Students' Creation and Interpretation of Circuit Diagrams

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Abstract

I report results of a study of representations of electric circuits and interpretation of circuit diagrams by students in a class for pre-service teachers and graduate students in science education. Students' representations of circuits prior to instruction on the conventions of circuit diagrams were collected and catalogued according to representative characteristics and classified as either figural/iconic or abstract/symbolic or a mixture. As might be expected, prior experience with circuits was related to the level of abstraction in the ways students chose to represent circuits before standard circuit diagrams had been introduced in the course. Students' native competence was also evident, however, as one student without prior experience developed her own abstract scheme for encoding information in circuit diagrams and continued to use it after conventional diagrams were introduced. Students were also interviewed as they interpreted non-standard and conventional circuit diagrams. The interviews revealed that previous experience with formal circuit diagrams, and the unstated but accepted conventions therein, led to difficulties in treating an existing circuit diagram as a completely abstract representation in one case, in contrast with expectations that experienced students would recognize circuit diagrams as complete abstractions. These results imply that students may be disadvantaged when conventional diagrams are simply presented as the norm, without explicit discussion of representation issues.

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Introduction

It is quite common for students to experience difficulties in developing a robust understanding of even the simplest electric circuits, despite instruction on the topic (Fredette & Lochhead, 1980; McDermott & Shaffer, 1992). An international comparison (Shipstone et al., 1988) found that these difficulties are essentially the same across countries, suggesting 'an almost 'natural' coherence to the learning difficulties within the cognitive structure' (p.315). In the same study, however, some problems had apparently been overcome by intense treatment of a given topic within a particular curriculum, showing that these difficulties are not insurmountable. Physics education researchers have demonstrated that carefully designed curriculum can address identified difficulties, allowing students to construct a more robust understanding (Shaffer & McDermott, 1992).

A key element of understanding electric circuits is the creation and interpretation of electric circuit diagrams. Johsua and Dupin (1985) argued that the 'privileged role played by the diagram' in electronics makes it critical to understand the relationship between students' cognitive representations of circuits and their encoding, reading, and use of circuit diagrams (p.129). These skills are prerequisite to solving many problems on standard assessments of circuit knowledge. To solve standard paper and pencil circuit problems, students must recognize the symbols used for electrical components, avoid attributing unintended meaning to conventions such as the use of straight, perpendicular lines, and extract information from the diagram about the completeness of the circuits, any elements bypassed by shorts, and series and parallel components. Although these perceptual skills might be considered primitive, successful interpretation/creation of circuit diagrams mirrors understanding of circuit behavior and is linked to developing a successful problem representation (Caillot, 1985).

In a European study at the secondary and university levels, students interpreted diagrams figuratively, focusing on surface perceptual features rather then the abstract indications of connectivity, and thus made incorrect predictions about the represented circuits (Johsua, 1984). In another European study, university students not currently enrolled in a circuits course used topological features of the circuit drawings (such as the fact that symbols representing resistors were parallel to each other or collinear with each other) to determine electrical features of the represented circuit, i.e., which resistors were electrically in series or parallel with each other (Caillot, 1985). Even after traditional instruction at the college level, students often have difficulty in interpreting standard circuit diagrams as abstract representations of the electrical connections between elements in a circuit as opposed to literal representations of the physical layout of an actual circuit (McDermott & Shaffer, 1992).

Still, most studies in the literature have primarily focused on students' ability to create and interpret standard circuit diagrams, without addressing what diSessa and colleagues have labeled 'metarepresentational competence,' that is, students' native capacities for representation and their responsiveness to instruction, in addition to the value of teaching about representation explicitly. This limited view 'overlooks not only a stunning pool of understudied native competence, but also a greatly undervalued target for instruction' (diSessa, 2004, p.294) Understanding how students might represent electric circuits in the absence of instruction, and the reasons for their choices, might not only enfranchise students whose views might have been excluded in the development of the sanctioned representations, but also provide clues about how best to develop students' abilities to evaluate standard diagrams in comparison to their own.

Thus, there is need for further investigation into the ways students, especially students who lack previous experience with electric circuits, would elect to represent circuits on paper, what these representations might indicate about student conceptualization of circuits, and how these native tendencies might influence students' interpretation of standard circuit diagrams. Such differences might ultimately help in explaining differences in success on assessments of circuit understanding (which often rely on successful interpretation of standard diagrams) and, by extension, in secondary and post-secondary coursework in this area. With this study, I sought to identify students' preferred ways of representing electric circuits prior to formal instruction in circuit diagram conventions, and the ways in which novice students interpreted conventional diagrams, both toward the ultimate end of designing curriculum that would address the needs of all students in understanding circuit diagrams more effectively. Specifically, the research questions for the study were:

(1) Are there differences in the way students represent electric circuits when not constrained by the conventions of standard circuit diagrams?

