contained circuits that were represented by circuit diagrams, and could then be replicated using physical circuits. Figure 1 has an example of Question 8 in both the diagram and the physical form. Each participant took each version of the test with at least a day in between. This was done so that it was less likely they would remember the questions, their previous answers and their previous line of reasoning.

B. Participants

The researchers conducted a post-study survey at the end of the participants second session that gathered information about the individual participant, and their prior experience with electronic circuits. The eleven participants were recruited from an entry level course required for electrical computer engineering at an institution in the South Eastern United States. Of these students, 4 were majoring in Electrical Engineering, while the remaining 7 belonged to Computer Engineering. The gender spread was 8 male participants to 3 female participants.

The questions on the post-study survey about prior experience focused on specifics about the type of experience—i.e. *Have you had experience with circuit diagrams before? Have you had experience working with physical circuits before?* All of the participants, except one had experience with circuit diagrams, while all but four students had some prior experience with physical circuits.

We further tried to classify their experiences through understanding the number of formal classes in which they worked with electronics compared to the number of informal activities that they participated in, which involved electronics (ex. workshops, summer camps, etc.). All eleven students mentioned that they had taken a class in circuits before, while four indicated that they had engaged in workshops that involved working with electrical circuits. Nine of students had taken the AP Physics exam.

TABLE 1. PARTICIPANT BREAK DOWN BY TEST GROUP

		Diagram Test 1st	Physical Test 1st
Gender	*Male*	2	6
	Female	3	0
Major	*EE*	2	1
	Comp E	3	5
At least one Experience	*Formal*	5	4
	Informal	2	2
	Diagram	5	6
	Physical	3	5
Took AP Physics		3	3

C. Interviews with think-a-louds

Throughout both of the assessments, the researchers used a think-aloud protocol [18], asking participants to communicate their thought process as they went through the questions. We gave each of the students a piece of scratch paper that was collected at the end of the session. During the think-aloud we audio and video recorded the students. As mentioned earlier, the two tests were conducted with a minimum of one day in between and a maximum of one week. Had we instead exposed students to both representations on the same day, they would have been more likely to create a common consistent explanation that fit both versions. Of the 11 participants, 5 completed the diagram test first and 6 completed the physical test first. Shuffling the order of the assessments gave us some control over the disparities we would see based on ordering. After the first session, they were told to not study the content before their next session.

D. Analysis

Each of the interviews was audio and video recorded with the camera focused on the physical circuit or circuit diagram and scratch paper if the student opted to use it. Over fifteen hours of video and audio was transcribed. This qualitative data revealed student reasoning within each of the questions bringing to light misconceptions that would have been missed without the students' explanations. The answers were all reviewed and analyzed for correctness and differences between the physical and diagram tests. Each of the researchers independently went through an initial pass of 10% of the qualitative data to develop an initial code book based on emergent themes. The researchers came back together to compare and solidify the codes. The researchers used a Pooled Kappa percentage [19] to identify their inter-rater reliability. In each iteration, one researcher would randomly extract 20% of the data evenly distributed across all of the questions to code. The other two researchers would code to complete tests on the same data. If the Pooled Kappa Cohen score was under 70%, the three researchers identified disagreements and clarified the description for each code. In most iterations, codes were consolidated and definitions were refined. When 70% Pooled Kappa Cohen was achieved, the training processes ended. The rest of the transcriptions were all coded for misconceptions from the final code book (seen in Table 2 and 3). Once the coding was complete, the code descriptions and hierarchy conveyed similarities and differences between the students' answers and explanations within and across the two versions.

TABLE 2. CODE BOOK FOR ANSWER CORRECTNESS

Code Name		Description
Right Answer	*Correct Reasoning*	Correctly answered question and no misconceptions within their explanation
	Has Misconception	Correctly answered question, but had a misconception within their explanation
	Unknown Reasoning/ Guessing	Correctly answered question, but we could not understand their reasoning or they guessed the answer
Wrong Answer	*Correct Reasoning*	Incorrectly answered question, but no misconceptions within their explanation
	Has Misconception	Incorrectly answered question, and had a misconception within their explanation
	Unknown Reasoning/ Guessing	Incorrectly answered question, but we could not understand their reasoning or they guessed the answer

