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DC circuits: Contextual Variation of Student Responses

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Abstract

Many studies have shown that students (at both school and university) have difficulties in understanding the concepts associated with DC circuits. Two competing theoretical frameworks have been advanced to explain these problems: “misconceptions” and “knowledge-in-pieces”. The former is based on the assumption that student ideas are unitary, static and independent of context, while the latter considers student ideas to arise dynamically from flexible combinations of “pieces of knowledge” and that a particular combination of pieces is primed by the context presented.

The present work explores the extent to which student responses change as a result of small, fine-grained changes to a simple open circuit with only three components: a battery, a single wire and a resistive element. Three different types of resistive element were used: a light bulb, a heater and a resistor. A previously piloted, eight-question written instrument, consisting of both forced choice responses and free response writing, was administered to two cohorts of non-major, first year physics students from different institutions. The results, consistent across both cohorts, confirmed that context (e.g., type of resistive element used) was critical in triggering student responses. Student reasoning varied widely, and the majority of students used more than one “foothold idea” on which to base their explanations. Only 10% of the combined cohort got all answers (canonically) correct, and all of these students used only the single idea of “loop continuity” as the basis of their explanations.

Based on the written responses, and a small number of clarifying interviews, it was clear that sense-making was a key driver in student reasoning. However, either (a) an incorrect explanatory interpretation of a prior experience, or (b) the absence of any experiences from which to extract a key abstract concept, such as “loop continuity”, lead to incorrect (canonical) answers. One implication of the findings is that, unlike mechanics, where prior concrete experience is used as the starting point and then refined toward abstract knowledge, it appears that starting with the abstract might be a more effective pedagogical approach. This stands in contrast to many curricula that start with a concrete instantiation such as the light bulb.

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Chapter 1
Introduction

Teaching and learning physics has proved to be a challenging task in general. A large number of studies have observed and documented student difficulties. These difficulties have been observed at all levels of schooling and across different areas of physics. For example, the "alternative" ideas of school pupils between the ages of 10 and 16 with regard to light, electricity, heat and states of matter are described in *Children's Ideas in Science* (Driver et al., 1985), while at the university level, the *Resource Letter* of McDermott and Redish (1999) lists a large number of studies carried out on almost every physics topic. The reported difficulties do not appear to be confined to any particular culture, but seem widespread geographically as evidenced by the recent World Conference on Physics Education in 2012. Stetzer et al. (2013) reported that certain basic difficulties were found in all population groups, including upper division courses involving analogue electronics. In addition, many of the findings that relate to the various groups mentioned also appear to be applicable to teachers (Schoon & Boone, 1998). In trying to understand the reasons for these difficulties, several perspectives have been put forward ranging from the inherent difficulty of physics as a discipline to the way it is taught. These include not only the method of delivery, but also its presentation from an epistemological perspective (Domert et al., 2012).

1.1 Nature of physics and student ideas

With regard to the nature of physics as a discipline, Hestenes (1992) has provided a useful working perspective by regarding physics as an enterprise at the heart of which is the idea of modelling the physical world. Hestenes suggests that there are three "worlds" that are involved in the process: (i) the Real (physical) World (RW) with real things and processes; (ii) the Mental World (MW) consisting of mental models with personal experience; and (iii) the Conceptual World (CW) consisting of conceptual models which comprise the accepted scientific knowledge of the day. Since the Real World is experienced differently by individuals through their own interactions, the properties of their "personal mental models" are both private and unique. However, the CW is universal and public, and reflects a shared understanding by the community that has been informed both by experiment and theory.

The physics description of the world is not the result of a simple linear sequence of events, but results from a more complex network, like a set of connected events. In many instances, different conceptions or explanations of a phenomenon have been offered, some of which have ended up being accepted while others have been rejected. However, much of physics is presented as self-evident without any of this background being known to students. Brooks and Etkina (2009) show that many difficulties exhibited by students, with regard to the physics understanding of force, are reminiscent of similar struggles experienced by iconic names in physics over the past centuries.

1.2 Frameworks for understanding student difficulties

It is clear, however, that the starting point of much of the literature in physics regards the canonical view in physics as normative and that a failure to understand this view is a failure on the part of the student. Thus, a deviation from the physics view is often labelled as a misconception or an alternative conception. Furthermore, the view that students "have a misconception" often leads to a pedagogical strategy that is aimed at "overcoming" (Brown & Clement, 1989; Hynd Alvermann, D. E., 1986; Quijas & Aguilar, 2007; Tsai, 1999) or "remediating" (Murray et al., 1990) or "confronting" (Brna, 1988;Tao 2001) this conception. For example, the sequence "elicit, confront, and resolve" (McDermott, 2001) is a well-known strategy that is often advocated as part of a process of trying to achieve "conceptual change" (Hewson, 1992; Chi et al., 1994). McDermott (2001) cautions that the idea of identifying misconceptions should not be confused with the overall enterprise of helping students construct their own more appropriate conceptions, as "misconceptions are often symptoms of confusion at a fundamental level".

However, in general, the "misconceptions" model appears to lead to approaches involving conceptual change (Duit & Treagust, 2003; Champagne, 1983) that tend to treat student intuitions as obstacles. Smith et al. (1994) have argued that this notion goes against "a constructivist view of learning in which student conceptions play productive roles in the acquisition of expertise".   Clement et al. (1989) have also advocated that students' initial ideas have the potential to be productive starting points on which to build conceptions that are more closely aligned with physics.

Key to the notion of misconceptions is that "concepts" exist, at some level, in the mind of the student and that a "concept" is a unitary construct. However, these assumptions have been challenged by what can broadly be termed a "knowledge in pieces" model, as described in diSessa's paper, *Toward an Epistemology of Physics* (diSessa, 1993). In this approach, intuitive physics (McCloskey 1983) is made up of fragmentary structures diSessa called phenomenological primitives (p-prims), which are small "pieces of knowledge" that were strongly associated with experience. Thus, rather than assuming the existence of large-scale static knowledge structures, diSessa argued that smaller fragments of knowledge, based on a process of having abstracted past experiences (Hammer, 1996), come together when confronted with a situation. Thus, for example, "more effort gives more result" is correct when dealing with resultant force and acceleration, but false when relating to net force and velocity (Scherr, 2007).

This more dynamic non-unitary perspective was further developed by various authors, such as Hammer (1996) who promoted the idea of cognitive resources (often just called resources), building on the notion that student ideas and experiences should be used as productive starting points. Taking a "knowledge in pieces" view leads to a different perspective on conceptual change, such as that of diSessa and Sherin (1998).

Other views that try to explain student difficulties suggest that these difficulties arise from ontological issues (Chi et al., 1994) rather than from incorrect conceptions. While this explanation can be regarded as being substantially different from those advanced by "misconceptions" advocates, a common thread that links both approaches is that concepts are static rather than dynamic, and created in the moment. The static, unitary nature of the way in which this view is presented has been challenged by Gupta, Hammer and Redish (Gupta et al., 2010). In particular, they point out that experts tend to switch between categories and often use mixed ontologies. Key to all approaches that advocate non-unitary, dynamic views underlying student-manifested ideas is that of context and context dependence. Driver et al. (1985, p. 196) comment on the issue of context dependence that "children often call upon different ideas to interpret situations which a scientist would explain in the same way". This comment is based on the observations of secondary school children who were probed with regard to a number of different areas in physics, such as light, simple Direct Current (DC) circuits, heat, force, motion and atomic physics. In addition, the authors raise the problematic issue of distinguishing between ideas that would appear to arise as a manifestation of a deeper underlying cognitive structure, and those generated spontaneously as a result of the probing procedure.