(2) Do students employ differing schema in interpreting standard circuit diagrams?

(3) Do these differences have implications for instruction?

Methodology

Setting

The study took place in a physical science course designed for pre-service teachers and graduate students in science education, for which I was the instructor. The class met three hours per week and the unit on electric circuits comprised seven weeks of the course. Students worked in small groups to explore topics in physical science hands on using the *Physics by Inquiry* curriculum (McDermott, 1996). As part of the curriculum, students were asked to sketch representations of circuits they had created before being giving formal instructions about how such circuits are commonly represented in circuit diagrams. After formal circuit diagram conventions were introduced, students were asked to match non-standard diagrams of circuits to their standard counterparts.

Sample

The sample consisted of 15 students in the physical science course. Five of the participants were graduate students in physics or science and mathematics education (three with previous teaching experience in science and two seeking secondary science teaching certification), three were chemistry majors seeking certification as composite secondary science teachers, four were education majors and three were undergraduate students fulfilling a general science requirement.

One of the education majors had previous experience with circuit diagrams in a high school physics class, and all of the science majors and graduate students had exposure to formal circuit diagrams in at least one college course. In addition, one of the chemistry majors, John, had extensive experience with electric circuits prior to entering the teacher preparation program (six years as an electronics technician and six years as a field service engineer for two electronics companies), and one of the graduate students had taught high school level physics briefly. The remaining five students reported no previous experience with formal circuit diagrams. In this report, all students are identified by pseudonyms.

Data Collection and Analysis

One source of data comprised work samples collected from all 15 students; these included diagrams from lab notebooks, homework, and exams. All students in the course gave informed consent for the study, indicating willingness to submit their work for analysis, which occurred subsequent to the end of the course and did not influence grades in any way. To get at students' native thinking, it was necessary to focus on representations created by students early in the curriculum, before formal circuit diagram conventions were introduced. In early tasks in the *Physics by Inquiry* curriculum, students are asked to sketch configurations of a battery, bulb and wire that cause the bulb to light (or not light) and to make representations illustrating arrangements of other simple circuit experiments. It was my expectation that these early tasks, calling as they did for illustrations of a physical set up rather than circuit diagrams specifically, might reveal how students, even those with previous experience with formal circuit diagrams, would naturally choose to illustrate the relationship between elements in a circuit. These representations, as well as those created later in the course, were examined and categorized according to their features following the typology of Karmiloff-Smith (1979).

I characterized as figural circuit diagrams in which students had made a clear effort to create an accurate, visual representation of the physical circuit, including details that were not necessary to convey the electrical characteristics or the topology of the circuit arrangement. Diagrams in which students had made some features abstract, but which still reflected the physical appearance or characteristics of the circuit in some way, I classified as abstract-analogic. I classified diagrams as abstract-nonanalogic when students used abstract symbols and indicated connectivity of the circuit in ways that were clearly not analogic to any aspect of the physical referent. These categories were not considered to be mutually exclusive; a single representation might have any combination of figural and abstract features.

Interviews comprised a second data source. The interview task was modeled after a typical *Physics by Inquiry* task (McDermott, 1996). After introducing standard circuit diagrams, and noting their conventions explicitly, this curriculum asks students to match a series of unusual diagrams to their conventional counterparts in order to challenge students' recognition that the circuit diagram is an abstraction, representing electrical connections only and not physical configuration. Repeated practice in analyzing such diagrams helps students to develop metarepresentational competence and overcome their tendencies to assume a direct correspondence between the appearance of a diagram and the appearance of the circuit it represents (Shaffer & McDermott, 1992).

In the interviews, students were asked to match the non-standard diagram on the left in Figure 1 to its standard counterpart shown on the right, selecting from a set of four standard diagrams. The problem was part of the midterm examination and students had the option of working it on paper and providing a written explanation, or working it as part of a clinical interview. Nine of the 15 students volunteered for clinical interviews. They used a 'talk aloud' protocol while they worked the problem shown in Figure 1. I conducted the interviews and they were audio recorded and transcribed. Subsequent to the end of the course, I examined the transcripts and accompanying artifacts for evidence of the interviewees' approaches to decoding circuits and clues as to the features they found to encode meaning.

Results

Representations of Circuits: Results from Student Work Samples

In response to the task of sketching the arrangements of a single battery, single bulb, and single wire for which the bulb did and did not light, no student in this small sample used a formal circuit diagram to represent the physical situation, despite the fact that the majority of them had some previous exposure to the accepted conventions. On the other hand, only one student, Greg (again, a pseudonym), produced completely figural representations of the circuit configurations he was documenting. Greg was a history major with no previous experience with circuit diagrams. As shown in Figure 2, Greg's sketches were very realistic, including features of a strictly aesthetic nature, such as the name Energizer on the battery.