The researchers added codes to the entire question evaluating it as a whole instead of going sentence by sentence. Therefore, one code could not be tagged more than once within a participant's answer to one question. For example, an excerpt in which the student demonstrates a misconception about *current splitting* in multiple sentences will only be tagged once. Additionally, all supersets of that code will automatically be tagged as well, which for *current splitting* would be *current* and *concept misconception*. While *mixing up open/closed switch* does not fall under the superset of *concept misconception* because it is a language issue, it is considered a misconception when coding for subset *has a misconception* under *right answer* and *wrong answer*. To account for students who may have arrived at the correct answer despite having misconceptions, we devised 3 separate codes for covering the different ways that a student may arrive at their answer: *right answer, correct reasoning*; *right answer, has a misconception*; and *right answer, unknown reasoning/guessing*.

We then used the transcripts and videos to assist us in coding each question that the student answered correctly. We also had a similar separation for covering ways that students can arrive at the wrong answer. *Wrong answer, correct reasoning*—to cover cases when students may have incorrectly selected the wrong answer even when they had reasoned correctly; *wrong answer, has a misconception*—to cover cases where a student gets a wrong answer due to a misconception; and *wrong answer, unknown reasoning/ guessing*—where either the student guessed or the researchers were unable to understand the reasoning behind the answer.

TABLE 3. CODE BOOK FOR MISCONCEPTIONS

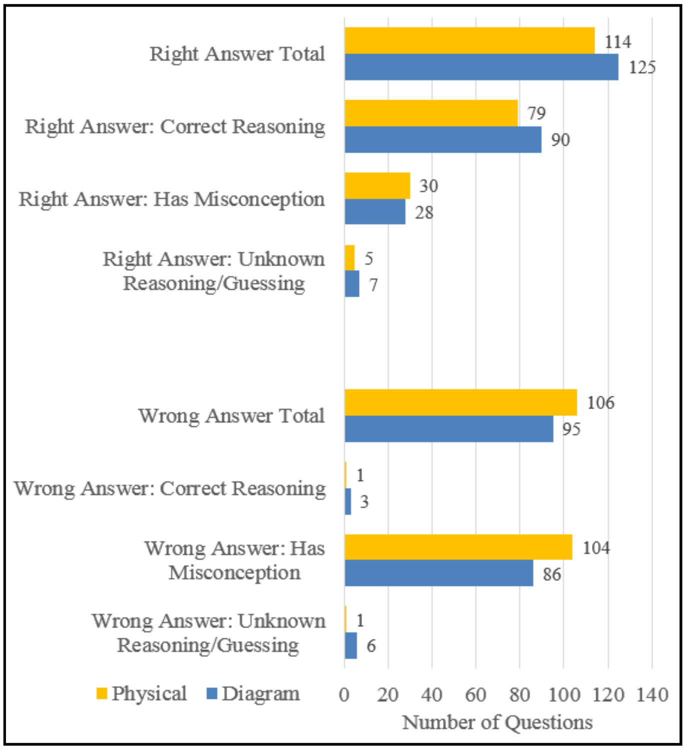
Code Name			**Description**	**Examples**
Concept misconception	***Resistance***	*Resistors in series/ parallel*	Recognizes resistors as parallel/series but: misidentifies them, thinks they are treated the same, or uses wrong equation.	"Those would be in series. So, if they were just 2, you'd just do ½ + ½ = 1, which is just 1. Then if now you had both, you have to add them in parallel first. So it would just be 4. Then you would do ½ + ¼ which equals ¾. So, that also goes to 4/3 ."
		Changing resistance	Thinking resistance only exists when current goes through an element.	"I just feel like it needs a closed circuit to work. So, I would say the resistance goes to zero, because it's just not working anyway. Like there's no flow of energy in the first place."
	Voltage	*Batteries in series/ parallel*	Recognizes batteries as parallel/series but: misidentifies them, thinks they are treated the same, or uses wrong equation.	"Oh, now I'm starting to remember the voltage equation for parallel circuits. The total voltage should equal 1 over v1, plus 1 over v2, I think."
		Making up voltage drop	Makes up numbers for what the voltage drop should be irrelevant of circuit elements.	"My thoughts are there's like 12 volt battery and then maybe this goes through and this is like 3 volts and then at this point now we have 9 volts, and at this point we have minus three more volts."
		Voltage is zero with open circuit	Voltage goes to zero when there is an open circuit and no current flowing.	"Actually, there's no current flowing. So, there cannot be any voltage. Yeah, so that was zero, because the circuit is open, no current, no voltage."
	Current	*Current splitting*	Thinks current is divided when it shouldn't be; current splits incorrectly; does not identify a short circuit.	"So I guess you add up current from 2 batteries flowing that's in parallel one goes here and splits this one. That one splits that way? Does it just go the other way here?"
		Sequential reasoning	Current hits one element before the other; current gets *used up* as it hits elements.	"I would probably say the current goes from the higher to low from this way, and then down."
		Battery as current source	Uses battery as a current source regardless of resistance.	"Yeah, yeah I think all 3 of them are the same, because in a series circuit, the current across a circuit should be the same, in each of the components, so they should glow with the same...intensity… they should have the same power, so same energy."
	Ignoring element arrangement	*Resistor arrangement*	Doesn't acknowledge parallel/series when they are both in the question.	"The power through these two will be the same, because the R remains the same throughout and the resistance remains the same throughout. So, they both are the same."
		Battery arrangement	Doesn't acknowledge parallel/series when they are both in the question.	"I'm going to go with circuit 1 because there is only one battery and here there are two batteries. And there there are two batteries."
	Referencing superficial parts		Takes superficial parts of the circuit into account for analysis.	"Although it's like a shorter wire, I dunno if that really affects anything. And this just seems to take an extra step. And go to this connector thingy and then the solder and then that way."
	Long tail		Other misconceptions.	"The potential difference doesn't change across the circuits. It can't really be any other answer, because if I thought of something else, you'd need to have more information. So, it has to be 12."
Mixing up open/closed switch			Thinking open means *on* and closed means *off.*	"So, when the switch is closed, you're basically removing another option for the current to flow."

