The Effect of Structured Peer-to-Peer Interactions on Conceptual Understanding of DC Resistive Circuits in Secondary Physics

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Abstract

This study examined the prevalence and persistence of some common misconceptions about DC resistive circuits and the role of social interaction in promoting changes in students' views. It explored the types of interactions that were common in student dialogues as they discussed conceptual questions and whether the number of correct responses to these conceptual questions significantly increased as a result of discussions with peers. Twenty-seven students in one 12th grade class, representing a broad, middle range of abilities (as defined by course placement) participated in the study. Over the course of four class periods, conceptual questions were posed each day and students immediately responded to them via an electronic polling system. They were directed to discuss or defend their thinking with peer(s), for approximately two minutes, and those conversations were recorded. After discussion students responded again, to the same questions, via the polling system. Pre- and post-discussion responses were used to assess the level of student understanding. Transcripts of student conversations were analyzed to identify what types of interactions were most common in student dialogues. Results demonstrated that the number of correct student responses to conceptual questions was, in a few cases, significantly larger after discussion with peers. Analysis of interactions revealed that the most common student statements during the discussion phase could be characterized as either simply stating their answer or as providing the reasoning behind their answer choice.

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Students enrolled in introductory physics courses at the secondary level rarely have experience or significant initial intuitive beliefs about the conceptual ideas required to understand the behavior of DC resistive circuits. This can make the teaching and learning of this material particularly challenging, as teachers routinely introduce new material by bridging from ideas that are well understood. Among the reasons such bridging may be useful is that it provides: "temporary frameworks or supports used to assist students during initial learning during a complex skill or cognitive strategy" (Savinainen et al 2005, p. 191). As a result, initial instruction sometimes centers on analogies that are imperfect at best. Two such analogies have been suggested for teaching about DC resistive circuits: "The Flowing-fluid Model" and the "Moving-crowd model" (Gentner, D . & Gentner, D. 1983 p. 115). Since neither analogy perfectly reflects the nature of the DC resistive circuits phenomenon, this instructional approach may lead to misconceptions as students attempt to construct a true understanding of these concepts.

More recently, as researchers and Science educators attempt to find better approaches to teaching Science, socio-interactive methods have been considered and seem to provide a fertile ground for the development of scientific knowledge. Many of the studies in the field of Physics Education Research (PER) have included a component of peer interaction as part of the instructional protocol. (see, for example, Crouch & Mazur, 2001; Hatano & Inagaki, 2003; McDermott & Shaffer, 2000; Meltzer & Manivannan, 2002; Schwarz et al, 2000; Sokoloff & Thornton, 1997) However, most have involved college level students and few have addressed how these learning strategies directly affect students' understanding of DC resistive circuits. Moreover, the mechanisms through which peer interaction may contribute or not to better learning and understanding are still unclear.

The general goals of the study are to identify common misconceptions held by students in a first physics course in a high school setting, and to examine the role of social interactions in promoting a more expert view. Specifically, the study will:

(a) analyze whether high school students in an introductory course would share naive beliefs that have been identified in the literature;

(b) investigate whether structured peer-to-peer interactions in a high school setting will result in significantly more correct responses to conceptual questions;

(c) examine closely how structured peer discussions will expose differences among initial responses provided by students and how students examine their own understanding as they negotiate these differences; and

(d) attempt to determine how patterns of interaction relate to different results in learning and understanding.

Literature Review

Common Misconceptions

Studies by McDermott & Shaffer (1992) and Engelhardt & Beichner (2004) provide an extensive list of common misconceptions students held about DC resistive circuits. The McDermott & Shaffer data originated from a series of interviews with college students, where a simple demonstration served as a basis for a discussion with the interviewee regarding his or her understanding of various concepts related to resistive DC circuits. Those interviews were followed by classroom and laboratory observation and reviews of homework and assessment responses. Subjects ranged from those who have never taken a formal physics course to some who had completed a minor or major in the subject. Most were enrolled in a calculus-based introductory course and some were pre-service physics teachers.

Conceptual difficulties of a general nature

One of the more general conceptual problems noted was a "*Failure to distinguish among related concepts*" *(p. 996)* The authors found that, while many students could state the definitions for current, voltage, energy and power correctly, they could not employ those concepts, as they related to the behavior of circuit elements. In fact, they "often referred to "current, voltage, energy and power inappropriately and interchangeably." (p. 996) Students were also noted to have very minimal real experience with circuits and they failed to understand the notion of a complete circuit.

Conceptual difficulties related to current

The concept of electric current was challenging for many students and analysis of responses about current revealed several common misconceptions. Many believed that "*the direction of current and order of elements matter"(p. 997)* and that "*current is' used up' in a circuit" (p. 997).* There was also a common belief that "*the battery is a constant current source" (p. 997).* In some cases students were found to overlook the effect of resistance in determining the current from a battery in a given circuit.

Conceptual difficulties related to potential difference

Many students do not distinguish between current and potential difference and are unclear about the role of the battery in a circuit. In particular, they generally failed to "*recognize that an ideal battery maintains a constant potential difference between its terminals(p. 998)".* Rather, as stated above, they consider the battery to be a source of constant current. Students also failed to "*distinguish between branches connected in parallel across a battery and connected in parallel elsewhere" (p. 998)* The failure to "*distinguish between potential and potential difference*" (p. 998) was evident as students were asked to support their responses to a question about bulb brightness in a compound circuit. Rather than using the potential difference across each bulb as a source of information, they used the potential at one end of each bulb to reason about brightness and ranked bulbs further from the positive battery terminal as being significantly less bright.

Conceptual difficulties related to resistance

Students also struggled with the concept of resistance, tending to "*focus on the number of elements or branches*" (p. 998) in a circuit, rather than their particular arrangement. They failed to "*distinguish between the equivalent resistance of a network and the resistance of an individual element*" *(p.998)* Interestingly, the authors noted that these same students had correctly solved more complex problems, quantitatively, using Ohm's and Kirchoff's Laws.

Students had trouble "*identifying series and parallel connections*" (p. 998). This was especially true when circuits were drawn in an unconventional way. In general, students failed to recognize that a schematic circuit diagram "*represents only electrical elements and connections, not physical or spatial relationships*". (p. 999) They also did not "*treat meters as circuit elements*" (p. 1000) and, as a result, ignored the implications of the way in which the meter was connected to the circuit.

In their overall analysis of circuits, students were often found to "*reason sequentially, not holistically*" (p. 1000) This type of reasoning underlies student responses that the direction of current or the arrangement of the bulbs will affect their brightness.

In general, the authors concluded that students most students had not developed a coherent, explanatory framework linking the individual concepts needed to understand the behavior of elements in DC resistive circuits.

The Engelhardt & Beichner (2004) data originated from the process used to validate their assessment instrument (DIRECT: Determining and Interpreting

Resistive Electric Circuits Concepts Test). Through this process, the authors identified a list of common misconceptions that had been expressed by high school and college students during those interviews.

Assessment items were initially developed through extensive reviews of high school and college textbooks and laboratory manuals and informal conversations with instructors of those courses. Follow-up interviews, using a subset of ten questions, were employed to assess the construct validity of the test. The interviews were designed to determine if the questions were being understood in the ways in which they were intended. In analyzing the interview results, the authors noted dominant misconceptions among the interviewees. Many of these overlap with misconceptions found by McDermott & Shaffer. They noted that "For the global objective of current, the dominant misconceptions for these questions were battery as a constant current source, term confusion I with V, local reasoning and battery superposition." (p. 105) They also explored student comments about the physical aspects of a circuit, finding that typical misconceptions were related to "topology, contacts and term confusion I/R." (p. 105) The I/R term confusion was described as indicated that students did not understand that resistors, including light bulbs, have an inherent resistance depending upon their material make-up and shape.

The common misconceptions found by the above studies provide the background for the present study in what concerns the analysis of participant students' naive beliefs about resistive DC circuits.

Physics Education Research: Interactive Methods

The field of Physics Education Research (PER) emerged largely from the disappointment of university physics instructors upon finding that their "traditional" instructional methods were largely ineffective in helping students build a conceptual understanding in introductory courses (Halloun & Hestenes, 1985). Although specific instructional methods have varied widely, most interventions that have included some form of peer interaction have demonstrated significantly improved student achievement, as compared to traditional, teacher-centered instruction.