The majority of the students produced drawings that included figural characteristics, sometimes in combination with abstractions. For example, five students, in addition to Greg, represented the battery in the circuit as a three-dimensional object, even though this aspect was unnecessary to convey the topological configuration of the battery-bulb-wire arrangement. Likewise, some students depicted the light bulb filament in a realistic way, even though this was not necessary in illustrating how the components were arranged. The majority of the students included the protrusion on the positive terminal of the battery in their drawings.

The majority of the female students joined Greg in producing naturalistic depictions of wires that exhibited an organic, as opposed to geometric, character. Two of the female students, Shaniqua, who had studied circuit diagrams in high school, and Inas, who had recently completed a university physics course including instruction in circuits, portrayed wires in a less naturalistic manner; their wires were symmetric and exhibited smooth curvature. They did not, however, employ regular geometric figures to represent the wires.

In contrast, the male students other than Greg all depicted wires using regular geometrical shapes early in the course. Mark and Daniel, both of whom had taught physics at the secondary level, used the straight, perpendicular lines expected in standard circuit diagrams. John, who had used circuit diagrams in the course of work as a technician and engineer, eschewed the straight, perpendicular line convention in favor of a non-standard, but geometrical, representation of wires as circles (see Figure 3).

John's very first representations of circuits did include some abstract elements. For example, from the start he used the formal symbol for a battery, two unequal parallel lines with the longer line representing the positive terminal of the battery (see Figure 3). This symbol does have an analogic aspect in that it represents the parallel metal plates that were used in the first batteries constructed, but it corresponds in no way to the outward physical appearance of the D-cells that he was using at this point. The way John draws the filament in the bulb is also highly suggestive of the filament representation in the symbol generally used in circuit diagrams to represent light bulbs, but he augmented the standard symbol by showing the threaded base of the bulb.

The representations of one student, Jessica, with no previous circuit experience, were particularly interesting. Jessica's earliest diagrams, illustrating configurations for which the bulb would light, are figural. They show wires naturalistically as simple curves. One of the goals of this first activity was to establish that in order for the bulb to light something must flow in a complete loop of conducting material that includes both terminals of the battery as well as both ends of the light bulb filament. The class established this idea by consensus in a group discussion reporting the results of the 'light the bulb' activity, and agreed to refer to this flow as 'current'.

From then on, Jessica represented wires in her circuit drawings using a distinctive curvature, indicating a native capacity for inventing representations. Figure 4a shows an example from the activity immediately after lighting the bulb. Here the wire exhibits a distinctive curvature entering and leaving circuit elements. Note the seemingly gratuitous curvature as the wire enters the base of the light bulb. Figure 4b shows an example from the next activity in the sequence, in which a switch element was introduced. Note that in this case the curvature seems to indicate that the current departs from and returns to the switch. Finally, Figure 4c shows remnants of this trend from a diagram that Jessica produced after formal circuit diagram conventions had been introduced. The consistency in this pattern indicates that although Jessica's wires appear to be strictly figural, they actually have a non-analogic character in that they encode information about the current flow. Her rule for representation is indeed systematic. One might have been tempted to dismiss the distinctive curvature in Jessica's wires as gratuitous embellishment without having heard her describe the current coming out and going in to the specific circuit elements (i.e., the bulb, switch and battery in Figures 4a, 4b, and 4c, respectively). The curvature did not mirror the way the wires actually looked, but rather indicated the way she believed the current was flowing.

In summary, students created representations that varied from highly figural to abstract non-analogic. There were differences in the way students in this small sample represented circuits, but these could be due to differences in the experience these students had with formal circuit diagrams. The three most abstract diagrams (Mark and Daniel's using straight, perpendicular lines and John's using a standard battery symbol and a near-standard representation of a light bulb) parallel the symbolism of standard circuit diagrams, and all three of these students had experience with such diagrams. On the other hand, the encoding scheme used by Jessica to represent current flow abstractly in her diagrams, although more subtle, is original to her, rather than a reproduction of something she had been taught.

Interpretation of Circuits: Results from Interviews

The nine students who volunteered were recorded as they talked through their solution to the problem shown in Figure 1, which was part of the midterm exam. The exam came after students had considerable practice with such tasks, and only two students had any difficulty in matching the two circuits correctly. To equate the diagrams, students must recognize that the configuration of lines in the drawing does not represent the physical configuration of real wires; their length, and in fact their shape, is arbitrary (although convention dictates the use of straight, perpendicular lines). Students must also realize that lines that simply cross (as in the center of the diagram on the left) do not indicate an electrical connection unless they are marked with a small circle. Both these conventions had been introduced and discussed.