The area of physics that the present study will report on involves that of electricity, specifically simple DC circuits consisting of only resistive elements. In the following section, a brief survey of work carried out is provided in order to locate the study, in which fine-grained changes to the immediate context are made and the changes to responses are investigated.

1.3 Brief survey on DC circuits

Extensive investigations into student understanding of DC electric circuits have been carried out over the past few years as described in the *Resource Letter* of McDermott and Redish (1999) and others (Hsu et al., 2004; Meltzer & Thornton, 2012). Such studies, including gender studies (Ates, 2005b), have ranged across different age groups of students (Arnold & Millar, 1987) and prospective teachers (Shen, Gibbson, Wiegers & McMahon, 2007; Shaffer & McDermott, 1992). These studies differed in nature and purpose, and some (Evans, 1978; Grayson, 2004) were used to adapt teaching methods to fit conceptions of students, while others (Kariotogloy et al., 1993) were used to develop appropriate curricula at different levels. Most of the studies were conducted using batteries and light bulbs, with the brightness of the bulb considered as a proxy for the strength of current, and a few exceptions which didn't use bulbs (Rosenthal & Henderson, 2006; Joshua, 1984). They used batteries, resistors, meters and capacitors in series and parallel circuits. While most of these studies emphasised current, a few stressed potential difference (Psillos, 1988; Rosenthal & Henderson, 2006). In the following sections the studies are separated on the basis of primary, secondary and university students, including teachers.

1.3.1 Primary school children

Various studies done on primary school children by different groups worldwide, and at different periods, reveal that knowledge obtained by young children is developed from their mother tongue, location, environment and routine (Arnold & Millar, 1987; Steinberg & Clement, 1996; Lee, 2007). Arnold and Miller (1987) conducted a study of 17 children in the United Kingdom, aged 11 to 12, aimed at developing an introductory curriculum. They conducted interviews to understand existing ideas and conceptions on simple DC circuits. Using the identified conceptions with the constructivist approach, developed by Driver and Oldhama (1986), they developed a curriculum. During the pre-interview, they used a battery, lengths of wire, a circuit board and a switch as options to light up a light bulb. While only two of the 17 children were successful in lighting up the bulb, others used the "monopolar" solution. In the post-interview, they found that some children's ideas, prior to instruction, were related to pictures or metaphors they had used to make sense of electrical phenomena. The authors identified two groups of students, each with a different model. While the first model was *clash of opposing currents* that produces light when the current meets in the light bulb, the second was *superposition of two currents*, one from either side, which produces brighter light. Furthermore, most of the children struggled to understand the bipolar solution because the conducting path within the bulb was unknown to them. They also found that children's explanations are localised and particular, not holistic. Further in the post-interview, they found that children use the terms "electricity", "current", "power" or "energy" interchangeably. Based on their findings, they designed a teaching sequence with emphasis on the following areas:

Bipolarity and rule of circuit closure

Circulation model of current

Some differentiation between electrical energy and electric current

Conservation of current

Relationship between current and resistance

In the post-interview, after the application of the constructivist approach, 14 out of 17 students grasped the bipolar theory.

In Taiwan, Lee (2007) used light bulbs and batteries to study primary school pupils' conceptions. He investigated their general knowledge about the battery and about electricity. He showed the students pictures of batteries connected in series and in parallel to a light bulb, and then he asked the students to predict the brightness of the bulb, finding that their conceptions were closely related to language and the lifestyle in Taiwan. Two years later, in Turkey, Özyurt (2009) asked 9 to 14-year-old children what came to their minds when they thought of electricity. Their responses were closely related to the concepts they had learned through their social experiences rather than what they had learned in books. The answers included light, lightning, lamps, sun, switch, television, computer and science.

Another study, from a different viewpoint, was conducted by Steinberg and Clement (2002) in the United States of America, on a 16-year-old girl who had never had a formal education in physics. They studied her mental model evolution and reported that this evolution can exploit the power of discrepant events to motivate complex learning. They conducted small experiments in steps, using capacitors, batteries and light bulbs, which motivated the child to participate in more complex learning activities. In their opinion, the use of the analogy of tyre pressure to a charged capacitor may have made it easier for the child to understand the concept.

Recently in Finland, understanding of six primary school children's conceptions on DC circuits was investigated by Kallunki and Lavonen (Kallunki & Lavonen 2010). They used pictures to interview three different graders and found that the understanding of the topic dc circuits was greater from grade three to nine. Based on their study, they reported that all of those children qualitatively understood the functioning of electric circuits, which is not agreeing with the existing literature.

1.3.2 Secondary school pupils

Data collected by Shayer and Adey (1981) from 50 children, aged 14 to 15, was analysed by Monk (1990) to study the Piagetian stage theory of genetic epistemology. He used pre-tests, post-tests and delayed post-tests, and made two claims: (i) pupils' cognitive processes are limited by the stage of their genetic epistemological development; and (ii) pupils do benefit from tuition in topic areas where their genetic epistemological stage of development enables them to develop operational schema.

A few studies used elements other than batteries and light bulbs, and placed emphasis on potential difference, since potential difference is the cause of current. In a study using diodes by introducing potential difference before the concept of current, Cohen et al. (1983) reported that no improvement in the pupils' understanding of the DC circuits was found.

Many others have studied the conceptions of high school pupils and teachers in an attempt to improve teaching methods. For example, in Israel, a study was conducted by Cohen et al. (1983) to investigate the functional relationship between variables in simple electrical circuits. They gave ten multiple choice questions and four open-ended questions to 145 (high achieving) school pupils, aged 11 to 18, and to 21 school teachers who were physics graduates. In the diagrams, unlike those of the majority of researchers who simply used light bulbs and batteries, they used various elements such as diodes, resistors, voltmeters and ammeters in series and parallel circuits. In addition to these elements, they used a one metre long resistive wire in one of the circuits. Since potential difference is the cause of current, they placed the emphasis on voltage in the curriculum they developed. The researchers introduced a basic circuit diagram on which they asked questions and then modified the diagram, asking further conceptual questions. In their study, they did not find a considerable difference in the students' understanding by introducing potential difference before current and after current. Furthermore, they found that many pupils considered the battery to be a source of current rather than a source of voltage. While the pupils selected current as their first choice in answering the questions, in the interviews they used mathematics to solve problems to conceptual questions. In the same study, it was found that the conceptions of some teachers, with many years of advanced study, had not changed their alternative conceptions after the instruction.

While the majority of studies assumed the brightness of a light bulb to be a measure of current, Psillos, Tiberghien, & Koumaras (1988) in France, used the brightness of a bulb as a measure of the voltage of a battery. They studied the perceptions of units in electricity among secondary school pupils. Their investigation used a constructivist approach for developing a teaching scheme using identified pupil conceptions. Since the primary concept is potential difference, which is a prerequisite for current in a circuit, they developed a teaching schema with an emphasis on voltage. In the same study, using open and closed circuits, they explored pupils' understanding of series and parallel resistors; the relationship between the brightness of the light bulb and the duration of battery operations; and the brightness of the light bulb and voltmeter readings, having added batteries. Furthermore, in the curriculum, emphasis was given (i) to the concept of voltage, and (ii) to the fact that there is voltage even if there is no current, but no current if there is no voltage. They found the most popular unit among French secondary pupils to be the Volt.