Thornton & Sokoloff (1998) reported impressive results through their use of Microcomputer Based Laboratories and Interactive Lecture Demonstrations. Each method utilizes real time data gathering and employs peer interactions as a mode of discourse and sense making. Students are asked to predict the behavior of physical systems, and to discuss those predictions with peers or laboratory partners. Culminating demonstrations are used to ensure a correct understanding. The authors noted that:" the total gain of over 75% from before instruction should be compared to the 7% to 10% gain we have seen resulting from traditional instruction." (p. 344)

Crouch & Mazur (2001) reported ten years' experience with the implementation of Peer Instruction methods in introductory physics courses at Harvard University. In those formerly traditional lecture settings, electronic polling systems were employed and structured peer discussions of conceptual questions were implemented. Immediately upon employing these techniques, in 1991, student conceptual understanding improved dramatically as demonstrated by the doubling of the average normalized gain achieved on the Force Concept Inventory (FCI). Unlike the work of Thornton and Sokoloff, this technique does not rely on gathering empirical data. It does, however, share the technique of requiring students to commit to either a prediction or answer to a question and to discuss those predictions with peers.

Meltzer and Manivannan (2002) achieved similar gains with a variation on this approach, replacing the electronic polling system with the use of flashcards. Because they found their new approach to be time-intensive, they also reduced the content of the course and implemented tutorial sessions. They reported dramatically improved assessment scores, although they admitted that they could not definitively attribute this success to one aspect of the several changes they had made to the course.

These studies, and many of the others in the PER literature have taken place in college or university settings involving students who may have had prior, formal physics instruction. The study of interactions in a secondary school setting would provide data not contaminated by the effects of initial instruction. This study aims to determine whether structured peer-to-peer interactions in a high school setting will result in significantly more correct responses to conceptual questions.

How Peer Interactions May Promote Improved Conceptual Understanding

The use of interactive approaches is supported by a social constructivist view of teaching and learning. Piaget proposed a distinction between 'spontaneous' and 'nonspontaneous' concepts. Spontaneous concepts represent the naive conceptions students construct through their interactions with their environment while nonspontaneous concepts represent the scientific or canonical view. To adopt a Newtonian view, students may need to restructure or replace their spontaneous concepts. Piaget suggested that the relationship between learning and development is complex and that, in some cases,

> "the gifts of instruction are presented too soon or too late, or in a manner that precludes assimilation because it does not fit in with the child's spontaneous constructions." (Piaget, 1962, p. 11).

Vygotsky countered that instruction should precede development by first providing the scientific concept.

> "The development of a scientific concept, on the other hand, usually *begins* with its verbal definition and its use in non-spontaneous operations -- while working on the concept itself" (Vygotsky, 1962, p. 192).

In this model, the scientific concept acts as a scaffold and the child builds a more systematic set of spontaneous concepts from the bottom up, eventually fitting them into the scientific concept acquired through instruction. This process, according to Vygotsky, is best accomplished through interaction with instructors and/or more capable peers.

In the current study it is assumed that students co-construct knowledge through interactions with peers, and that language plays a key role in this process. The process of explaining their initial response demands that students organize and commit to an idea, in order to express it. Peer interactions may force them to perceive a contradiction between their existing content knowledge or conceptual beliefs and those of a peer. This disequilibration can motivate a student to examine his or her current understanding more closely and, perhaps, consider new ideas:

> "From this perspective, as learners participate in a broad range of joint activities and internalize the effects of working together, they acquire new strategies and knowledge." (Palincsar, 1998 p. 351-352).

Perret-Clermont (1993) questioned the distinction between learning as "always precisely defined as the learning of something" and development as "the emergence of something new" (p. 199), suggesting that this distinction may be a function of the purpose and point of view of the researcher. She attributed the differences found between data on learning and data on development to differences in data collection paradigms and concluded:

> "This might open the way to new understandings of the teaching activity not as a one-way process but as a double-sided cognitive and social adventure concerned both with the transmission of previous experience and the emergence of new ideas -- two equally socially mediated processes" (p. 204)

Somewhat in contrast to the Vygostskian approach, Hatano & Inagaki (1991) proposed that *horizontal* (peer to peer) interactions are more effective than *vertical* (adult-child) interactions. In one study, fourth graders participated in a science lesson about the conservation of weight when sugar was dissolved in water. Students in the experimental group participated in Hypothesis-Experiment-Instruction (HEI) protocol that included time for students to explain and discuss their choices with one another. Results demonstrated that in "the experimental condition children could give adequate explanations about why the weight of dissolved sugar was conserved more often than could the control condition children." (Hatano & Inagaki, 1991, p. 341) It appears that the HEI method resulted in a stronger understanding and, perhaps, the ability to generalize specific findings to other, more general situations.

Forman, and Ansell (2002) suggested that: "peer interaction enhances the development of logical reasoning through a process of active cognitive reorganization induced by cognitive conflict. . . cognitive conflict is most likely to occur in situations where children with moderately discrepant perspectives . . . are asked to reach a consensus" (p. 330) In their study, they employed inscriptions in an attempt to create peer-to-peer argumentation in the classroom. In general, inscriptions may be any form of representation of an idea that permits public discussion of that concept. These may be diagrams, graphs, or any other source of information that lend themselves to the creation of an argument about that concept. Forman and Ansell utilized two sets of inscriptions: data about battery performance and data about various methods of treating patients infected with AIDS to create argumentation among peers in the group. In the analysis of the peer-to-peer argumentation that resulted from analysis of the inscriptions they found that "the classroom discourse was truly multi-voiced despite the inherently unequal footing of teachers and students."(Forman & Ansell, 2002, p. 272)

In another setting, Damon (1991as cited in Palincsar, 1998) employed peer discussions in studies of children's moral judgments. Children were given the task of dividing ten candy bars fairly, considering issues such as equality, gender, merit, effort and special need. They found that "56% of the children markedly increased their awareness of fairness issues . . . compared with 34% and 20% of children in control groups not exposed to *in vivo* peer discussions (the 34% group being one that was individually tutored by an adult on a similar but hypothetical set of issues" (Damon, 1991, p. 396)

While the above studies point to the positive effect of peer interaction in learning and understanding, this may not be easily achieved. In fact, as Smith et al (2004) suggest, while argumentation can play an important role in the development of conceptual understanding in science, "The ability to construct such arguments is hard won. There is a long tradition of research (using a variety of different types of tasks) that indicates that students do not consistently differentiate theories and evidence, and that even by college age most students still do not understand the role of indirect data and argument in the construction of scientific theories. At the same time, there is increasing recognition that these results are more an indictment of current practices in science education than of students' learning capacities." (p. 16)

There is no clear consensus on the mechanisms through which students change or restructure their naive beliefs. Piaget (1977) described three processes as crucial to conceptual change and development: assimilation, accommodation, and equilibration. Assimilation describes the process through which students adjust incoming information to fit with their existing knowledge structures. Accommodation refers to the way in which students may adapt their current ways of thinking due to the influence of new information. Assimilation and accommodation work simultaneously and neither can take place without the other. Equilibration describes the process through which conceptual development or change takes place. It happens in three phases: at first, students are satisfied with their current conceptions (and are in equilibrium); next they become aware of ideas that conflict with their current beliefs (disequilibrium); finally they adopt a more advanced, expert view.

From a Piagetian standpoint peer interactions may perform two functions: they may provide the conflicting information, in the form of another opinion or interpretation. Otherwise, they may expose conceptual flaws in the current reasoning. In either case, it is unlikely that such close examination of current thinking would take place without some form of interaction.

There are those who doubt the role of conflict in this process. Chan et al (1977) studied how individuals and peers dealt with conflicting information. They found that, unless students were tasked with undertaking further explanations or problem solving, using the concept under study, conflict in and of itself did not support conceptual change. They concluded that: "conflict itself is not enough; it needs to be mediated by students' knowledge building activity." (p. 35)

Posner et al (1982) argued that conceptual change may result from the interaction between existing ideas and new knowledge. The learner assesses the knowledge to determine if it is understandable, believable and useful. If so, the new knowledge gains a higher status and may be adopted.

Wiser and Amin (2001) provide a good example of the many aspects to be dealt with in promoting scientific understanding, starting from students' own initial views. They suggest that conceptual change depends upon a student's ability to integrate both their everyday and emerging scientific understanding of that content. In a study with a small group of high school students they employed "metaconceptual teaching" in which the instructor explicitly referenced both the everyday and the scientific understanding of concepts related to heat and temperature during instruction. Results demonstrated that "metaconceptual lessons helped students capitalize on what they had learned from the models and direct instruction. Their pre-metaconceptual intuitive distinction between (heat) energy and $heat_E$ was clarified and formalized but also radically restructured: $heat_E$ became hotness, a perceptual entity, and (heat) energy became $heat_S$, the only physical entity in objects. The two new entities became causally linked instead of simply correlated . . . or coalesced."(p. 351) Although the work of Wiser and Amin is promising, students rarely have a coherent everyday view of the concepts related to electricity and DC circuits. Thus, fostering conceptual change through this process may not be feasible.

Structured peer discussions in this study may provide new information, or expose differences among initial responses provided by students that will allow for a close analysis of how students examine their own understanding as they negotiate these differences. As a result, they may achieve a more expert understanding of resistive DC circuits.