Coding of the transcribed interviews for indications of how students were interpreting the diagrams yielded two major themes: (1) tracing the circuit with respect to current flow and (2) orientation with respect to voltage.

All of the students used the process of tracing the current flow at some point in interpreting the circuit, most of them referring to current explicitly as they did so. Lauren described it in this way:

Lauren: Okay. Okay. Well, there are two ends to the battery. And the way I usually figure it out is by tracing where the current could go, like, where it has to go or it has an option to go.

Using this procedure, students had little trouble identifying the salient features of the circuit. Emily's thinking is typical in this regard.

Emily: So when you follow that wire, you have to come through what I've labeled as Bulb A. and so after I did that, I immediately got rid of choices 2 and 3, because anyway you go, it's multiple bulbs, instead of just one single bulb that all the current has to go through. Then from Bulb A, [I] just picked this wire. And when you follow… Actually, I'll do the other one first. Go from here to where I had B. It [the current] has to go through this one bulb. Then it has to go through what I have as Bulb C. So those two are in series. Come to this connection and eventually back to the negative terminal.

The issue of orientation with respect to voltage, by contrast, arose only for more experienced students, most noticeably for John, who had worked for many years as an electronics technician and engineer. Although he was able match the circuit correctly by tracing the current flow, John indicated that the task was extremely disconcerting to him, describing the circuit as 'the worst one I have ever seen.' When pressed, John had difficulty describing exactly what about the circuit was troubling, as shown in the following transcript.

JM: Worst in what regard?
John: Oh, just…it's…confusing in the way it's drawn. Just because the lines all cross each other so many times. Alright..[Pause] 2 and 3's to the negative side… Around this way this way.. you go through….one...that has its own path directly back. The other one has its own path directly back. So those two are gonna be in parallel with each other and in parallel with these two which are in series with each other. Which tells me it's going to be that one.
JM: OK. You said this was the worst you've ever seen just because lines cross each other?
John: Um… It's got a little more 'spaghetti' look to it than some of them do. I mean, I've seen some where it's drawn intentionally messed up but that one, that one is a little tougher than most, just because the lines curl and twist around. Have to keep track of where they all go so…
JM: In a normal circuit diagram, how do you keep track of how they all go?
John: (silence)
JM: Is it just that none of the lines cross and that's the only difference?
John: Um. Let me think. Well sometimes they cross. I mean that's entirely possible. On a complicated circuit diagram you run out of real estate and you have to cross things a lot. So… but normally the lines are straight and they, you know, they've tried to clear off a little space for… Usually, a discrete circuit group will kind of get its own little chunk of real estate on the paper so that's how I'm used to seeing them. But same basic idea, just following along from one side or the other.

John acknowledged after some thought that it was not the fact that the lines crossed each other so many times that bothered him. In fact, he was quite used to seeing lines cross each other on the complicated circuit diagrams he had encountered in the course of his work with electronic circuits. This is so common that the convention of using the dot to indicate where wires actually connect electrically, as opposed to just crossing on the diagram, was developed to address it. John does indicate that he is used to seeing straight lines, but his final statement gives an indication of what about this drawing actually disturbed him: He is used to diagrams that are organized based on voltage. He typically can 'follow along' from the positive (high voltage) side of the circuit to the ground (zero voltage difference with respect to the Earth, accepted as the standard voltage reference).

Although he does not state it (and probably does not think about it explicitly), the fact that this is easy to do in standard diagrams is the result of *unacknowledged* convention that circuit diagrams will be organized according to voltage in an analogical way, that is, moving down (or across) the diagram corresponds to moving down in voltage. Circuit boards are typically constructed with a high voltage rail (line of electrical connectivity) on one side and a ground rail (zero voltage) on the other. With the high voltage line oriented at the top of the diagram, moving down the page corresponds to moving down in voltage.

In the diagram on the left in Figure 1, the bulb that appears at the *top* of the diagram is actually electrically connected to the negative (*lower* voltage) side of the battery. This placement, above the rightmost bulb which is electrically connected to a higher voltage, violated John's tacit expectation that the diagram will display a figural organization with regard to voltage.

Liz, a graduate student in science education, also made references in her interview that might have been indicative of a vertical organization scheme. In independently creating a standard diagram to represent the convoluted one, she commented that she would draw lines representing connections to elements at the same voltage 'down to the same level.' Daniel, who had taught physical science, also referred to the higher voltage end of the battery as the 'top.'