The conceptions of pupils aged 15 to 17, from five European countries, were studied by Shipstone and Rhöneck (1988). They studied 164 pupils from England, 189 from France, 114 from the Netherlands, 194 from Sweden and 189 from West Germany. They used 13 questions, comprising true/false and multiple choice questions. The focus was on basic concepts such as the closed circuit, the relationship between current and voltage, the conservation of current and the charge and flow in simple series and parallel circuits. Using circuit elements such as batteries, light bulbs with sockets, resistors, voltmeters and ammeters, they found that pupils' difficulties across the countries were similar. Conceptions they identified included that: (i) current is consumed; and (ii) voltage across light bulbs is equal to applied voltage. They also cited localised reasoning and sequential reasoning, in which the pupils believed that current in the circuit is influenced by the circuit elements.

Two studies included in an article by Liégeois et al. (2003) were conducted on 100 French pupils aged 14 to 18 (Grades 8 to12) on their understanding of potential difference. The first study was in the context of current and resistance, while the second was on the efficiency of a learning device developed on the basis of social judgement theory. The methodology used in the first study was Functional Theory of Cognition (Anderson & Wilkening, 1991) which contains two basic concepts, namely valuation and integration. They used 12 cards with circuit diagrams containing voltmeters and ammeters, and asked the students to predict readings of the voltmeter. Students were assessed before and after the course. In the pre-test, students were allowed to compare and consult among themselves and, if necessary, change their answers. The results showed that students lacked an understanding of resistance, and that the majority considered the position of the ammeter to be irrelevant. The overall performance in all grades showed no significant improvement after the course. In the second study, three groups were involved: (i) children younger than 14 years; (ii) high school children; and (iii) adult technical employees. They found that group 1, who had no prior knowledge of electricity, could easily be taught the correct concepts, while groups 2 and 3, who had done electricity courses, retained inaccurate preconceived ideas.

A study of 157 15-year-old secondary school pupils, by Miller and Beh (1993), was conducted on conceptions about parallel circuits, using a diagnostic test. The authors used simple parallel circuits consisting of meters, resistors and batteries (without light bulbs). The test asked the students to predict the readings of ammeters and voltmeters, and to show the calculations in the spaces provided. The analysis revealed that students were using the formula $V = IR$ to calculate the readings in the voltmeters and ammeters, and that most of them had no physical model with which to solve the problems in simple parallel circuits. In the same year, a further study by Miller and King (1993) was conducted on 175 15-year-old pupils using a diagnostic test on series circuits. They used voltmeters, ammeters, batteries and resistors in series circuits, but no bulbs. The diagnostic test consisted of six multiple choice questions, in which they were asked to give explanations for their choices. It was found that the students had a limited understanding of voltage, even in very simple circuits.

Conceptual change based on socio-cultural views was the aim of the study conducted Kock and others (Kock et al. 2013) on 9 students of grade 12 in Netherlands. They studied the effectiveness of enquiry based instructional practices in dc circuits. The study used bulbs and batteries in series and parallel circuits emphasising the two concepts, current and voltage, and used the brightness of the bulb as a proxy to current and voltage. Using DIRECT (Engelhardt & Beichner 2004) as a post test, they found that learning did not take place as expected; only less than half of the students answered the questions correctly.

1.3.3 Post secondary level students

McDermott and Shaffer investigated university (and high school) student conceptions of simple DC circuits in two related papers in the *American Journal of Physics* (1992). In the first paper, they reported on their studies of student difficulties based on a number of different sources. This included individual demonstration interviews and classroom studies. In the second paper, they developed a set of instructional materials based on the results from their investigations using the framework for *Physics by Inquiry* (1982-1992, laboratory based) and *Tutorials in Physics* (1991-1992). An important aspect of these materials is that they centre the teaching around the use of light bulbs that had been suggested by Arons (1997).

A study on false conceptions about Ohm’s Law was conducted on 169 17 to 20-year-old Electrical Engineering Technology students in Canada, by Métiouia et al. (1996). The study used a combination of light bulbs and resistors in simple series and parallel circuits. They reported that students tend to view all circuits as linear and use Ohm’s Law to find solutions for all questions, and therefore always consider voltage as proportional to current. Furthermore, students view Ohm’s Law as a universally applicable law.

Various other studies have been conducted on misconceptions by students, aimed at developing diagnostic tests. One of these, by Maloney et al. (2001), investigated conceptions of electricity and magnetism among university students using an instrument they developed, the Conceptual Survey in Electricity and Magnetism (CSEM). The CSEM comprises a set of 32 multiple choice questions, covering a wide range of aspects of electricity and magnetism in introductory physics courses, designed to diagnose the misconceptions of students. Another instrument was developed by Engelhardt (1997) in which she used the findings of McDermott and Shaffer (1992) as well as others (Psillos et al., 1988) in order to develop a diagnostic instrument, the Determining and Interpreting Resistive Electric Circuit Test (DIRECT), a set of 29 multiple choice questions, to explore the conceptions of high school and college students in the United States of America. The brightness of the light bulb is used as a measure of current in 23 of the 29 questions. Engelhardt et al. (2004) published another paper in 2004, in which they contended that the main reason for students' difficulties was not because they do "… not understand the concept of a complete circuit", [but] because they do " … not understand the internal wiring of the light bulb".

In California, Abbott et al. (2000) conducted a study on introductory physics students to compare the effectiveness of real laboratory and research-based tutorials by using pre-tests and post-tests. The experimental group did a laboratory activity based on *Tutorials in Introductory Physics* (McDermott & Shaffer, 1998) while the traditional group did the traditional lab work and a standard lab report. The two groups were post-tested using questions from DIRECT. The experimental group performed better than the traditional group, presumably because they had used research-based tutorials rather than traditional lab work, leading to the conclusion that a research-based tutorial is more effective than lab work.

In Turkey, Ates (2005a) explored the effectiveness of the learning-cycle method, developed by Lawson (1995), on prospective science teachers. Ates investigated three aspects: (i) whether the learning-cycle method is more effective than the traditional method; (ii) whether there is any relationship between gender and the understanding of electric circuits; and (iii) whether there is an interaction effect between methods of teaching and gender. The cohort was made up of 55 female and 65 male first-year students. The experimental group was exposed to a three-phase inquiry method consisting of exploration, term introduction and concept application. The traditional group was taught from the standard textbook by Serway (1992). The results did not differ significantly, in the statistical sense, between the two groups. In the case of the male students in the experimental group, however, there was a noticeable improvement in the understanding of concepts. The mean score favoured the male students.

Circuits used by Rosenthal and Henderson (2006) were generally different from those employed in many other studies, i.e. no light bulbs were used in any of these circuits. Instead, they used capacitors, voltmeters, resistors and batteries to teach potential difference. They studied the conceptions of undergraduate students to develop a new instructional sequence based on potential difference across capacitors. An elicit-confront-resolve approach was used. In the process of the development of the instruction, the authors emphasised the definition of potential difference. Questions from DIRECT (Engelhardt, 1997) and CSEM (Maloney et al., 2001) were used to test the effectiveness of their instructional approach. The result was that the students performed better with the new approach than the national average.