IV. Results and Findings

A. *Overview Diagram Vs. Physical*

The average overall scores for the two tests were similar. With a maximum possible score of 20, the average score of the students taking the circuit diagram test was 11.36 and on the physical circuit test it was 10.36. This was slightly higher than the average 6.88 scored by students on the same questions in the original study [16]. Seven students scored higher on the diagram test, three performed better on the physical test and one student scored the same in both. Graph 1 shows the breakdown of the right and wrong answers coded in each of the tests based on the codes in Table 2.

Graph 1. Right Vs. Wrong Answers



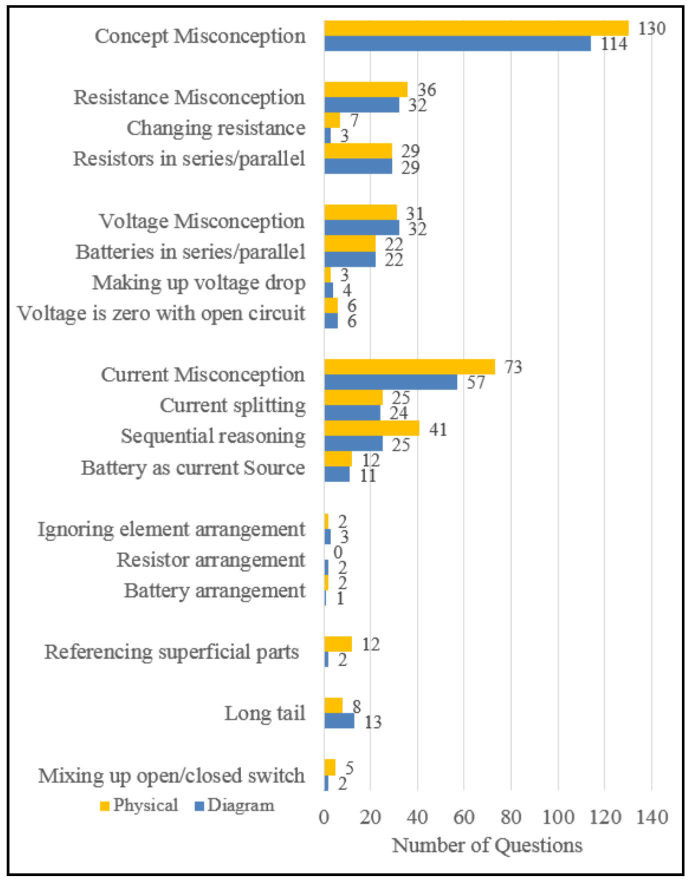
To control for variation in the order of the tests, 6 candidates gave the physical test first and 5 gave the diagram test first. The average on the first was 10, which was slightly lower than the average on the second, which was 11.7. Seven students performed better on their second test.