Inas, a chemistry major, also exhibited a clear preference for diagrams organized by voltage, but in her case the organization was horizontal rather than vertical. She deliberately redrew every circuit diagram placing the highest voltage connections immediately to the right of battery and progressed through lower and lower voltages moving further and further to the right before finally connecting back to the negative end of the battery, as with a typewriter return. Figure 5 shows one of her drawings. She did this even for standard circuit diagrams arranged vertically in order to make sense of them for herself. The textbook used in the second-semester physics course Inas had taken (Haliday, Resnick & Krane, 2001) follows a convention of organizing circuit diagrams by voltage throughout much of its presentation of simple circuits, most often using a horizontal scheme, so it is possible that she absorbed this convention from her previous coursework.

In summary, more novice students were generally able to treat the circuit diagram in this task as a completely abstract representation of electrical connectivity, bearing no figural relationship to the signified circuit. John, on the other, with the most formal experience with circuit diagrams, was disturbed by the lack of an analogic relationship to voltage.

Discussion

With regard to the first research question, there are indeed differences in the way students represent electric circuits when not constrained by the conventions of standard diagrams. The fact that no student in this sample produced a standard diagram, despite the fact that most had experience with such diagrams, some extensive, may indicate that they interpreted the command to make a sketch as a call for a more pictographic representation, and felt free to use naturalistic representations. This parallels work indicating that even students who are competent with standard representations do not necessarily consider them to be the most appropriate way of 'conveying story-like information [e.g., how they assembled the battery, wire, and bulb, and what happened] to others' (diSessa, 2004, p.309).

Greg, the one student who produced a purely figural representation did so in a very realistic manner, but it should be noted that even he distorts perspective in order allow the viewer to see clearly how the connections were made to the battery, indicating that he does indeed recognize the critical features of the story he is telling with his picture (Fig.2). Figural elements employed by other students, such as the protrusion on the position end of the battery depicted by many students and John's illustration of the threaded base of the light bulb, might also have been considered necessary to provide enough detail of the physical configuration of the bulb, battery and wire to show how the connections were actually being made. Indeed, a fundamental characteristic of circuit diagrams is that they show *that* electrical connections exist but not *how* they are made physically, so the standard symbol was not sufficient. The task at hand required the class to show different ways that connections could be made physically to achieve the same result; all of these could have been represented by one circuit diagram. As diSessa (2004) points out, it is critical that we recalibrate our judgment about representations that deviate from the abstract scientific norm in light of the likelihood that students will employ the norms of more familiar contexts, such as story-telling and realistic depiction, in generating them.

Another indication of metarepresentational competence can be found in the nonanalogic way of representing current flow that Jessica, with no previous circuit experience, quickly invented on her own. To the extent that her representation might indicate a conception that current originates from a particular circuit element, as opposed to traveling in a continuous loop, it may be problematic. Even so, such thinking would never have been revealed had she been required to produce only standard circuit diagrams. Jessica's diagrams add curvature to the extensive catalog of visual attributes used by students to represent intangible properties of systems, including length, width, color, and slant of line segments as documented by Sherin (2000). Jessica's representation is limited in that it seems to indicate only the direction, as opposed to the magnitude, of the current, but it could serve as a building block toward representations that might preserve metric relations with the magnitude of the current.

In regard to the second research question, all students in this small sample resorted to tracing the path of the current to interpret the circuits in the interview task, despite the fact that the voltage construct had been established prior to the time of the midterm and had been the subject of their most recent exercises and homework. John typically referred to electrical connections rather than current flow, but he did use the term path and earlier in the interview referred to 'start[ing] off from one side of the battery and just start moving along.' Once again, however, there appeared to be differences related to formal experience with circuits. Here, in contrast to the earlier task, more experienced students, particularly John, had difficulty treating circuits in a completely abstract manner. Although John expressed no expectation that circuit diagrams should correspond in appearance to physical circuits, he did appear to expect them to be analogic in the sense that elements at higher voltages should appear higher on the diagram. This expectation may have been the result of an unacknowledged convention for circuit diagrams that he had subconsciously subsumed into his decoding schema.

An analogic correspondence to voltage may be also at the heart of some of the difficulties experienced by European students in interpreting diagrams (Caillot, 1985). The diagrams that yielded the fewest correct answers were those in which elements violated the expectation of a relationship between voltage status and position on the diagram. In all but the simplest cases, the diagrams with the highest success rate maintained this convention. Students were confounded when components of circuits were drawn at the same level in diagrams, but were not at the same voltage. Dupin and Joshua (1987) also found that students had a higher success rate, particularly in lower grades, on a series of questions (their Table VI) that referred to a diagram in which the same vertical position corresponded to the same voltage in two circuits students were asked to compare, versus another one (their Table V) in which there was no analogous correspondence.