Shen et al. (2007) studied 16 K-8 (elementary) teachers in the United States of America to develop a course for teaching basic electricity and magnetism. The conceptions identified from a test were discussed with those student teachers, aimed at replacing their false conceptions with more acceptable ones. This was done because of the perception that alternative conceptions were firmly embedded in the minds of teachers as well as those of students.

Marshall (2008) studied the representation of circuit diagrams and their interpretation by 15 graduate students, pre-service teachers and experienced teachers. The study used the *Physics by Inquiry* curriculum by McDermott et al. (1996). Having constructed the experiment manually, students were asked to draw circuit diagrams illustrating their handiwork. This was done prior to any instruction. Following instruction, they were asked to compare the standard diagrams with their own, thereby helping them to understand the correct version. Marshall found that the students' drawings were pictorial, if not scientifically accurate. Furthermore, of those who had had prior experience of electrical circuits, none had represented them accurately in their illustrations. She recommended that some students' alternative representations might be useful if incorporated into the introductory curriculum.

In engineering education, Hussain and others (Hussain et al. 2012) studied the alternative conception, of first year students, on open and short circuits. They used simple DC circuits with resistors and a switch, opened and closed. The post-test indicated that some of the concepts improved significantly after the intervention and others did not.

Another study on 225 engineering and science major undergraduates was conducted by Slater and others (Slater et al. 2000). The aim of the study was to determine the ability of lighting up of a bulb with socket and without socket. They used their TAs to collect data from interviews. This project also aimed to develop a training strategy for TAs' interview skills. They found that only half of the students could light an un-mounted bulb successfully, though most of them were able to light a mounted bulb. They commented that "this problem truly demands a robust conceptual model of current flow" in a complete circuit.

Smith and Kampen (Smith & van Kampen 2011) studied the students' understanding of DC circuits in a different way. They used multiple batteries to study the conceptual understanding of pre-service science teachers in single and multiple loops, with the aim of developing a suitable curriculum to enable them to understand the topic. In their post-test, they found that majority of students developed a model to answer the questions correctly. In another recent study, (Smith & Kampen 2013) they investigated students functional understanding of RC circuits in 51 pre-service teachers. They used brightness of light bulb as a proxy to voltage and current, with multiple batteries, and a capacitor with a switch. They found that, even though, the students answered correctly the qualitative questions on resistive elements, they were unable to use the same reasoning in RC circuits.

In the field of Electricity and Magnetism, studies (Hekkenberg et al. 2015; Dega et al. 2013) were conducted recently to understand the students' conceptions and categorised these conceptions in to different categories. In South Africa, Hekkenberg et al. studied the conceptions of teachers in the area of Electric field and Magnetic field. They used written questions and interviews to identify the confusion of these two concepts in in-service teachers. They investigated the aspects that make them unable to distinguish between these two concepts and identify the difference between them. Based on the findings, they recommended that instructors and text books should discuss more about the difference between these two fields in addition to their similarities.

Categorisation of alternative conception in Electricity and Magnetism was done by Dega et al., in Ethiopia on 35 physics major students. They specifically studied the alternative conception in Electrical Potential Energy. They used group discussion for data collection and identified six categories. Of these, four were similar to the existing literature and other two were new "loose ideas". They supported the notion that the students' conceptions are fragmented rather than coherent.

Garzon and others (Garzón et al. 2014) studied the thinking of university students in three countries about the concepts of electromotive force and potential difference in different contexts. They asked question related to *emf* and potential difference in kitchen lighters and van Der Graaff generators, and questions related to different DC resistive circuits. They found that only a few students correctly thought that *emf* is the work done per unit charge by battery. The majority of students did not have conceptual understanding of these concepts because these concepts are introduced in introductory physics instructions abruptly in two different contexts, electrostatics and electrodynamics. They suggested that introducing *emf* as a driver may be a productive starting point.

Fredlund et al., (Fredlund et al. 2015) proposed a theoretical framework to enhance students' learning possibilities. They proposed three representations: identification of relevant aspects, selecting appropriate representations and creating variations, and advocated that these three factors will enhance the learning of students.

1.3.4 Studies using computer simulations

In recent years, various studies have been carried out using computer simulations. Finkelstein et al. (2005) compared the effectiveness of using a virtual lab, Circuit Construction Kit (CCK), with that of a real lab. They used *Physics by Inquiry* (McDermott et al., 1996) as the curriculum in the course. The study was conducted to check whether a real lab can be substituted with a computer simulation. The cohort consisted of second- and third-year university students. They divided the students into two groups: one given real lab equipment such as light bulbs, meters and wires (traditional), the other using CCK (experimental). Both groups were tested using a worksheet. The findings were that, both in conceptual understanding and in writing reports, the experimental group outperformed the traditional group.

In the following year, Keller et al. (2006) studied the effect of combining computer simulation with tutorials on 599 introductory physics course students majoring in engineering and physics. In two separate studies: (i) the students were divided into two groups to compare the effectiveness of combining tutorials with either computer simulation (CCK) or with real equipment; and (ii) the impact of computer simulation in the visualisation of the concept "current flow" in a circuit. They used the CCK in conjunction with *Tutorials in Introductory Physics* (McDermott et al., 1996), and real laboratory equipment such as batteries, wires, switches, digital multimeters and light bulbs. All students attended the same lectures; and questions from Brief Electricity and Magnetism Assessment (BEMA) (Ding et al., 2004) and Electric Circuits Concept Evaluation (ECCE) (Thornton & Sokoloff, 1998) were employed in the tests and examination. Although the students who had used CCK performed better in the tests than their counterparts in the real lab, in the year-end examination, there was little difference between the two groups.

Zacharias (2007) studied the effect of combining tutorial with Real Experiment (RE) and Virtual Experiment (VE). The cohort consisted of 88 undergraduate students in a university in Cypress. He used a pre-test to evaluate their preconceptions prior to instruction, followed by a post-test to measure the effectiveness of the instruction. He conducted two studies: (i) one on the effectiveness of combining real lab with tutorial; and (ii) a comparative study of the use of real lab and virtual lab. The students were divided into a control group and an experimental group. Both groups used the same curriculum, *Physics by Inquiry* (McDermott et al., 1996). While the control group used only real equipment for their experiment, the experimental group used both real equipment and virtual equipment (i.e. software from Riverdeep Interactive Learning, 2003). Both groups were assessed using the conceptual tests developed by the Physics Education Group (PEG) of the University of Washington. Zacharias reported that the experimental group, using the combination of real and virtual equipment, performed better than the traditional group using real equipment only.

Recently, a similar study was conducted by Kolloffel and de Long (Kollöffel & de Jong 2013) on 56 boys of secondary vocational engineering course. They compared the effectiveness of the use of virtual lab in combination with the traditional lectures, and real lab with traditional lectures.

They found that student who used combination of virtual lab and traditional lectures showed greater ability with regard to procedural skills.

Lea et al. (1994) reported that computerised programs can be used to test the students' understanding in physics. They used graphics to represent possible answers in a diagnostic tool to measure students' understanding of DC electric circuits. The goal of using the graphics was to avoid English text. The cohort consisted of 54 in-service and pre-service teachers. The course was based on the curriculum, *Physics by Inquiry* (McDermott et al., 1996). The declared assumption in this study was that the brightness of a light bulb is the measure of current. They suggested that computerised diagnostic testing in physics is feasible and that graphic representation can be used to measure students' understanding.