The two students who had not taken any classes in electrical circuits before, tended to perform better on the diagram circuits than the physical (by 5 or more questions), even when they had some prior experience with physical circuits. Students who had taken two or more classes were more consistent in their performances on both tests but did not always score higher than those who had taken fewer classes.

B. *Misconceptions Leading to Correct Answers*

Some questions were more likely to be marked with correct answers, even though the transcript revealed student misconceptions. One such question was Question 8 (Figure 1). In this question, as the figure shows, students have to decide which light bulb(s) will shine the brightest. The correct answer and reasoning here is that as there exists a short, no current will flow to B, and hence circuit 1 reduces to circuit 2, and both bulbs A and C will be equally bright. However, many students did not recognize the short in Circuit 1 and assumed current to split between the short and bulb B. Some of these students also then reasoned sequentially, stating that because bulb B was *'after'* bulb A and the junction in this circuit, "*B will get only partial current, so B will be lesser*". But bulb A, "*should be equal to C because it's like starting over and this is just one* (referring to A)". Despite exhibiting multiple misconceptions and an incorrect line of reasoning, these students still reached the correct answer (that bulb A will be the same brightness as bulb C). This example shows that misconceptions may assist students in getting the right answer, thereby reinforcing those misconceptions. Therefore, the total counts on the *right answer, correct reasoning* code for each student is a more accurate measure of student understanding. In this light, the average score, taking into account student understanding on the physical was 7.18 and that on the diagram test was 8.18, with 8 students having a higher score on the diagram test, 2 higher on the physical, and 1 student scoring the same in both.

Graph 2. Misconceptions



C. *Resistance Misconceptions*

The resistance misconceptions were classified into two categories: *resistors in series/parallel* and *changing resistance*. The resistance misconceptions were almost evenly distributed across the diagram and physical tests (see Graph 2). With an even distribution of *resistors in series/parallel* across the two versions of the test and four more instances of the *changing resistance* misconception code tagged in the physical.

Resistance misconceptions were tagged in over half of the questions (11 of the 20 questions), across each of the tests and all of the students. In [16] they found a greater number of resistance misconceptions in the questions that tested the physical aspects of DC circuits. Similarly, 68% of the misconceptions in our study came from the 6 questions under this objective. The majority of the misconceptions were *resistors in series/parallel,* found in 10 of the questions while *changing resistance* was only found in two of the questions.

The resistance misconceptions were prevalent across all the participants with each participant having at least three questions in which they demonstrated misconceptions of *resistors in series/parallel*, while seven of the participants had at least one question where they made the mistake of *changing resistance* when current wasn't flowing through the element.

D. Voltage Misconceptions

The voltage misconceptions were divided into three subgroups: *batteries in series/parallel*, *making up voltage drop*, and *voltage is zero with open circuit*. Similar to the resistance misconceptions, discrepancies across diagram and physical versions of the test were also minor within the voltage misconceptions. *Batteries in series/parallel* and *voltage is zero with open circuit* were exactly evenly split, while *making up voltage drop* had just one instance more tagged in the diagram version of the test.

The voltage misconceptions were confined to the least number of questions: only 6 of the 20 questions showed any instances of voltage misconceptions, 4 of which were designed by [16] to target voltage objectives. Furthermore, *making up voltage drop* and *voltage is zero with an open circuit* were each only tagged in 2 of the 20 questions.

Within the participants, all except one had at least one answer tagged with the misconception *voltage is zero with open circuit*. All of these students did not realize that a potential difference is what is needed in order for electrons to move and for current to exist; instead, they saw voltage as being the result of current flowing in the circuit. The majority of the students (all but 2) also exhibited mistakes with *batteries in series/parallel* at some point during the tests. While only five students made the mistake of *making up voltage drop*.