The Study's Questions and Hypotheses

Although the benefit of peer interactions has been demonstrated in many studies, few have closely examined student interactions in an attempt to identify what types of interactions are common as students discuss their understanding of conceptual questions. This paper will report the findings of an exploratory study using structured peer-to-peer response methods in a secondary physics classroom in a suburban public high school. Pre- and post-discussion responses were used to assess the presence and persistence of some common misconceptions and how they may be affected by peer discussions. Transcripts of students' discussions were examined to explore what types of interactions are typical and whether and how they may help students develop a more expert understanding. The following are the study's specific research questions:

1. Do high school students enrolled in a first course in physics share common misconceptions identified in the literature, including:

- A tendency to think sequentially, rather than holistically, about circuits;
- A belief that current is consumed in a circuit;
- A tendency to consider only the number of elements or branches in a circuit, rather than their particular arrangement.
- A failure to distinguish among the related concepts of voltage, current and resistance;

2. Will the number of correct responses to conceptual questions significantly increase following peer discussions?

3. What is the nature of student comments, in peer discussions, and how does it support a more expert understanding?

It is expected that:

1. Students in the introductory high school course will share many of the common misconceptions about resistive DC circuits identified in the literature.

2. The number of correct responses to conceptual questions after discussion with peers will be significantly larger than before discussion.

3. There may be identifiable patterns in student comments that seem to support improved conceptual understanding.

Methods

School and participants:

The study took place in a local, suburban high school. The school has a four-year science requirement, and nearly every senior (N=451) studies physics. Five physics courses are, as shown in Table 1 below:

Table 1: Typical Enrollment in Physics Offerings at the Subject High School

Course Name	# students enrolled	% students enrolled	Brief description
AP Analytical Physics	45	10%	One-year, introductory calculus-based advanced placement course. Prepares for AP C exams in physics (mechanics and electricity & magnetism).
Honors Physics	125	28%	Algebra-based, one-year introductory course. Taught at the level of rigor of the AP-B Physics. Students may elect to take the AP-B examination.
Level One Physics	195	43%	Algebra-based, college preparatory introductory physics course. (Students may elect to take the SAT Subject test in physics).
Integrated Math and Physics	50	11%	Co-taught with a mathematics teacher. This course teaches algebra in the context of physics and was designed to strengthen algebra skills in the context of physics instruction.
Conceptual Physics	36	8%	Takes a conceptual approach with little algebra required.

Participants in this study were enrolled in one section of "Level One" physics (N = 27) at the 12th grade level. In general, students enrolled in Level One Physics represent the largest portion (43%) of the senior class population and the mid-range of abilities (as assessed by course placement). Level One classes tend to be the most heterogeneously grouped of all of the physics offerings. The 27 participants in the study were randomly assigned to their Level One Physics section by the school's administration during the computer-generated scheduling process. In this class there are two students with diagnosed disabilities addressed through 504 curriculum accommodation plans and two students with Individual Education Plans managed by the Special Education department. Students who complete this course might choose to take the SAT Subject Test in Physics, though few actually do because of their senior status.

The study was conducted in early spring. Students had completed the study of Newtonian mechanics and an instructional unit entitled "Electrostatics and Introduction to DC Circuits". They had been introduced to the concepts of potential difference, current and resistance and had received instruction on Ohm's Law and Kirchoff's loop and junction rules. During the week of the intervention analyzed in this study, the class met for 50 to 55 minutes on four days and for 90 minutes on the fifth day. The structured peer interactions took place during the four 50 to 55 minute class periods.

Procedure

During those four class periods a series of multiple-choice conceptual questions were posed to students during the course of regular instruction (see Appendix A). Each student was asked to respond individually to each question. Those initial responses were recorded using an electronic polling system and a histogram of the class consensus was displayed. Students were directed to discuss or defend their thinking with peers in groups of two or three. Nine groups were formed. Each group's discussion was audio recorded. Finally students were asked to respond to the same questions and again those answers were recorded, via the electronic polling device. The collective final class response in each meeting informed the instructor for the next class meeting.

Several of the questions posed were designed to determine the prevalence and persistence or change on four common misconceptions:

- A tendency to think sequentially, rather than holistically, about circuits;
- A belief that current is consumed in a circuit;
- A tendency to consider only the number of elements or branches in a circuit, rather than their particular arrangement.
- A failure to distinguish among the related concepts of voltage, current and resistance;

Data Sources and Analysis:

Pre- and post-discussion responses, recorded via the electronic polling device, were associated with each student's identification number. Student conversations were transcribed and identified in the same manner, so that conversations could be correlated with response patterns, as recorded by the peer response system.

The total numbers of correct responses to each question, before and after discussion, were tallied to determine whether peer interactions resulted in a significant increase in correct responses. Students' responses to specific questions were analyzed in detail to determine if they reflected common misconceptions identified in the literature. In instances where a student did not provide a response either before or after discussion, an incorrect response was assumed.

Peer dialogues were transcribed and utterances were coded using the following coding scheme:

Ask:
Asks a question
Authority:
Defers to teacher's authority to justify an answer
Clarify:
Clarifies a previous statement
Equation:
Uses an equation or numerical calculation to justify an answer
Lab:
Refers to a lab finding to justify an answer
Law:
Refers to a physical law to justify an answer
Reasoning:
Explains reasoning (without explicit reference to a physical law) to justify an answer
State:
Simply states an answer

Coded transcripts were reviewed to determine which types of utterances were most common. The same coding system was utilized to search for a correlation between the type of utterance employed and the incidence of conceptual change, as indicated by a significant change in the number of correct answers to conceptual questions, post-discussion.

RESULTS

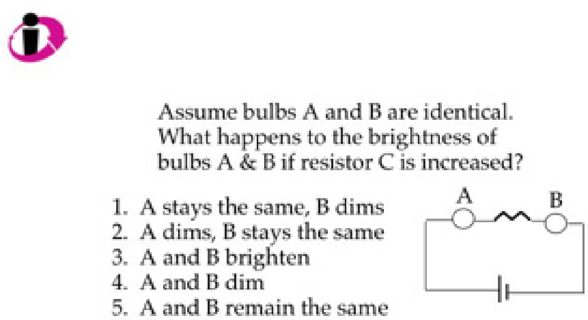
Research Question One: Do high school students enrolled in a first course in physics share common misconceptions identified in the literature?

The first goal of this study was to determine if high school students enrolled in a first course in physics share some of the common misconceptions identified in the PER literature. The results presented here are organized by the misconceptions of interest. Some of the questions posed were designed to directly address these misconceptions. Analyses of student responses to those questions, via the electronic polling system, were used to assess the level to which students held the misconceptions in question, prior to discussion, and whether those misconceptions appeared to persist, despite interactions with peers.

Misconception 1: A tendency to think sequentially, rather than holistically, about circuits;

Question 2 was designed to address this misconception.

Figure 1: Question 2:



An increase in the center resistor would create an increase in the equivalent resistance of the entire circuit and result in a decrease in current through all circuit elements. This would cause a dimming of both bulbs (correct response #4).

Table 2: Student Reponses to Question 2

Response	Before Discussion	%	After Discussion	%

1	12	48%	11	44%
2	3	12%	0	0%
3	0	0%	0	0%
4	5	20%	11	44%
5	0	0%	0	0%
NR	5	20%	3	12%
Total	25		25	

Table 2 above shows that in their pre-discussion responses, many students (48%) choose response one, and some (12%) chose response #2. Either of these answers could be chosen as a consequence sequential thinking. Those who hold a sequential view of the behavior of elements in a circuit might assume that, when the middle resistor increases, it would only affect the circuit elements that precede or follow it. (Note: NR indicates no response, either before or after discussion).

After discussion, 44% of students responding continued to rely on a sequential model, as indicated by their choice of response #1. This would indicate that the tendency to think sequentially is both prevalent and persistent among this group of students. Although the percentage of students responding with the correct answer more than doubled (from 20% to 44%), this result is not statistically significantly and equally as many students chose answer #1 in the final polling.

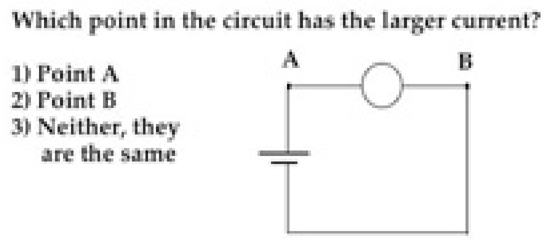
A review of student comments in peer conversations about this question reveal some explicit references to sequential thinking. Student comments are identified by Q# (for question number), G# (for group number) and L#(for transcript line number) For example:

> *Q2G2 L3:" I picked one because of where the resistor was I thought that if either of them would dim, I thought it would be b,"*

Misconception Two: Current is consumed.