Another study (Quezada-espinoza et al. 2015) was conducted to assess the learning gain of using research based simulation (PhET) in a Chilean university with engineering students. They used DIRECT in their pre- and post-tests and found that, certain areas had gained "high-level" and "low-level" in others.

1.3.5 Broad attempts to categorise student reasoning in DC circuits

As is evidenced by the preceding sections, there is a large body of data on student reasoning and engagement with DC circuits. Various attempts have been made to systematise the findings in order to allow teaching approaches to address broad categories rather than several unrelated issues. One approach has been to try and understand the patterns of reasoning in terms of alternative models. Amongst the more well-known models of this type are: monopolar/unipolar, clashing currents, superposition, current is used up/less current in return path, the battery as a constant current source, and the train carrier model.

When students connect only one end of the battery to one end of the light bulb to light it up, it is referred to as the "monopolar" model (Arnold & Millar 1987), the "sink model" (Fredette & Lochhead, 1980) and the "unipolar" model (Osborne, 1981). On the other hand, when students use two wires to light up a bulb, but explain things in terms of two opposing currents flowing in opposite directions, this is referred to as the "clashing current" model (Osborne, 1983). The "superposition" model (Shipstone et al., 1988; Sebastia, 1989) is suggested to describe the observation that students believe that the brightness of the light bulb increases as the number of batteries increases, whether or not they are configured in series or parallel.

Another set of models suggests that students resort to a "current is used up" model. Osborne (1983) has suggested a "less current in return path" model, based on students' responses to the questions relating to a series circuit where students stated that the "current is used up" by bulbs, and that more elements connected in series meant less current returning to the battery. Another variation is the "source-consumer" model (Maichle, 1981) in which "something" is used up to light up a light bulb, which Shipstone (1984) has referred to as an "attenuation model". While these models tend to assume that a continuous quantity is being used up, Gauld (Gauld, 1988) has suggested a more particle-like model, the "train and carrier model", in which the carrier conveys current and returns empty to the battery (engine) for a refill.

Another class of explanations is the "battery as current source" notion that has been put forward by Cohen et al. (1983), Dupin and Joshua (1987), Heller and Finley (1992), and Picciarelli et al. (1991). One difficulty that has been noted is the apparent difficulty that students have in dealing with the circuit as a whole, as opposed to dealing with individual elements as if they could be treated in isolation. Cohen has identified that pupils reasoned locally rather than holistically, while Shipstone (1988) found that they reasoned sequentially.

One theoretical perspective that appears to unify some of the models, in particular the "something is used up model", is that of concept substitution proposed by Grayson (2004). She noted that, if another variable such as energy was substituted for current, then students' ideas would in fact align with the physics explanation. Her perspective was based on findings using *Physics by Inquiry* (Shaffer & McDermott, 1992), together with laboratory activities using light bulbs and batteries. However, while this appears to be a positive development, it tends to underline the difficulty that students have with the concept of charge flow/current.

1.4 Scope of the present study

While much work has been done in mechanics, using both the "misconceptions" and Knowledge in pieces (KIP) frameworks, the area of electricity and, in particular, DC circuits has not received the same level of attention. One of the main differences between the two areas of physics is that, in mechanics, there are many artifacts and daily experiences that act as the starting point of the modelling exercise as noted by Hestenes (Hestenes 1992). Thus, the aim of modelling leads from concreteness to abstraction. On the other hand, electricity starts out as being much more abstract, and daily experiences tend to be associations with light or heat or complex appliances. It would therefore appear that the cognitive and experiential starting points for dealing with mechanics and electricity are very different. While the idea of mass is intuitive, the notion of charge is much less so. In teaching sequences, the starting point is often the demonstration of static electricity in order to establish the notion of (invisible) charge, and then to suggest that current is the flow of this (invisible) charge. Many analogies then have to be resorted to, in order to try and link this to students' prior experience and knowledge. The previous sections have clearly illustrated that none of these approaches appear to be very successful, and that students experience a range of difficulties.

As noted previously, while many models have been proposed, there does not appear to be a unifying perspective, even though many studies have been carried out to probe the nature of these difficulties and many innovative curricula have been constructed to introduce the topic. See, for example, Engelhardt and Beichner (2004), McDermott (1992) and references therein. However, it seems clear that the underlying reasons for these difficulties of students are not well understood by the researchers and instructors or that the issues are not necessarily being addressed in the instructions at a fundamental level.

One possibility is that the framework for carrying experiments, as well as their interpretation, uses "misconceptions" perspective rather than "knowledge in pieces" (KIP) view. In particular, the degree of sensitivity to changes in context has not been addressed in any systematic way. In the KIP framework, context plays a central role in trying to understand the way in which students engage with physics content. However, no systematic studies appear to have been carried out to investigate the extent to which student difficulties could be related to this area.

1.4.1 The issue of context

It is difficult to provide an exact definition of context (Vermeulen, 2012) even though there appears to be an immediate intuitive understanding of the term when the word is used in everyday conversation. The meaning of the word "context" depends on the context in which it is used. While the Latin meaning of the term "contexture" is given as "to weave together", online Oxford Dictionaries (www.oxforddictionaries.com) defines it as "the manner of being woven together to form a connected whole" and Cambridge Advanced Learner's dictionary (2008) gives the meaning as "the situation within which something exists or happens, and that can help explain it". Cole (1996, p. 133 & p. 135) provides two versions of "context" as follows:

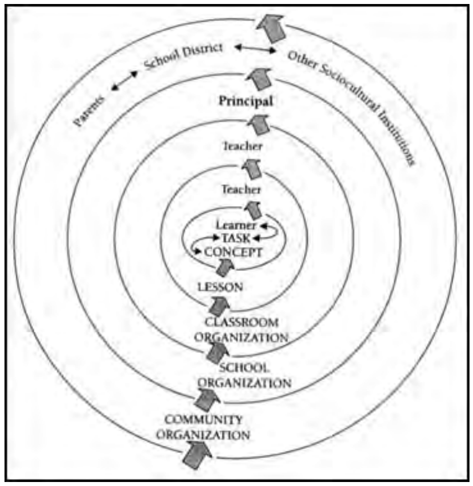


Figure 1.1: Cole's concentric circles representing the notion of context as "that which surrounds", with a learner at its centre. The context here is the one surrounding the learner's performance in a lesson.

"something that surrounds" a particular object or event; and the linguistic meaning derived from the word "contexture" as "to weave together". Using concentric circles to represent the elements surrounding the learner placed at the centre, he indicated the following "levels" of context, with task and concept "in the middle" as shown in Figure 1.1. The context expands in one direction from the learner to the teacher, principal, school district, parents and sociocultural organisation; and in the other direction more closely related to the academic organisation, starting from the learner to the lesson, classroom organisation, school organisation and community organisation.

Based on the conceptual metaphor perspective, Brookes and Etkina (2009) have suggested that what appears to be context dependence can be explained by language considerations. They argued that students' difficulties are primarily due to linguistic and ontological difficulties, and the interplay of their experience with the concept. Furthermore, physicists' language indicates that physicists categorise the concept of "force" into different ontological categories, depending on the context. For the purposes of the present work, views such as the above will be included under the umbrella of context and will be largely limited to the "textual, social, and educational ‘surroundings’ of a physics question” (Scherr, 2007) that allows meaning to emerge i.e. the central core of Figure 1.1 above.