E. Current Misconceptions

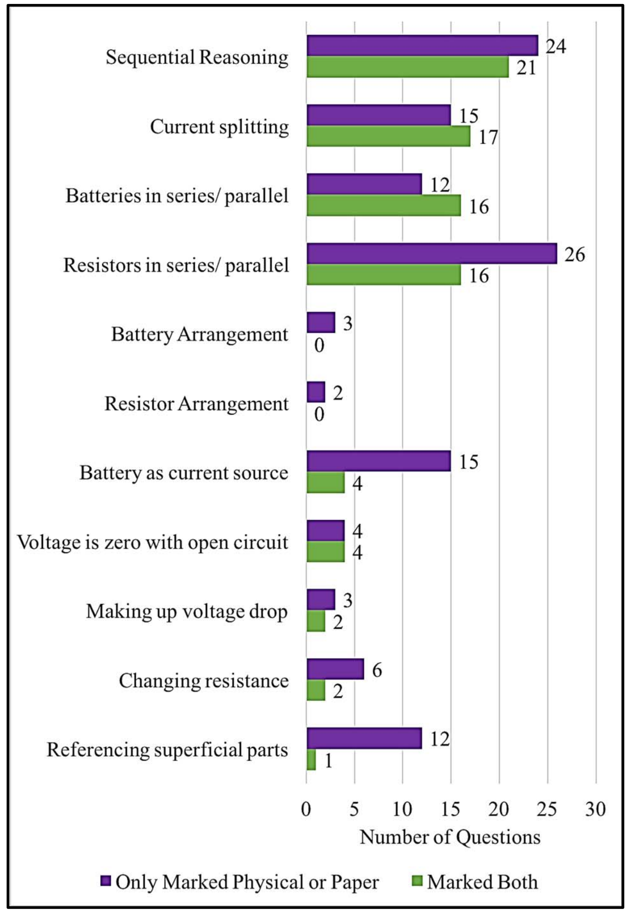
The current misconceptions were categorized into 3 subgroups: *current splitting, sequential reasoning*, and *battery as a current source*. Of all of the misconception supersets, this section had the most discrepancy between the physical and diagram tests. Furthermore, these differences were localized mostly to the *sequential reasoning* misconception which had a difference of 17 instances—41 tagged misconceptions in the physical and only 24 tagged instances in the diagram. There was only a difference of one in both the *current splitting* and *battery as a current source misconception*.

Compared to the resistance and voltage misconceptions, the current misconceptions were more prevalent across all of the questions with 17 of the 20 questions receiving the current misconception parent code, which was similar to [16] in which they found current misconceptions associated with all 10 of the questions they interviewed students about. In our study, this was caused by the *sequential reasoning* code's presence in 15 of the questions while only 8 questions contained *battery as current source* and 7 questions contained *current splitting*.

All participants had at least 2 of the current misconceptions in the combination of both tests. All participants also had at least one answer tagged with a *current splitting* misconception. Of all the participants, only two did not demonstrate the *sequential reasoning* misconception, and only four did not demonstrate the *battery as a current source* misconception.

F. Inconsistencies within Questions on Diagram and Physical

GRAPH 3. INCONSISTENCIES IN QUESTIONS

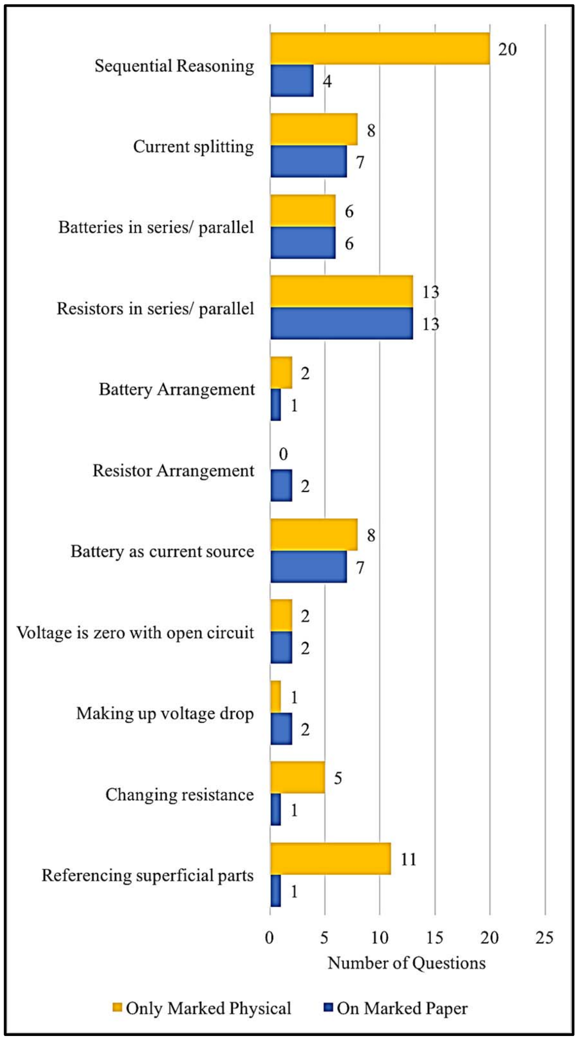


We analyzed how consistently students were marking the same misconception across both forms of the test. Graph 3 shows that students were not consistent within many of their answers. About half of the time they didn't display the same misconception across both the diagram and physical forms of the question. Relatively, students had the most inconsistent answers on*, resistors in series/parallel, battery as a current source,* and *referencing superficial parts.*