The second misconception anticipated is a belief that current is consumed by elements (i.e. bulbs) in a circuit. This misconception was addressed by question 3, shown in Figure 2 below:

Figure 2: Question 3



Response #3 is the correct response. Because charge is conserved, the flow of charge (current) through any point in the circuit should be the same. For students who believe that current is consumed by circuit elements, answer #1 would be a logical choice. The current at point A would be the greatest and, as current flowed through the bulb, some of it would be used up, leaving less current at point B. Response #2 may also indicate a belief that current being used up, with a different directional orientation.

Table 3: Student Responses to Question 3

Response	Before Discussion	%	After Discussion	%
1	4	17%	0	0%
2	1	4%	0	0%
3	18	75%	20	83%
NR	1	4%	4	17%
Total	24		24	

This misconception was not as prevalent as some of the others under study. Results showed that 17% of students initially chose response #1 with an additional 4% choosing response 2. Thus, up to 21% of responding students may believe that the bulb consumes current. Peer discussions did seem to support students in developing a more expert understanding, at least in the short term. After discussion all responding students chose the correct answer (3).

Due to time constraints, no conversational data was recorded for this question. However, student discussion of some of the other questions polled did reveal explicit references to the notion that current is consumed by circuit elements. For example:

> *Q2G9L2: "I think because the resistor will use up some of the charge so b's brightness will go down."*

> *Q6G6L3: "No, there's more like stuff, because the resistor is like stuff taking out current. It's like stuff that uses up current I guess."*

In summary, the misconception that current is consumed was somewhat prevalent, though not persistent in student responses to question 3. It was also noted in student dialogues about other conceptual questions.

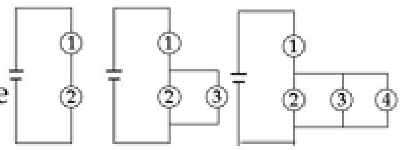
Misconception Three: Tendency to consider the number of elements or branches, rather than their arrangement

Question 5 examined the prevalence of this misconception.

Figure 3: Question 5

As bulbs are added in parallel to this circuit, bulb # 1 will:

1. Dim
2. Brighten
3. Remain the same



The initial circuit has two bulbs in series. The equivalent resistance of this circuit can be found simply by summing the resistances of each of those bulbs, as putting resistors one behind the other in series has the effect of lengthening the resistor and resistance is directly proportional to the length of the resistor. However, as bulbs are added parallel to bulb 2 the equivalent resistance of that portion of the circuit decreases because the parallel resistors have the effect of increasing the cross-sectional area of the resistor and resistance is inversely proportional to the cross-sectional area of a resistor. This would cause the resistance of the entire circuit to decease, resulting in an increase in the flow of current through the battery, causing bulb #1 to brighten. Answer 2 is the correct response.

Table 4: Student Responses to Question 5

Response	Before Discussion	%	After Discussion	%
1	4	22%	0	0%
2	0	0%	0	0%
3	9	45%	19	95%
NR	7	35%	1	5%
Total	20		20	

Responses summarized in Table 4 above show that no responding student answered this question correctly, either before or after discussion. Initially 22% of responding students chose response 1. This could reflect the misconception that the number of circuit elements (in this case bulbs) determines the behavior of circuit elements (i.e. bulb brightness), rather than the particular arrangement of those elements. Students may believe that the additional bulbs will increase the resistance of the circuit and, thus, decrease the current flow and bulb brightness.

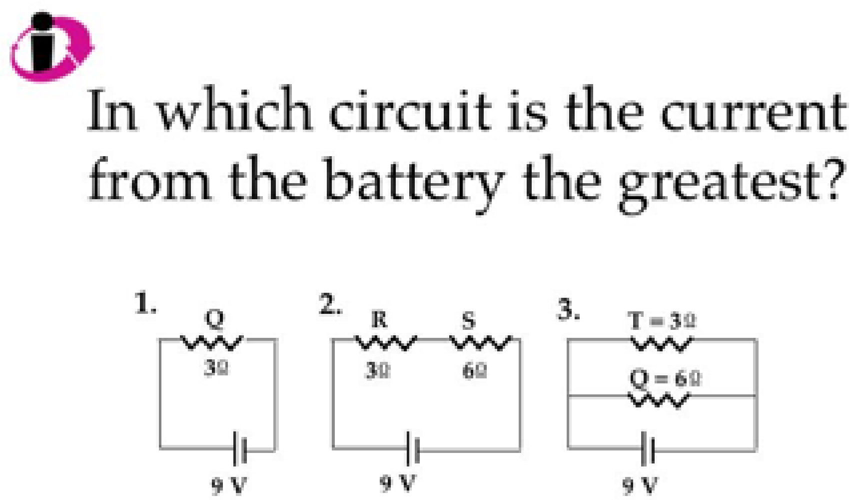
Note that 45% of students responded initially by choosing answer #3. This response is not clearly indicative of the same misconception and may be more reflective of the belief that *"the battery is a constant current source" (McDermott & Shaffer, 1992 p. 997).* If the battery is a constant source of current, adding circuit elements beyond bulb #1 should not change the brightness of that bulb. After discussion, all responding students chose answer #3. Peer conversations do seem to have affected student thinking, though not resulting in an expert understanding of this question.

One student comment explicitly revealed the "battery as a constant source of current" misconception:

> *Q5G9L1: "They will be the same for the adding bulbs because it won't affect the first bulb. The first bulb will still be getting the same amount of charge, energy, current, etc. But as the bulbs are being added in parallel, part of the circuit will be getting less and less."*

Question 10 shown in Figure 4 below, addressed this same misconception regarding the focus on the number of circuit elements, rather than their particular arrangement.

Figure 4: Question 10



Although circuit 3 has more resistors than circuit 1, their parallel arrangement results in a smaller equivalent resistance and a larger current flow as compared to the other two circuits. The correct response is 3. Student responses are shown in Table 6 below:

Table 5: Student Responses to Question 10

Response	Before Discussion	%	After Discussion	%
1	3	14%	0	0%
2	4	19%	1	5%
3	10	48%	17	81%
NR	4	19%	3	14%
Total	21		21	

The 14% of students who initially chose response #1 can be assumed to hold this misconception. Their answer suggests that they believe that both circuits 2 and 3 must have a greater resistance (and thus a smaller current) because each has a larger number of resistors (regardless of their arrangement). The fact that 19% of students responding initially chose answer #2 is more difficult to understand as it is clear that circuit two has more resistors than circuit one. This finding may reflect a misreading of the question.

Peer discussions appear to have had a generally positive effect on this misconception, as no students chose answer #1 in the final polling (and the percentage of students choosing the correct response (#3) rose from 48% to 81%). Still, 5% of students have chosen response #2, demonstrating that they do not clearly understand how the arrangement of resistors affects the equivalent resistance of the circuit.

Misconception Four: A failure to distinguish among the related concepts of voltage, current and resistance;

If students do not have a clear understanding of the concepts of voltage, current and resistance and fail to distinguish among those concepts, they will be unable to develop a coherent explanatory framework to understand any arrangement of circuit elements. Although this misconception is likely to underlie many of the student conceptual difficulties seen in this study, it is not explicitly evident except through analysis of dialogic interactions. To search for the presence of this misconception, all transcripts were examined in an attempt to identify student comments that might explicitly reveal such a lack of understanding of these concepts. Some examples of these are as follows

Q6G2L1:" I don't understand how current is measured --"

Q6G2L3:" No, but like, do you lose current as you go or do you maintain the same current, or what do you do?"

This demonstrates clear confusion between the concept of current and that of potential difference.

Q7G6L6:" I think, OK, well, current isn't like part of its dropped here and part of its dropped there, but volts is, right? Current is, like the whole thing you add the current, and then for volts its dropped as it goes along. We're talking about the potential energy between the two. R1 just by itself is going from 12V to 0 and in the second one R2 goes from 12 to something and then something to zero. Right?"

This student appears to be struggling to clarify his or her understanding of current and voltage.