Cohen, Eylon and Ganiel (1983) come close to acknowledging the importance of an analogic correspondence to voltage in their study when they report the results of a question on their questionnaire that used a diagram with the elements again arranged analogically with respect to voltage, this time horizontally rather than vertically. Only a quarter of the students and 40% of the teachers responding to the questionnaire were able to answer the question correctly; 1/3 of the students did not respond at all. The authors argue that the problem ‘could be solved almost *by inspection*, provided the concepts of pd [potential difference], emf [electromotive force], and current are correctly understood’ (p.411, emphasis added). Solving this problem by simple inspection of the diagram without further analysis, however, requires that the diagram be organized according to voltage.

Finally, these differences in the way that students represented and interpreted diagrams could indeed have implications for instruction, assuming they are found to hold in larger populations.

First, insofar as they have demonstrated students’ native competence at creating representations, these findings point toward the importance of providing students with opportunities to display this competence and to acknowledge its validity. Students who are able to employ representational skills developed in other areas may become more engaged in school science. DiSessa (2004) posits that differences between the standard school science practice of simply presenting a sanctioned representation and enforcing its use and allowing students to develop metarepresentational competence based on their native capacities may be ‘particularly important in engaging students from segments of the population who have been systematically underrepresented in scientific careers’ (p.300).

Next, the issue of organizing circuit diagrams analogically by voltage may mask difficulties in circuit understanding, to the extent that they allow some students a short-cut to analyzing circuits that does not require a complete understanding. If students have been *told* that the arrangement of lines in the circuit drawing is completely arbitrary, other than to show connections, but, in fact, the arrangement always conveys information about the voltage levels of circuit elements, they are likely to have trouble when this tacit convention is violated. Instructors might make the voltage convention explicit and provide students with opportunities to discuss whether it held true in certain diagrams, and whether diagrams that violated this convention were indeed more difficult for them. Scientists have an obligation to articulate the principles of representation they employ, as well as their interpretive strategies (diSessa, 2004). Perhaps more importantly, science educators also have an obligation to articulate these principles and strategies explicitly to students.

Use of the implicit voltage convention may also affect the outcome of assessments that invoke it. In addition to those described earlier, the assessments of circuit understanding used others in large-scale studies typically maintain the convention of an analogic correspondence with voltage (either vertically or horizontally) except on problems explicitly designed to test interpretation of the circuit diagrams themselves, such as problem 4 on the DIRECT (see, for example, Engelhardt & Beichner, 2004, p.108-114). One can only speculate about the effect on their results of including more items that violated the analogic expectation. The reported advantage for students with practical experience in circuits (see, for example, Sencar and Eryilmaz, 2004) might be diminished.

Further, some reported gender differences in circuit understanding may in fact be traceable to the diagrams used to represent the problem situations. In one study that investigated the issue of gender difference in understanding circuit diagrams, female students had slightly higher overall error rates than male students on a multiple choice quiz assessing understanding of electric circuits (Meltzer, 2005). Nonetheless, the only statistically significant gender difference, favoring males, was on a question that used a circuit diagram (as opposed to a verbal description) to convey information about the configuration of a circuit. (There were, however, also differences in the way that the responses to the questions on the quiz were represented, confounding the issue of the influence of the circuit diagram, as opposed to a strictly verbal description, in the question itself.)

Finally, alternative representations such as the one created by Jessica may comprise one of the missed opportunities for instruction described by diSessa (2004). Failing to critique the sanctioned representations, and to evaluate other possibilities, may limit some students' opportunities to make sense of circuits. Many authors have argued the priority of either current or voltage as the appropriate organizational construct for analyzing circuits (e.g., Cohen, Eylon &Ganiel, 1983), but ultimately students are better served by being able to address circuits in both ways, evaluating the affordances and limitations of each. Explicit comparison of circuits like Jessica's with those of other students, as well as standard circuit diagrams, might provide the first step in developing the metarepresentational competence that would scaffold this enhanced understanding. In additional to providing more equitable opportunities for learning, including representations from female students like Jessica, and other students from groups who were largely excluded from the original codification of the constructs governing electric circuits, could enrich the existing ways of representing and analyzing electric circuits as established in school science. This is not to imply that such students necessarily think about circuits in a different way from those who originally developed the established canon. Rather, representations such as those produced by Jessica, might constitute 'a larger canon, rather than a different one, a richer, perhaps even multifaceted representation of reality, but not a separate reality' (Keller, 1987, p.46).

Conclusions, Limitations and Implications for Further Work

The ways that students in this study chose to represent electric circuits were varied, in some cases in alignment with standard conventions, likely based on previous experience with circuits, and in some cases completely original to the students. It is of interest that, in contrast to expectations, previous experience actually limited a student's ability to treat circuit diagrams as abstractions in one case reported here. This points to the fact that the ability to decode standard circuit diagrams may not reflect the ability to think abstractly about circuits so much as a familiarity with, or inclination toward, one particular way of organizing circuits.