When the students were inconsistent (Graph 4), the *sequential reasoning, referencing superficial parts*, and *changing resistance* misconceptions occurred more frequently in the physical test as opposed to the diagram test. Of these instances the researchers looked at how consistently each of the participants were demonstrating the same misconception across both the physical and the diagram versions of the same question.

Across all participants and both tests there were 66 instances of the sequential reasoning misconception, and 42 of those times the participants were consistent in having this misconception within the same question across the physical and diagram test. This means there are 21 times in which a participant had the same misconception in both the physical and diagram test. There are 20 instances in which the participant had this misconception only in the question on the physical test, and only 4 instances in which the participant had this misconception only in the question on the diagram test.

GRAPH 4. INCONSISTENCIES IN DIAGRAM VERSUS PHYSICAL



The participants had the misconception *referencing superficial parts* 14 times: 2 of times the participant was consistent across the physical and diagram test; 11 of those times it was only displayed in the physical test; and 1 of those times it was only displayed in the diagram test. These misconceptions however, were mostly the result of one participant who demonstrated this misconception 10 times during his physical assessment.

The participants had a *changing resistance* misconception 10 times, and 4 of those times were for the same question across the physical and diagram test. There are 5 instances in which the subject had this misconception in the physical test and not the diagram test for a particular question, and 1 instance in which the subject had this misconception in the diagram test and not the physical test for a particular question.

Ignoring resistor arrangement and *ignoring battery arrangement* misconceptions were tagged seldom, 2 and 3, times respectively. *Batteries in series/parallel*, *resistors in series/parallel, current splitting, making up voltage drop*, *battery as a current source*, and *voltage is zero with open circuit* misconceptions were tagged evenly throughout physical and diagram tests. Subjects either had the misconception on a particular question in both tests, or had a near 50% distribution of the misconception in only the physical test or only diagram test for a question.

The long tail was the only misconception tag which was skewed higher in the diagram compared to the physical (13 to 8 respectively). However, due to the nature of this code being a conglomeration of several misconceptions which could not be categorized, this does not tell us anything.

G. Other Misconceptions

The *mixing up open/closed switch* was more prevalent in the physical assessment (5 versus 2 instances), which was not a large difference, but we noticed that the *on/off* terminology printed on the switch often conflicted with their ideas of what *open/closed* should mean—i.e. *open* = *on*, and *closed* = *off*.

While the overwhelming majority of the misconceptions identified could be classified into the categories described in the code book, there were still 21 instances which did not fit into any of those categories and were therefore labeled as *long tail*. Furthermore, these uncategorized misconceptions were found in all but three participants and their particular misconception did not prevail across multiple students.

V. DISCUSSION

We set out to investigate two research questions based on the representational form:

1. *Do students' understanding of DC circuits change based on the representational form?*
2. *Do students articulate different misconceptions based on the representational form of the assessment?*

The first question sought to understand whether form can influence a student's understanding. The second focused on whether form influences students to have certain kinds of misconceptions over others. While there were no significant differences between test results of the two versions, there were slightly more correct answers in the participant's diagram test score. Previous research suggests advantages in using abstract diagrams; however, while this might be beneficial for initially learning concepts [7]–[9], it might not be so in the long run. The point of the diagrammatic form is to eventually be related to the physical circuit suggesting that more work should be done in understanding this translational phase.