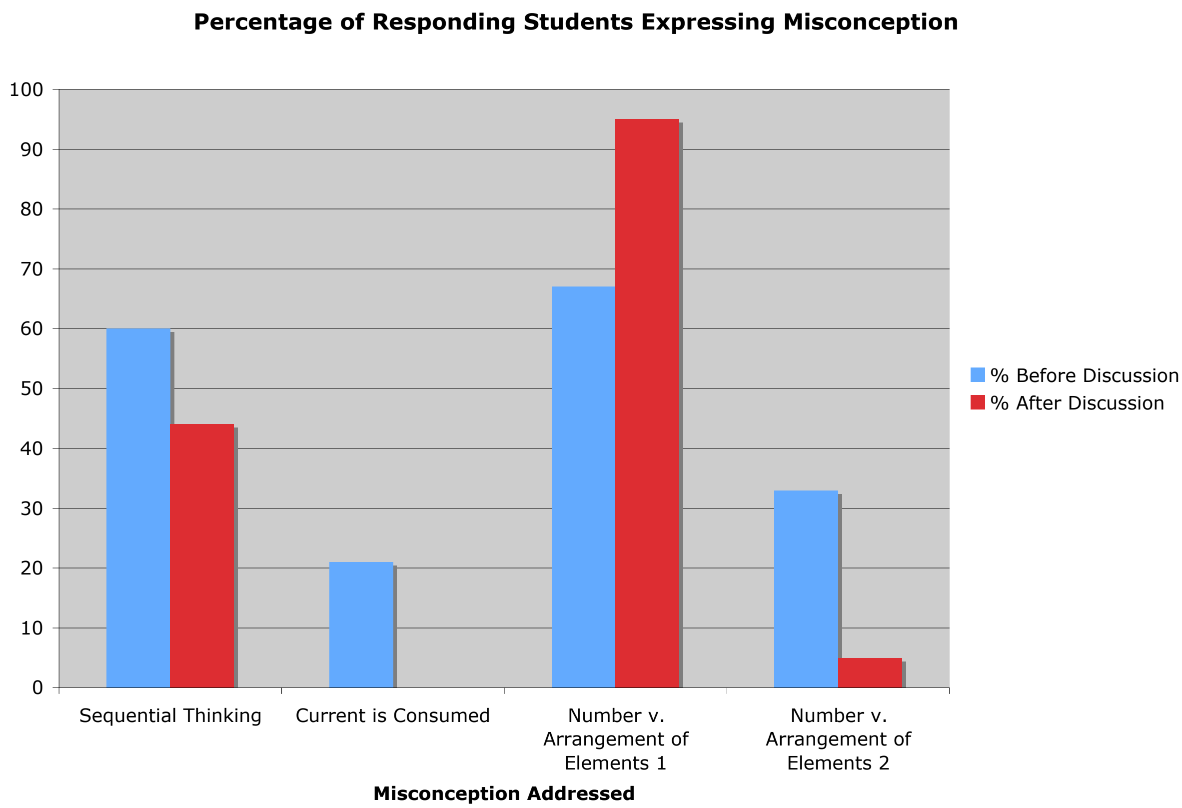
Q7G7L1:" I wasn't really sure about this one. I kinda forget what the potential difference is. Maybe you guys can help me out."

This evidence is clearly anecdotal. Yet, it is common enough in these transcripts to support the hypothesis that this is a serious issue, for at least some students in this study. If students do not have a firm grasp of the concepts of potential difference, current and resistance, any responses they provide to conceptual questions are suspect, as they may be based on a lack of understanding of the language of the question or of the language they use in their own response.

Summary -- Prevalence and Persistence of Misconceptions

Each of the misconceptions considered was identified, to some extent, in students' responses to targeted conceptual questions. Figure 6 below summarizes those findings:

Figure 5: Percentage Expressing Misconceptions



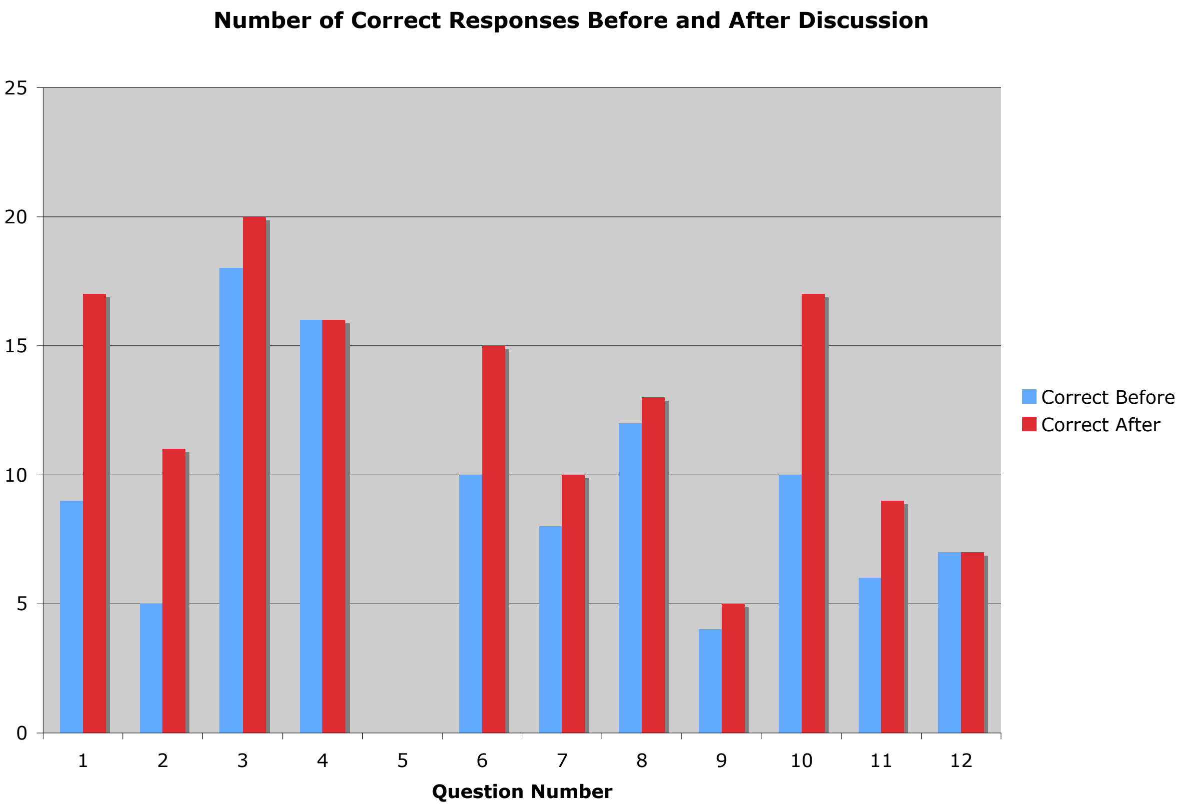
In each case, the misconception was present to some extent prior to peer discussion. In most cases, the percentage of responding students expressing the misconception declined (though rarely significantly) after discussion. In one case, no responding students answered correctly pre-discussion and the misconception actually appears to have been strengthened through discussion.

Although quantitative findings are not available for the fourth misconception (*A failure to distinguish among the related concepts of voltage, current* *and resistance)* there is anecdotal evidence to suggest that this problem is both prevalent and persistent among students in this group and that a lack of understanding of these concepts would preclude students from building a coherent framework to make sense of any of the circuits under consideration here.

In summary, students in introductory courses at the secondary level have been found to share, to some extent, all of the misconceptions noted in the literature about DC resistive circuits. In this study, although peer interactions demonstrated some impact on these misconceptions, most persisted despite these discussions. Student confusion about the concepts of potential difference, current and resistance were noted in many interaction sequences. The impact of the inability to understand these concepts and to distinguish between them is severe enough to preclude the development of any coherent understanding of DC resistive circuits and may be a root cause in the conceptual difficulties seen. Research Question Two asked: *Will the number of correct responses to conceptual questions significantly increase following peer discussions?*

In this study, on some occasions, discussions with peers led to an increase in the number of correct responses to the conceptual questions. Figure 6 depicts the number of correct responses to each question polled, before and after discussion with peers. In this analysis, non-responses are counted as incorrect, even in cases where student answered correctly before discussion.

Figure 6: Total Number of Correct Responses Pre- and Post- Discussion



For nearly every question posed to students, the total of number of correct responses is greater after peer discussions as compared to before. Table 6 looks in detail at these findings, in a question-by-question analysis of significance. A Fisher exact probability test was used to determine whether the number of correct responses was significantly changed in the post-discussion polling of each question.

Table 6: Number of Correct Responses, Before and After Discussion

Question	Before	After	Significance
1	9	17	**Sig, $p < 0.05$**
2	5	11	NS, $p > 0.05$
3	18	20	NS, $p >0.05$
4	16	16	NS, $p > 0.05$
5	0	0	NS, $p > 0.05$
6	10	15	NS, $p > 0.05$
7	8	10	NS, $p > 0.05$
8	12	13	NS., $p > 0.05$
9	4	5	NS, $p > 0.05$
10	10	17	**Sig., $p < 0.05$**
11	6	9	NS., $p > 0.05$
12	7	7	NS., $p > 0.05$

Although, in most cases, there was an increase in the number of correct responses to conceptual questions as a result of peer discussions, those results were rarely significant when questions were taken in isolation. However, when we consider the full set of 12 questions, the Wilcoxon signed-rank test shows a significant increase in the overall number of correct questions ($W=45$, $p<.005$, 1-tail). These findings would suggest that, while it is possible to promote student understanding through interaction, the methods used here (and the knowledge that students brought to those interactions) may have been insufficient to make a substantial difference in the conceptual understanding related to each specific question.