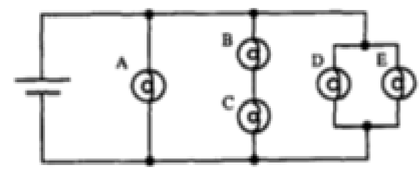


Figure 1.2: Circuit used in research

1.4.2 The light bulb as context

It is common practice to use the light bulb for introducing DC circuits in text books (Hewitt, 1988), curriculum sequences (McDermott & Shaffer, 1992), as well as for research purposes (McDermott, 1996). For example, McDermott and colleagues used the circuit shown in Figure 1.2, in which a battery and bulbs were used in their investigations. They asked the students to rank the brightness of the bulbs in the circuit and to provide reasoning for their answers. Similar circuits were used in developing teaching instructions by the same group, followed by many others.

As is apparent from the preceding sections, light bulbs often feature in research studies. Thus, many of the findings that have been carried in the area of DC circuits have done so using light bulbs (Dupin & Joshua, 1987; Tiberghien & Delacote, 1976; Fredette & Lochhead, 1980; Evans, 1978).

However, the issue of using brightness as a proxy for either current or voltage was not problematized in any of the studies noted. In a few instances, the possibility of students’ unfamiliarity with aspects of the light bulb itself was raised as a possible impediment to understanding. In particular, Engelhardt et al. (2004) contended that the reason for students’ difficulties is not because the student “…does not understand the concept of complete circuit [but that] the student does not understand the internal wiring of the light bulb…”. However, while intuitively attractive, no systematic investigation has been carried out to explore this issue and there does not appear to be any strong experimental evidence for this idea.

Another feature of the studies to date is the implicit notion that the findings on students’ conceptions, that were identified by the use of the light bulb, could be generalised to other resistive elements, and that student understanding was of a unitary nature, and not dependent on context. Thus, the overall thrust of the studies purports to be about student understanding of DC circuits (in general), rather than about student conceptions of circuits with light bulbs. Relating to the discussion in Section 1.2, the overall interpretative framework was more in keeping with the "misconceptions" framework, rather than with the "knowledge in pieces" (KIP) perspective.

This difficulty was reported to be associated with the construction of the light bulb itself (Shipstone, 1988). Thus, in the present study, the author makes changes to physics questions at what will refer to as a fine-grained level. For the reasons outlined, it was decided to construct an instrument in which the assumptions that have been discussed are not adopted, and in which a "misconceptions" perspective is not used as the framework, with particular attention to the contextual differences as highlighted by the KIP view.

It is argued in the present work that the light bulb is a specific context that, far from being "neutral", evokes a large number of associations of knowledge schemas, epistemologies and student behaviours (Redish & Burciaga, 2004; diSessa et al., 2002; Leander & Brown, 1999). This aspect of both teaching and research appears to be central to both teaching and research, yet it does not appear to have been studied systematically or in any depth. The present work aims to focus on some of these aspects as summarised below.

1.5. The present study

As seen in the preceding sections, while a considerable amount of effort has been put into researching student difficulties in the area of DC circuits, there is as yet, no fundamental theory or explanatory model. One issue that appears to have been ignored to date, is the way that prior experience at a fine-grained contextual level, influences student engagement. In short, both teaching and research do not appear to have placed context at the centre of their approaches. Thus, when researching student understanding of introductory DC circuits, using the brightness of a light bulb as a proxy for current will lead to results that can be generalized. While this conclusion may indeed be consistent with a classic "misconceptions" view, it is not clear that this is true from a "knowledge in pieces" perspective, in which context and cognitive "grain-size" are key components. As can be seen from literature, little is known about how fine-grained contextual changes impact student reasoning in the context of DC circuits.

The main purpose of the present work is to measure the effect of such changes in student responses. To this end, an instrument was designed to investigate these aspects, in particular, the effect of representational, linguistic and (circuit) elemental variation on student engagement.

In summary, in the present study, the author investigated to what extent seemingly small contextual changes to a DC circuit affected students' responses. The present study focused on the following three aspects: (1) changes between equivalent resistive elements, (2) changes to the circuit orientation, and (3) changes to wording. The development of the instrument and other issues pertaining to the way in which the investigation was carried out are presented in the following chapter.

Chapter 2
Methodology

The studies that were summarized in Section 1.3 were carried out using a variety of different methods. These varied from questionnaires using a simple true/false format, to multiple choice questions with several options. In some instances, students were also asked to explain their choices in writing, while in others, formal interviews were conducted. From a teaching intervention perspective, the most widely used method for measuring the effectiveness of teaching strategies was pre- and post-tests. Of importance to the present work is the observation that a significant percentage of the studies presented students with (a) series and/or parallel circuits in which (b) light bulbs were used as the resistive elements. However, (a) no systematic studies appear to have been carried out completely with open (incomplete) circuits and (b) only in a few cases were resistors, diodes or capacitors shown in the circuits. The primary justification for the use of light bulbs included the facts that students are somewhat familiar with them from everyday experience, and that there is a visible proxy for the strength of the current namely, brightness. (In some instances, brightness was associated with voltage.)

2.1 Construction of the instrument

The present work is directed at two aspects of the way in which students engage with DC circuits. The present work firstly seeks to establish to what extent context plays a role in the engagement with dc circuits to their responses, and secondly, to probe students' reasoning without pre-conceptions as the expected outcomes. While the degree of variation in the student responses could easily be done using multiple choice questions, the second part of the study relied on either written or oral explanations. Rather than using two separate instruments, it was decided to use the approach of Allie et al. (1998) in which both types of responses were captured in a single instrument. The form of the questions described in Allie et al. was framed as debates amongst posited participants who provided different opinions as to the task at hand. Respondents were asked to choose one of the opinions (Forced Choice Responses) and then provide a detailed written reason for the choice (Free Response Writing).

The questions used by Allie et al. (1998), as well as those used in later studies (Buffler et al., 2001; Volkwyn et al., 2008), provided detailed guidance in the design and construction of the questionnaire. However, for reasons outlined in their work, Allie et al. used cartoon-type characters to present the arguments. It was not clear, however, whether the present study required the use of such figures, and the arguments were therefore simply presented in words. A similar approach was used in Takane's thesis (Takane, 2014).

The broad thrust of the study was to look into the effect on students' responses to a number of questions in which contextual changes were made to the simplest possible configuration that would be recognized as being part of an electrical circuit. To this end, a battery and a resistive element, connected by a single wire in a straight line, were thought to be the most appropriate instantiation. One of the reasons for opting for this "open circuit" was because it was then possible to investigate to what extent, or in which ways students treated vertical and horizontal orientations differently. While it is possible to probe student understanding of an open circuit by introducing a break in a usual closed loop series circuit (switch open), it was not clear that this would be perceived in the same way as presenting a horizontal and a vertical drawing separately. The central issue that formed the core of the study was to see to what extent students shared the expert view of treating different types of resistive elements in the same manner, from an electrical perspective. As noted earlier, many studies assumed that this would be the case for a light bulb and a resistor. Therefore, these two elements were chosen at the outset to be part of the investigation. In addition, a heating element was added, as it is a familiar appliance that has an experiential proxy (hotness) associated with current and voltage. Thus, the contextual changes involved three resistive elements and two orientations. The effect of making small changes in the terminology used was added as a third angle of the study. To this end, in a number of questions, the term "current" was replaced with "charge flow".