On the other hand, there are indications here that some students may indeed treat circuit diagrams as abstract objects, but use non-standard rules for encoding/decoding information from them. As long as the 'accepted' conventions remain tacit, such students, in addition to others who have simply not absorbed the standard rules on their own, may be at a disadvantage. Further, the results offer the possibility that such alternative coding schemes might form the basis for representations that many students, particularly students who are less likely to have internalized the formalisms of standard circuit diagrams prior to instruction, might find useful. Such alternative representations might be profitably incorporated into the introductory instruction on electric circuits, if instructors were willing to deviate from circuit diagram conventions. Curriculum thus modified would have the potential to benefit all novice learners, but would be of particular benefit for future teachers who will be called upon to interpret the variety of representations that their own students will produce. At a minimum, instruction should make students explicitly aware of accepted but unstated conventions in formal circuit diagrams.

The results here are of limited generalizability due to the small sample size. A larger sample of students would permit a clearer test of how students are most likely to represent circuits given freedom to do it in any way they choose. A larger sample might also reveal additional students who, like Jessica, use curvature, or possibly other mechanisms not seen in this sample, to encode information in circuit drawings. These results are also limited by the descriptive methodology. Repeated tests with more students and a variety of coders would indicate whether the coding schema employed here is robust.

Although it did examine students' representations and interpretations of representations over a longer period (several weeks) than most described in the literature, this study also was not designed to investigate the trajectories of students as they developed metarepresentational competence with regard to electric circuits or the co-evolution of circuit concepts and circuit representations. A detailed study of changes in students' thinking over time will be required in order to maximize the potential of these initial findings to inform the curriculum. Finally, it remains to be seen whether the development of metarepresentational competence, in particular including the perspective of alternative representations, enhances students' understanding of circuits, as well as their ability to interpret the standard diagrams they are likely to encounter in further course work and in dealing with electric circuits outside of the classroom setting.

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Figure Captions

Figure 1. Diagram matching task (after McDermott, 1995). Students were asked to match the unusual circuit drawing on the left with the standard drawing on the right.

Figure 2. Greg's representation of a circuit configuration for which the bulb did not light.

Figure 3. John's earliest circuit representations, including the conventional double parallel line symbol for the battery and a geometrical representation of the wire.

Figure 4a. Jessica's initial diagram encoding information about current flow.

Figure 4b. A second example of Jessica's diagrams.

Figure 4c. A representation that Jessica created after the introduction of formal circuit diagram conventions.

Figure 5. Inas' representation of a circuit using a horizontal voltage information encoding scheme.