Research Question 3: "*What is the nature of student comments, in peer discussions, and how does it support a more expert understanding?*"

To address the first part of this question, all peer dialogues were coded to reflect the type of statement made by students in their discussions of conceptual questions. Codes were chosen to display not only what students were saying but also how the were using those statements to support their initial answers. The codes utilized were:

Ask:
Asks a question
Authority:
Defers to teacher's authority to justify an answer
Clarify:
Clarifies a previous statement
Equation:
Uses an equation or numerical calculation to justify an answer
Lab:
Refers to a lab finding to justify an answer
Law:
Refers to a physical law to justify an answer
Reasoning:
Explains reasoning (without explicit reference to a physical law) to justify an answer
State:
Simply states an answer

A summary of these findings is included below:

Table 7: Frequency of Types of Student Comments

	Sum	Percentage
Ask	26.00	12%
Authority	1.00	<1%
Clarify	9.00	4%
Equation	17.00	8%
Lab	1.00	<1%
Law	7.00	3%
Reasoning	75.00	33%
State	88.00	39%

As seen in Table 7 above, the most common form of utterances found in peer interactions were of students simply stating their initial answers to the conceptual questions posed. Although simply stating your response may not necessarily affect your understanding of a concept, making your current beliefs explicit to others does require that you consider the question and commit to an initial belief.

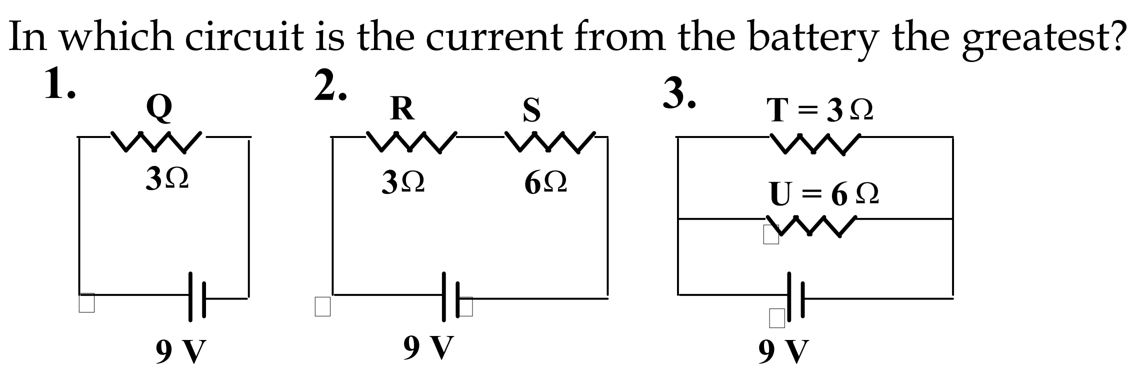
The second most common type of comment was in the form of providing reasoning for an initial answer. From a cognitive perspective, having to provide reasoning for your response may contribute to conceptual understanding through two effects. First, it may force a student to organize his or her own conceptions so they can be coherently shared with others. Doing so may expose any flaw or lack of coherence that exists in the current conceptual model. Second, when a student expresses his or her reasoning aloud, peers then have an opportunity to disagree with their reasoning and, through that conflict, students may be forced to consider alternative beliefs or ideas.

Asking questions was the third most common form of utterance, followed by referring to an equation or calculation to justify an answer. The remaining forms of utterance each occurred less than ten times.

To answer the second part of research question three ("*how do student interactions support improved conceptual understanding?*") the analysis will focus on one of the questions for which there was a significant change in the number of correct responses, post-discussion and for which transcripts of student conversations are available. (Question 10).

Question 10 assess student understanding of equivalent resistance and Ohm's law. The discussion of question 10, shown below, also resulted in a significant change in correct responses, with ten students answering correctly in the initial polling and seventeen correct in the post-discussion poll.

Figure 7: Question 10:



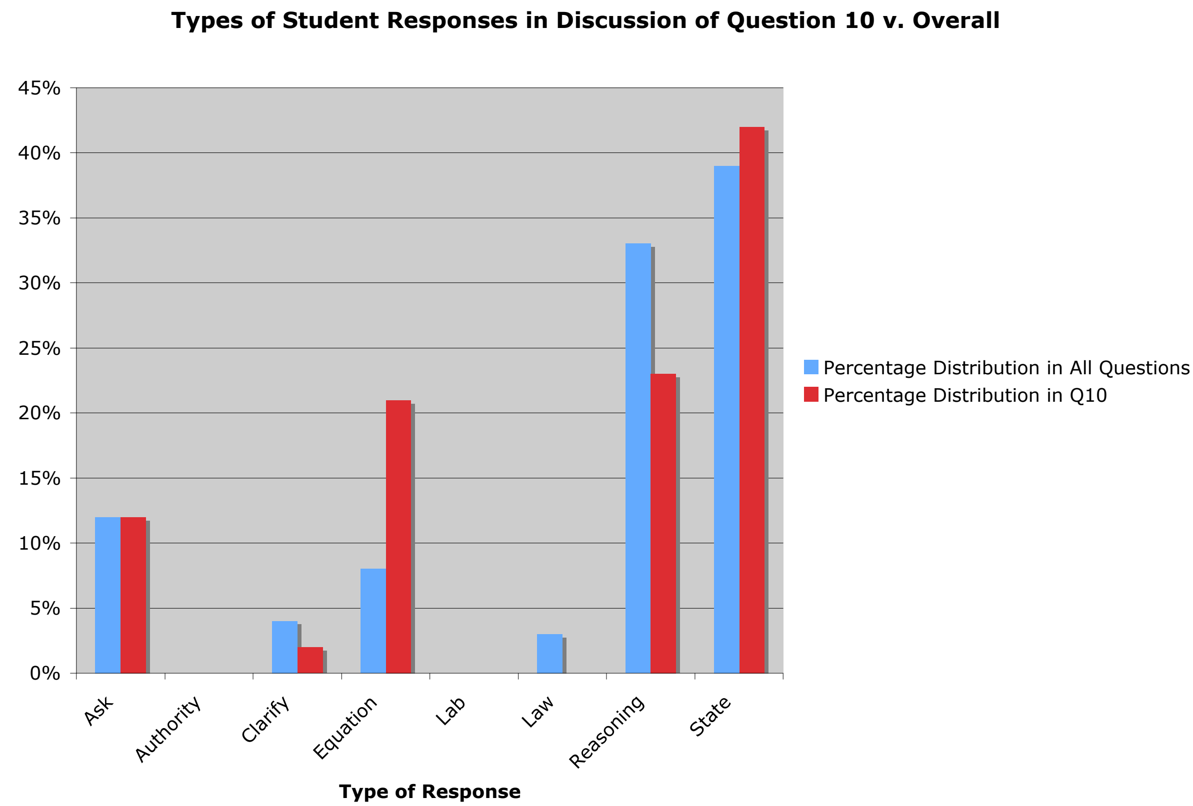
Although circuit number one has the fewest resistors, circuit number three has the smallest equivalent resistance and, thus, the largest current from the battery. Students' comments while discussing this question were coded as follows:

Table 8: Student comment codes form Question 10

Type of Utterance	Percentage Distribution in All Questions	Percentage Distribution in Q10
Ask	12%	12%
Authority	0	0%
Clarify	4%	2%
Equation	8%	21%
Lab	0	0%
Law	3%	0%
Reasoning	33%	23%
State	39%	42%

In this case, students appear to have relied more heavily on equations or calculations to explain or justify their responses, as we see in Figure 8 below:

Figure 8



This reliance on the use of equations or quantitative calculations is understandable given the nature of question 10. Students' ability to utilize that very concrete information may have made their reasoning seem more plausible to peers, as we see in the conversation from group 1:

Table 9: Group One's Discussion of Question 10

Student Comment	**Code**	**Notes**
L1: They have the same voltages and the #3 has the smallest resistance, so the current must be the greatest.	Reasoning	Using Ohm's Law and an understanding of the relative resistances
L2: Wait - which number?	Ask	
L3: #3	State	

L4: I thought it was #1 because the area is the least, so if you have the smallest the area, it's going to be dividing a larger number by a smaller number.	State Reasoning	Reference to the formula for resistance, which is inversely proportional to the cross-sectional area of the resistor. Perhaps confusing resistance with current.
L5: But I don't know -- why did you think #3?	Ask	
L6: Because the resistance in #3 is the smallest -- and the voltage is the same, equals 9 volts.	Reasoning	Restating comment from L1
L7: You're saying the resistance in #3 is the smallest?	Ask	
L8: The resistance in #3 is 2.	Equation	Student has calculated the equivalent resistance
L9: #3 equals 2, and voltage equals 9, so I equals 4.5 A,	Equation	Using Ohm's Law to calculate the flow of current
L10: But then, isn't it . . .		
L11: and #1 the resistance is 3.		
L12: Oh yeah --		

For group one, initially, one student responded correctly and one student responded incorrectly. After this discussion, both students chose the correct response, and actual calculations of equivalent resistance seem to have supported that change.