Sequential reasoning was the one misconception that was displayed more often by students on the physical circuit assessment compared to the diagram. This misconception is one of the most consistently studied misconceptions due to its overwhelming prevalence in students throughout their education [12], [13]. Furthermore, it was prevalent in the prior studies with DIRECT as well. Engelhardt and Beichner marked this as a misconception in 9 of the 10 questions they interviewed students on [16]. Similarly, Goris found both novice and senior students treating electricity as a substance that can be "used up" as it passes through circuit elements [20]. We find it is important for educators to recognize the ability of physical forms of circuits to provoke students in displaying this misconception. If the student is only exposed to a symbolic diagram version of a circuit, it could be hidden. Furthermore, due to the emergent nature of electricity it could be more difficult to correct this type of misconception [2], [12] supporting the necessity for educators to determine if students have this misconception as early as possible. We believe that the emergent nature of electricity is the same reason in which students were making more mistakes in the physical representation rather than the diagram representation. When the participants were forced to translate between a theoretical perspective and reality, they were more likely to fall back on the sequential explanation that works in most real-world contexts. Using physical circuits could provide teachers with the tool they need to identify students that still harbor the *sequential reasoning* misconception. Furthermore, the physical form might also be necessary to challenge students to transfer their knowledge to the physical representation, ensuring that they have consistent conceptions of electricity and bringing to light any other misconceptions they might have.

Overall, outside of *sequential reasoning,* the majority of the participants had many misconceptions that they demonstrated throughout both versions of the exam. This suggests that since there is not a large difference in how students are able to reason around these representations it could be beneficial to introduce the physical versions within the classroom, which have added benefits for engaging students [4]. Adding the physical without much detriment to the students' learning could also provide options for supporting various approaches to learning through project based activities. Using both versions could support various types of learning. From the ideas of Turkle and Papert on epistemological pluralism [21], one could classify the diagram version of circuits as the *abstract* way of knowing that has most often been advocated throughout history, while classifying the physical version as the concrete, *tangible* way of knowing that has historically received less credence. By integrating both we may create a more equitable learning environment, incorporating multiple student approaches.

One student within our findings showed a trend of referencing superficial parts of circuits during his physical circuit test. His interview brought to light several aspects of physical circuits, such as solder, wire coloring, and perceived complexity as aspects that educators should address when transitioning students between diagram and physical representations. Furthermore, the mistakes students made in mixing up the terminology between open/closed and on/off shows that it could be important for educators to discuss terminology and language more closely, especially if it is going to be used differently within representations. Language was also found to be of great importance in Grotzer and Sudbury's study investigating sequential reasoning misconceptions. Students interviewed claimed that it was easier to articulate a *cyclic sequential* misconception than an accurately describing the *cyclic simultaneous* flow of electrons. They admitted to defaulting to the wrong misconception because it was easier for them to talk about even though they knew it was wrong [11]. Therefore, seeding discussions with both types of representations may give the students opportunities to be exposed to correct vocabulary and suffice their need for accurate language.

A. Inconsistencies within Questions on Diagram and Physical

The second research question was posed to understand if the various forms of the circuit made students articulate different misconceptions. We analyzed if students were having the same misconceptions for the same question on each form of the assessment. The participants were relatively more consistent in having the same misconception across both exams for the *sequential reasoning, current splitting*, and *batteries in parallel/series*. When participants were inconsistent (meaning they had a misconception in one test form but not the other for the same question) they didn't favor one representation over another. The number of times they only had a misconception in one form versus the other is balanced between physical and diagram forms. This suggests students are considering the underlying concepts behind the question or making the same mistakes on the question without prejudice towards any particular medium.

B. Ordering of Tests

We intended to control between the first and second test by giving half of the participants the diagram test first and the other half the physical. The students performed slightly higher on the second test, which suggests the act of taking the first test could have made students re-think their answers, discuss the questions, or study the subject (despite being prompted by the researcher not to).

VI. Conclusion

In conclusion, we found that overall there were not large differences in the ways that students reasoned about circuits between the physical and diagram representations. These small differences show that educators could capitalize on the benefits of engagement and inclusion that physical circuits afford if they augment them with the diagram forms. Furthermore, through including physical circuits into assessments, educators could identify more accurately if students have the deep seeded misconception of sequential reasoning or other language of concept gaps. Even though there are no significant differences in performances between the diagram and physical assessments due to the limited number of participants, this study hints at a few possible differences that may become magnified with a larger sample set, such as reasoning sequentially about current, and referencing superficial parts of a circuit. By teaching students a combination of circuit diagrams with their physical counterparts, students will be more likely to transfer better between both media.

VII. Acknowledgment

We would like to thank the students who participated in the study for the time they dedicated.