In summary, using the elements shown in Table 2.1 below, the systematic arrangement of the elements together with the possible battery orientations (plus/minus), a bank of 120 questions was drawn up.

Each circuit that is used as the basis of question, was presented to students, and was comprised of a number of features, including that the circuit element was connected by a single wire to one end of a battery. The battery-wire combination was connected to the elements either in a horizontal or vertical configuration. In the set of vertical configurations, the connection was always made at the bottom of the element. There were two possibilities for making the horizontal configuration: turning the whole circuit by 90 degrees; or turning the battery-wire combination to 90 degrees and keeping the elements vertical. However, it was decided to keep the elements vertical and the battery-wire combination in the horizontal orientation, which made it possible to connect the wire to the top, side or bottom of the element. In addition, the terms “charge flow”, “current” and “heat-up” (or “light-up”) were interchanged in the text for otherwise identical circuits.

Table 2.1 summarises the elements and the phrase combinations that were used to construct a series of questions from which the instrument would be drawn. The question bank consisted of 120 questions.

Table 2.1: The elements and phrases used in the questions

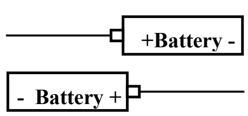
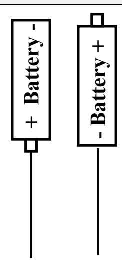
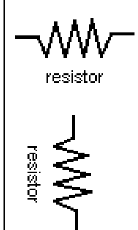
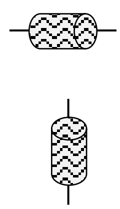
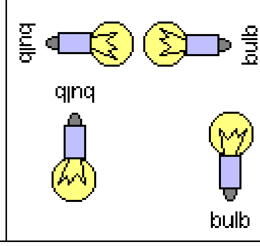
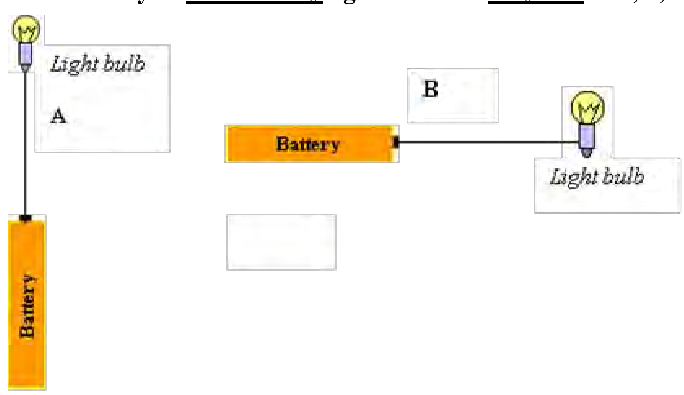
Horizontal battery and wire	Vertical battery and wire	Resistor	Heating Element	Light bulb	Phrases
					“Current” “Charge flow”

Figure 2.1 (below) shows an example of a question in the format that was used during the piloting of the instrument (described in Section 2.2 below). As is illustrated in the figure below, the question consists of a “stem” in which the background to the problem is sketched, followed by a debate consisting of five opinions. While the first four opinions covered all the possible combinations, a fifth opinion was also included in order to cater for situations that had not been considered. The respondents were asked to circle a number (1 – 5), and explain the reason for choosing that particular opinion. A number of issues are noted that can be seen in the figure. For example, it is clear that the elements have been depicted in schematic form rather than using electrical symbols. This was done in order to avoid issues relating to the understanding of such symbols, as the symbols used in high school textbooks are not uniform and can cause confusion in and of themselves (Mautjana, 2015)

One student connects a light bulb to a battery as shown in circuit **A**. Another student connects the light bulb to a battery as shown in circuit **B**. The following discussion takes place among the students:

Student 1 says, "The bulb in circuit **A** will light up, but not the bulb in circuit **B**!"
Student 2 says, "No! The bulb in circuit **B** will light up, but not the bulb in circuit **A!**"
Student 3 says, "I disagree! Both bulbs will light up!"
Student 4 says, "No! None of the bulbs will light up!"
Student 5 says, "I have another idea which I will explain to you!"
With whom do you most closely agree? Circle only one of 1, 2, 3, 4 or 5.



Explain the reasons for your choice in detail below.

……………………………………………………………………………………..…………

Figure 2.1: Example of a question in which a light bulb is connected either to a vertically or horizontally orientated battery and wire

2.2 Pilot Study

The section below describes the piloting of the instrument that was carried out as part of the development of the instrument. The main reason for the pilot study was to see whether or not there were any issues that could not be anticipated in the question itself, in terms of the language used in the text as well as the circuit diagrams themselves. A second reason for the pilot study was to develop a suitable protocol for administering the instrument and to see the way in which the students responded. Lastly, the pilot study was also used to develop a step-by-step strategy for the data analysis for the main study.

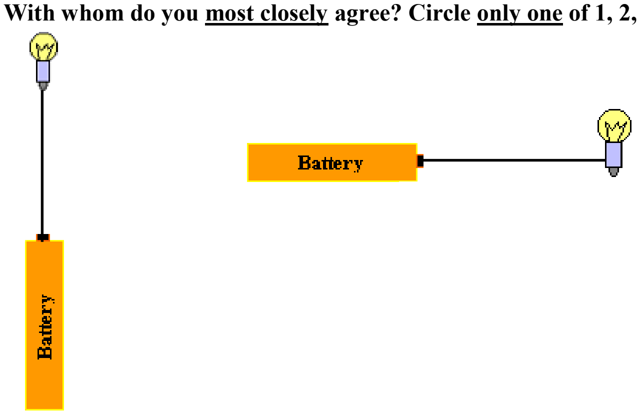
2.2.1 Instrument developed in the pilot study

In order to test how students responded to the questions, from the perspectives of understanding and interpreting the questions, an instrument was constructed using five questions from the bank of 120 questions. The number of questions was based on considerations of how long it would take students to complete all the questions without experiencing “questionnaire fatigue”, bearing in mind that each question required a full written response. The five questions consisted of the following features: (i) two questions relating to the light bulb and the two terms “light up” and “charge flow”; (ii) two questions relating to the resistor and the two terms “current” and “charge flow” and; (iii) one question relating to the heater and its heating. In addition, each question provided a vertically and horizontally orientated battery-wire attached to one end of an element (light bulb, heater and resistor). Furthermore, there were five options from which the respondents had to choose one and give an explanation for doing so. The five-question instrument used in the pilot study is presented below in Figure 2.2:

Q 1

One student connects a light bulb to a battery as shown in circuit **A**. Another student connects the light bulb to a battery as shown in circuit **B**. The following discussion takes place among the students.

Student 1 says, “The bulb in circuit **A** will light up, but not the bulb in circuit **B**!”
Student 2 says, “No! The bulb in circuit **B** will light up, but not the bulb in circuit **A!**”
Student 3 says, “I disagree! Both bulbs will light up!”
Student 4 says, “No! None of the bulbs will light up!”
Student 5 says, “I have another idea which I will explain to you!”
With whom do you <u>most closely</u> agree? Circle <u>only one</u> of 1, 2, 3, 4 or 5.



1
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Explain the reasons for your choice in detail below.

Q 2

One student connects a resistor to a battery as shown in circuit **C**. Another student connects the resistor to a battery as shown in circuit **D**. The following discussion takes place among the students.