For the same question, group 8's conversation reveals a reliance on *both* qualitative and quantitative reasoning:

Table 10: Group Eight's Discussion of Question 10

Student Comments	**Code**	**Notes**

L1: I said it was 3 because that circuit has more area, so the resistance is smaller - more branches, and I also calculated it.	State Reasoning Equation	Student reasons that the effective cross-sectional area of the parallel circuit is larger, lowering its equivalent resistance of that circuit, resulting in a larger current. He/she was able to verify this reasoning mathematically, using the resistance equation and Ohm's law.
L2: I calculated it.	Equation	

The student speaking referred not only to the quantitative calculation (equation) but also to the inversely proportional relationship between cross sectional area and resistance. In the initially poll, two students from group 8 answered correctly and one answered incorrectly. All were correct in the final polling.

Summary: "*What is the nature of student comments, in peer discussions, and how does it support a more expert understanding?*"

To answer this question, we first examined the types of comments that were typical in peer discussions. Students often began by simply stating their answer (and this comprised the largest number of types of comments made). Next most common were comments in which students provided explicit reasoning for those choices. In doing these two things, students might be required to consider and commit to an answer choice and to organize their thinking in a way that can make it explicit to others. Students sometimes attempted to rely on symbolic formulae they had been exposed to through formal instruction to justify their responses. However, in some of those cases, the formulae were incorrectly recalled (See, for example, question 2, group 2, student C's comment: "I was thinking about the equation -- if like resistance is V over the current, but I think I had the equation flipped.")

Despite these weaknesses, the reliance on symbolic equations or calculations seems to have resulted in at least one of the few cases in which there was a significant increase to the number of correct answers, post-discussion. This is demonstrated in group one's discussion of question 10 where the equivalent resistances were calculated and used, in conjunction with Ohm's law, to justify responses. It was also evident in group 8's discussion of the same question, where a student said:

> "Q10G8 *L1: I said it was 3 because that circuit has more area, so the resistance is smaller - more branches, and I also calculated it.*"

In this succinct comment, this student reveals an understanding of the inverse relationship between the effective cross-sectional area of a resistor and its resistance, as well as how Ohm's law helps to use that information and reason about current.

Findings from this study would indicate that, although in most cases the number of correct responses to conceptual questions increased after discussion, the increase was rarely significant.

Discussion

Social constructivist theory suggests that knowledge may be co-constructed through social interaction and that language plays a key role in this process. The role of instruction is to provide the "scientific" concept. Students, through their own conceptual work, must develop the spontaneous concept representing their own construction of that new understanding. Physics education research has identified many common misconceptions that students harbor about DC resistive circuits. Research has also reported that peer interactions can be powerful tools to improve conceptual understanding. The hypotheses for this study will be discussed, in order, below:

Hypothesis 1: Students in the introductory high school course will share many of the common misconceptions about resistive DC circuits identified in the literature.

Students in this study were found to share, at least to some extent, many of the misconceptions about DC resistive circuits that have been identified in the literature. In spite of being afforded an opportunity, most of these misconceptions persisted, in some students, even after discussion.

Some students were found to think sequentially, rather than holistically and for many this misconception persisted after peer discussion. Most, however, did not demonstrate a belief that current is consumed and, for those who did, peer discussions seemed effective, at least in one case, in changing their views.

Some students were initially unable to consider the particular arrangement of resistors, relying on the total number to determine the current that would flow. In some cases, peer discussions were effective in promoting a change to a more expert response.

One overlying misconception, confusion about the concepts of potential difference, current and resistance, was noted in many transcripts of student dialogues. The inability to clearly articulate the meaning of these concepts and to distinguish between them may underlie many of the more specific misconceptions found.

Hypothesis 2: The number of correct responses to conceptual questions after discussion with peers will be significantly larger than before discussion.

The study found that, although the overall number of correct responses to conceptual questions significantly increased after discussion, when questions were taken in isolation, for only two questions this change was statistically significant. These were questions 1 and 10, which addressed the tendency to think sequentially, rather than holistically, about circuits and the tendency to consider only the number of elements or branches in a circuit, rather than their particular arrangement..

Hypothesis 3: There may be identifiable patterns in student comments that seem to support improved conceptual understanding.

The most common types of comments found in student dialogues were in the form of stating an answer and providing the underlying reasoning for that response. Students also asked questions of each other and sometimes relied upon symbolic equations or quantitative calculations to justify their thinking.

They rarely referred to authority (by quoting a teacher) or to lab investigations or demonstrations they had seen in class.

A comparison of the distribution of the types of responses, overall, as compared to the types of responses found in the cases where significant changes occurred did not reveal a clear difference. In one case, a reliance on proportional relationships and quantitative calculations of formulas seemed to provide the type of convincing evidence needed to help peers adopt a more expert response.

Implications and Suggestions for Future Research:

Although the findings in this study were not statistically significant for most of the specific questions asked, the overall results do suggest that collaborative interactions may hold promise in supporting strong conceptual change in the classroom. The current study was limited in duration (four class periods) and conducted in a classroom where such structured peer interactions were not routinely used in instruction. There may be a learning curve for students and, once students come to see the value in conversations with peers, those conversations may be richer and more valued. More research is needed in the use of this instructional mode as a sustained form of teaching and learning, over the course of a semester or year.

Many of the specific misconceptions in the literature were found to be prevalent and, in some cases, persistent. A larger concern is the fact that students demonstrated confusion among the concepts of resistance, current and potential difference. Unless this issue is successfully addressed, the other misconceptions cannot be dealt with, as students would be working from an incomplete or flawed foundation. Further research is needed in helping students to attain a strong conception of these foundational ideas. A future study might closely examine how often and in what ways students referred to potential difference in discussion, as compared to current and resistance. It may also be helpful to explore that ways in which students describe voltage (as, perhaps, "flowing" or "going through a resistor"). Such a study could point to specific ways in which instruction might support a stronger understanding of these concepts.

This study examined the types of comments that were typical in peer discussions of conceptual questions about DC resistive circuits. Among the most common types of utterances were: statements of answers, providing the reasoning behind answer choices and raising questions. Other studies have shown these strategies to support knowledge construction in peer collaborative discussions. Chan (2000) pointed to problem recognition, question formulation and explanation as being key to explaining what promotes or hinders knowledge construction in peer collaboration. Chi et al (1994) found that "high explainers" learned more than others who did not participate fully in self-explanations. In a comparison of teacher- and peer-led discussions Hogan et al (2000) found that although teacher-led discussions were generally more efficient, discourse was more varied in peer groups and some of those groups achieved higher levels of understanding as compared to the teacher-led groups.

In the current study, although some patterns were noted in the types of statements students used to express and support their thinking, the mechanisms of conceptual change remain unclear and the question as to whether students can build knowledge through discussions with peers remains unanswered. A longer-term study, with more interactional data, could provide additional insight. Such a study should focus not only on the types of statements students employ (questions/queries, explanations, elaborations) but also whether these strategies change, over time, as students gain more experience in collaborative knowledge building and whether they result in sustained conceptual change.

A question remains as to whether increased numbers of correct answers, post-discussion, represent reliably improved understanding. In this study, after the initial polling of each question, a histogram displayed the class consensus. It is possible that, in some cases, students' second responses may have been influenced by the histogram. Without pre- and post-testing data, this question remains open. Future studies should provide pre- and post-testing data in order to determine if the short-term gains reflected in the "clicker" data truly do translate into longer term improved conceptual understanding.

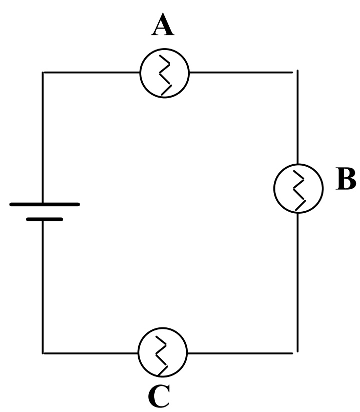
In summary, students enrolled in introductory physics courses, at the secondary level, may well benefit from regular implementation of peer collaborative methods. These methods provide opportunities for them to state and support their thinking, compare their ideas to those of their peers, elaborate and build on each other's explanations and raise questions that may support improved understanding. A future study, of longer duration, taking a combined quantitative and qualitative approach that includes pre- and post-testing data might provide stronger evidence of the value of this approach.