VIII. REFERENCES

[1] L. S. Vygotsky, *Mind in society: The development of higher psychological processes*. Harvard university press, 1978.

[2] E. Beheshti, A. Aljuhani, and M. S. Horn, "Electrons to light bulbs: Understanding electricity with a multi-level simulation environment," in *Frontiers in Education Conference (FIE), 2014 IEEE*, 2014, pp. 1–8.

[3] Q. T. Le, A. Pedro, and C. S. Park, "A Social Virtual Reality Based Construction Safety Education System for Experiential Learning," *J. Intell. Robot. Syst.*, vol. 79, no. 3–4, pp. 487–506, Aug. 2015.

[4] J. Chan, T. Pondicherry, and P. Blikstein, "LightUp: an augmented, learning platform for electronics," in *Proceedings of the 12th International Conference on Interaction Design and Children*, 2013, pp. 491–494.

[5] P. Blikstein, "Digital fabrication and 'making'in education: The democratization of invention," *FabLabs Mach. Mak. Invent.*, pp. 1–21, 2013.

[6] P. Blikstein and D. Krannich, "The makers' movement and FabLabs in education: experiences, technologies, and research," 2013, p. 613.

[7] R. Moreno, G. Ozogul, and M. Reisslein, "Teaching with concrete and abstract visual representations: Effects on students' problem solving, problem representations, and learning perceptions.," *J. Educ. Psychol.*, vol. 103, no. 1, pp. 32–47, 2011.

[8] R. Moreno, M. Reisslein, and G. Ozogul, "Pre-college electrical engineering instruction: Do abstract or contextualized representations promote better learning?," in *Frontiers in Education Conference, 2009. FIE'09. 39th IEEE*, 2009, pp. 1–6.

[9] A. M. Johnson, K. R. Butcher, G. Ozogul, and M. Reisslein, "Introductory Circuit Analysis Learning From Abstract and Contextualized Circuit Representations: Effects of Diagram Labels," *IEEE Trans. Educ.*, vol. 57, no. 3, pp. 160–168, Aug. 2014.

[10] C. Viegas, N. Lima, G. Alves, and I. Gustavsson, "Improving students experimental competences using simultaneous methods in class and in assessments," 2014, pp. 125–132.

[11] T. A. Grotzer and M. Sudbury, "Moving beyond underlying linear causal models of electrical circuits," in *annual meeting of the National Association of Research in Science Teaching, New Orleans, LA*, 2000.

[12] M. T. H. Chi, "Commonsense Conceptions of Emergent Processes: Why Some Misconceptions Are Robust," *J. Learn. Sci.*, vol. 14, no. 2, pp. 161–199, Apr. 2005.

[13] R. Cohen, "Potential difference and current in simple electric circuits: A study of students' concepts," *Am. J. Phys.*, vol. 51, no. 5, p. 407, 1983.

[14] C. R. Smaill, G. B. Rowe, E. Godfrey, and R. O. Paton, "An Investigation Into the Understanding and Skills of First-Year Electrical Engineering Students," *IEEE Trans. Educ.*, vol. 55, no. 1, pp. 29–35, Feb. 2012.

[15] J. D. Bransford, A. L. Brown, R. R. Cocking, and others, *How people learn*. Washington, DC: National Academy Press, 2000.

[16] P. V. Engelhardt and R. J. Beichner, "Students' understanding of direct current resistive electrical circuits," *Am. J. Phys.*, vol. 72, no. 1, p. 98, 2004.

[17] K.-E. Chang, S.-H. Liu, and S.-W. Chen, "A testing system for diagnosing misconceptions in DC electric circuits," *Comput. Educ.*, vol. 31, no. 2, pp. 195–210, 1998.

[18] K. Duncker and L. S. Lees, "On problem-solving.," *Psychol. Monogr.*, vol. 58, no. 5, p. i, 1945.

[19] H. De Vries, M. N. Elliott, D. E. Kanouse, and S. S. Teleki, "Using Pooled Kappa to Summarize Interrater Agreement across Many Items," *Field Methods*, vol. 20, no. 3, pp. 272–282, Mar. 2008.

[20] T. V. Goris, "Analysis of misconceptions of Engineering Technology students about electricity and circuits: A mixed methods study." 2012.

[21] S. Turkle and S. Papert, "Epistemological pluralism," *Signs J. Women Cult. Soc.*, vol. 1, no. 16, p. 11, 1990.