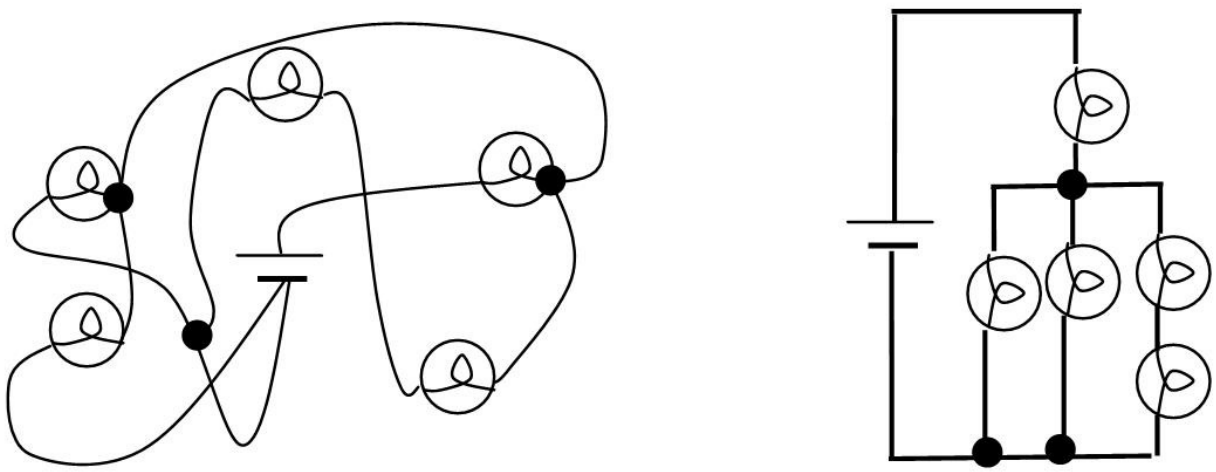

Figure 1

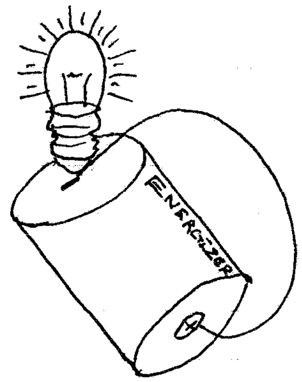

Figure 2

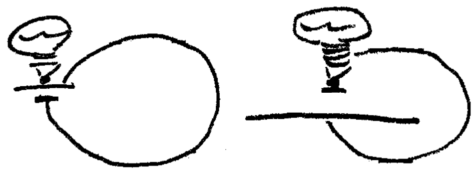

Figure 3

Figure 4a

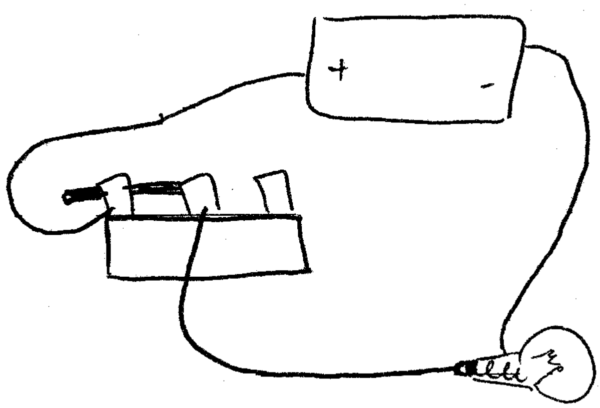

Figure 4b

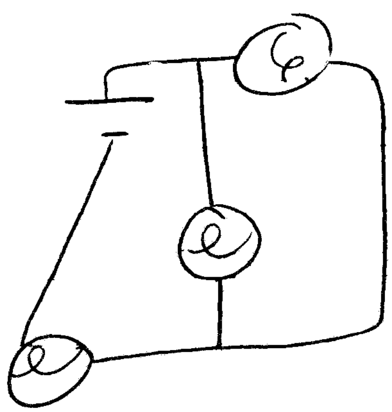

Figure 4c

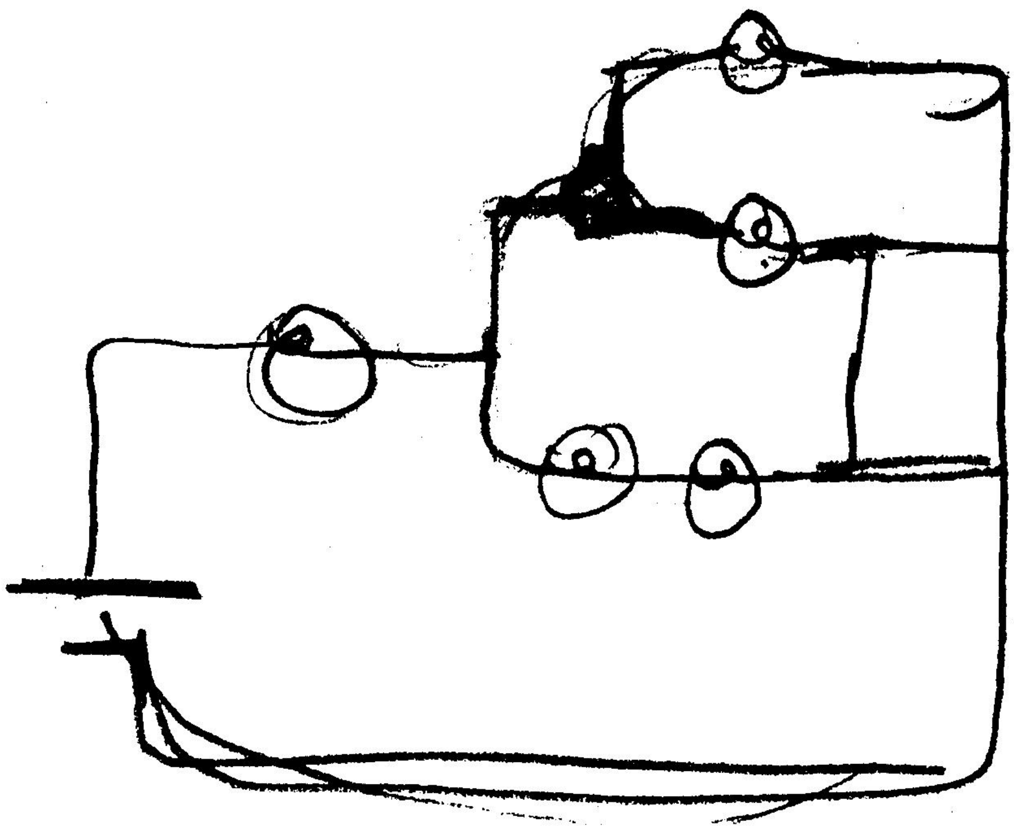

Figure 5