Specifically with regard to DC resistive circuits, it seems clear that an inability to distinguish among current, resistance and potential difference may be at the heart of many of the specific misconceptions examined in this study. A study designed to look more closely at this issue might inform how we approach these concepts in the classroom and result in improved overall understanding of DC resistive circuits.

Appendix A: Conceptual Questions Used With Electronic Polling

Q1 (polled, no conversation recorded)
Assume bulbs A, B and C are identical.
Rate the relative brightness of these bulbs:

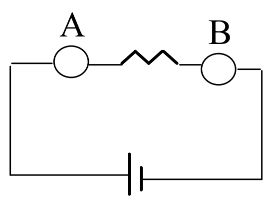
1) A = B = C
2) A < B < C
3) A > B > C
4) A > B = C



Q2 (polled & conversation)

Assume bulbs A and B are identical.
What happens to the brightness of
bulbs A & B if resistor C is increased?

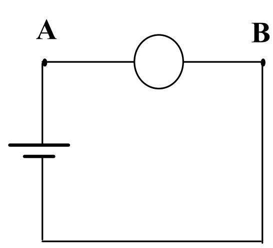
1. A stays the same, B dims
2. A dims, B stays the same
3. A and B brighten
4. A and B dim
5. A and B remain the same



Q3 (polled, no conversation recorded)

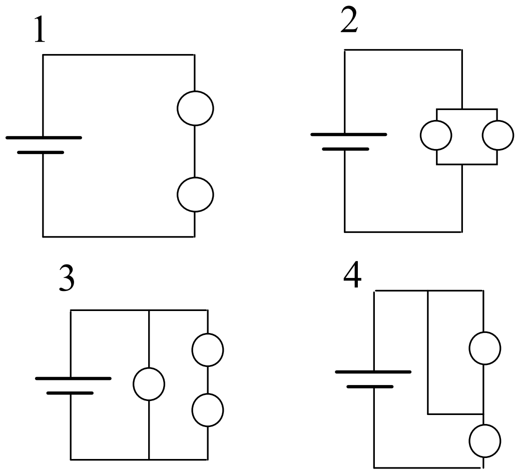
Which point in the circuit has the larger current?

1) Point A
2) Point B
3) Neither, they are the same



Q4 (polled & conversation)

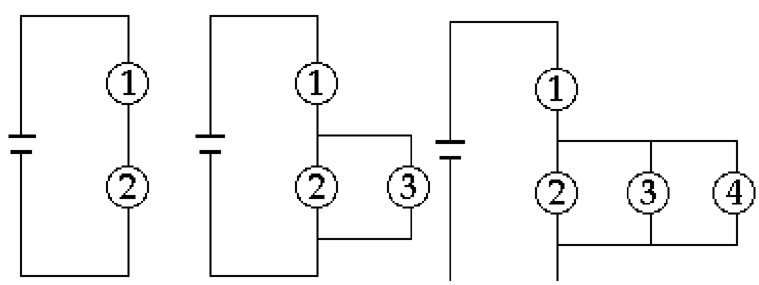
Which of the following circuit diagrams represents a parallel circuit?



Q5 (polled & conversation)

As bulbs are added in parallel to this circuit, bulb # 1 will:

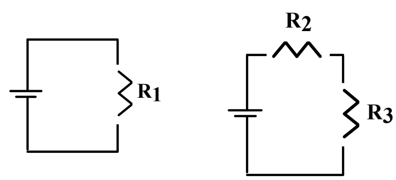
1. Dim
2. Brighten
3. Remain the same



Q6 (polled & conversation)

Assume the batteries and bulbs are identical in each of the circuits below. Compare the current flowing in R1 to the current flowing in R2 and R3.

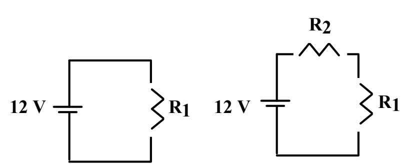
1. **The current in R1 is smaller that that in R2 and R3**
2. **The current in R1 is greater than the current in R2 and R3**
3. **The current in R1 is the same as that in R2 and R3 because the batteries and bulbs are identical**
4. **Not enough information is given**



Q7 (polled & conversation)

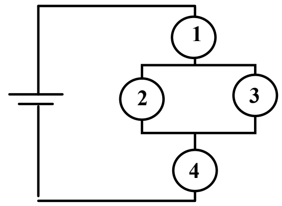
In the first circuit, there is one resistor and the battery is a 12 V battery. In the second circuit, an additional identical resistor is added. How does that additional resistor affect the potential difference across the first resistor?

1. **There is no change. The resistor is the same.**
2. **The potential difference is greater with two resistors**
3. **The potential difference is less**
4. **There is no way to tell how the potential difference is being shared.**



Q8 (polled, no conversation)

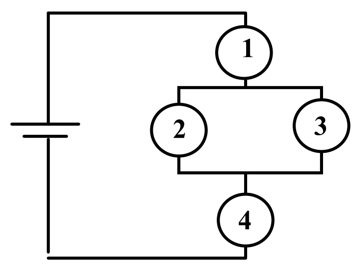
In the circuit at right, which of the following describes the current flowing through the bulbs (which are identical)?



1. **All bulbs have the same current**
2. **The current through bulb 1 is the greatest. Bulbs 2 and 3 have equal current which is less than bulb 1. Bulb 4 has the least current.**
3. **Bulbs 1 and 4 have the same current. Bulbs 2 and 3 have the same current, which is smaller than bulbs 1 and 4.**
4. **The current through bulbs 2 and 3 are equal. The current through bulb 1 equals the current through bulb 4, and both are less than the current through bulbs 2 and 3.**

Q9 (polled, no conversation)

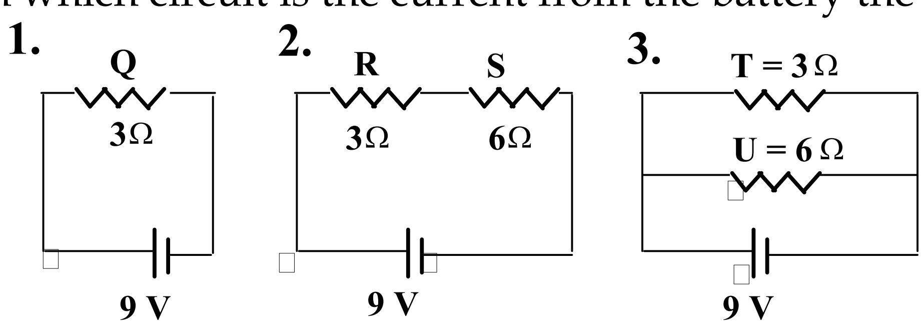
Bulbs 1 and 3 are connected in:



1. **Series**
2. **Parallel**
3. **Series and Parallel**
4. **Neither Series nor Parallel**

Q10 (polled & conversation)

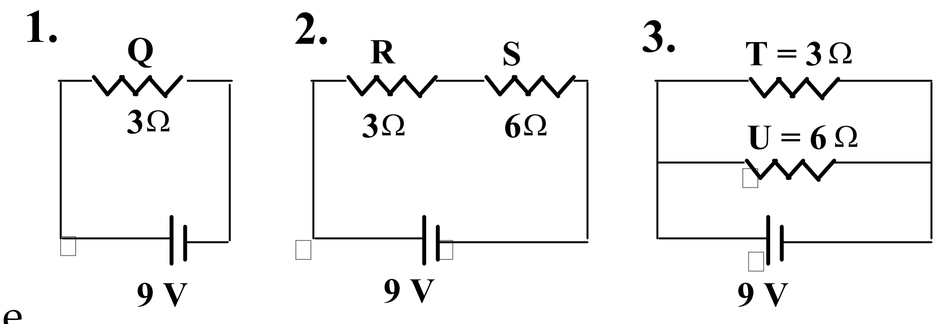
In which circuit is the current from the battery the greatest?



Q11 (polled & conversation)

In which resistor is the voltage lost the greatest?

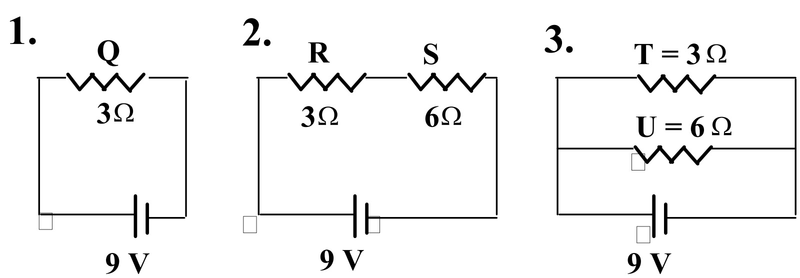
1. Q
2. T
3. U
4. Same



Q12 (polled & conversation -- rushed as bell rang mid-question)

How will the current through S change
if the resistance of R increases?

1. Increase
2. Decrease
3. Same
4.



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