Student 1 says, “The resistor in circuit **C** will have a current, but not the resistor in circuit **D**!”
Student 2 says, “No! The resistor in circuit **D** will have a current, but not the resistor in circuit **C**!”
Student 3 says, “I disagree! Both resistors will have current!”
Student 4 says, “No! None of the resistors will have current!”
Student 5 says, “I have another idea which I will explain to you!”
With whom do you <u>most closely</u> agree? Circle <u>only one</u> of 1, 2, 3, 4 or 5.

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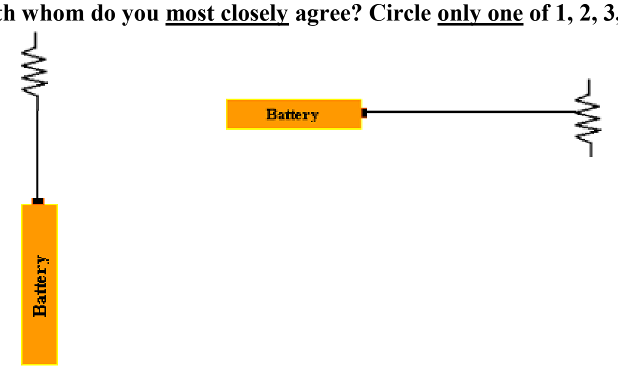

Explain the reasons for your choice in detail below.

……

Q 3

One student connects a heating element to a battery as shown in circuit **E**. Another student connects the heating element to a battery as shown in circuit **F**. The following discussion takes place among the students.

Student 1 says, “The heating element in circuit **E** will heat up, but not the element in circuit **F**!”
Student 2 says, “No! The heating element in circuit **F** will heat up, but not the element in circuit **E**!”
Student 3 says, “I disagree! Both heating elements will heat up!”
Student 4 says, “No! None of the heating elements will heat up!”
Student 5 says, “I have another idea which I will explain to you!”
With whom do you <u>most closely</u> agree? Circle <u>only one</u> of 1, 2, 3, 4 or 5.

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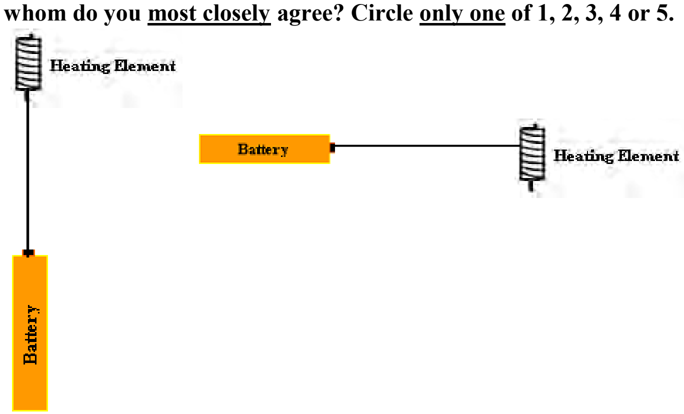


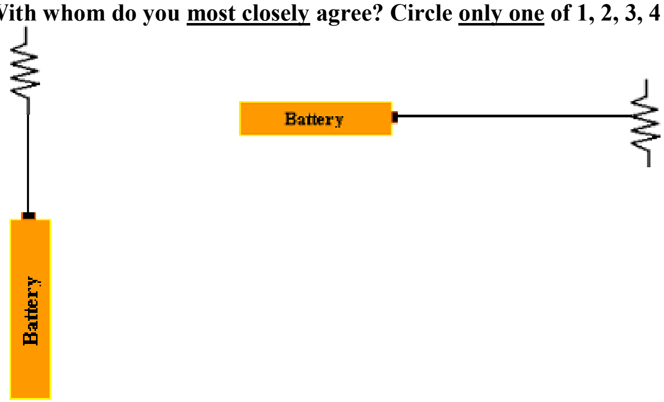
Explain the reasons for your choice in detail below.

……

Q 4

One student connects a resistor to a battery as shown in circuit **G**. Another student connects the resistor to a battery as shown in circuit **H**. The following discussion takes place among the students.

Student 1 says, "Charge will flow in the resistor in circuit **G,** but not in the resistor in circuit **H**!"
Student 2 says, "No! Charge will flow in the resistor in circuit **H,** but not in the resistor in circuit **G!**"
Student 3 says, "I disagree! Charge will flow in both resistors!"
Student 4 says, "No! Charge will not flow in any of the resistors!"
Student 5 says, "I have another idea which I will explain to you!"
With whom do you <u>most closely</u> agree? Circle <u>only one</u> of 1, 2, 3, 4 or 5.



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Explain the reasons for your choice in detail below.

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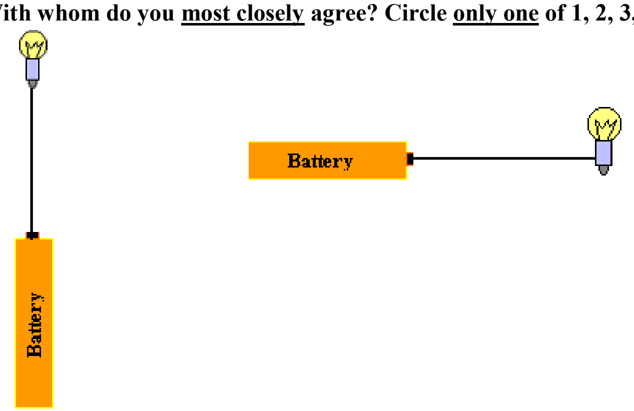
Q 5

One student connects a light bulb to a battery as shown in circuit **I**. Another student connects the light bulb to a battery as shown in circuit **J**. The following discussion takes place among the students.

Student 1 says, "Charge will flow in the bulb in circuit **I,** but not in the bulb in circuit **J**!"
Student 2 says, "No! Charge will flow in the bulb in circuit **J,** but not in the bulb in circuit **I!**"
Student 3 says, "I disagree! Charge will flow in both bulbs!"
Student 4 says, "No! Charge will not flow in any of the bulbs!"
Student 5 says, "I have another idea which I will explain to you!"
With whom do you <u>most closely</u> agree? Circle <u>only one</u> of 1, 2, 3, 4 or 5.



1
2
3
4
5

Explain the reasons for your choice in detail below.

....

Figure 2.2: Questions used during the piloting of the instrument

2.2.2 Sample used in the pilot study (UNP)

The piloting of the instrument was conducted on a sample of 97 first year (non-major physics) university students registered in 2009 (called as UNP throughout the thesis). The average age of the cohort was 18 years old. High school pupils in South Africa study Physical Science as one of their subjects in Grades 10, 11 and 12. Thus, electricity – and the DC circuit in particular – forms part of the syllabus. All these students had passed the National Senior Certificate in Grade 12 with Physical Science as a subject, and this part of their curriculum had been included in the examination. For most of the students, English is a second or third language. A typical question that students would have answered at high school level (Grade 12) is given in Appendix 3. This is extracted from an actual question paper set by the South African National Department of Education, with full acknowledgement of their copyright.

2.2.3 Protocol used in the administration of the pilot study

The administration of the test was conducted during an afternoon laboratory session, since the students were busy during the morning session due to their lectures. Students were not warned about this test beforehand. The test was introduced as a diagnostic test. They were told that this was a test used to develop a new curriculum in view of their revised school curriculum. Moreover, the students came from different schools (and different countries) and were taught by different teachers in different mediums of instruction and facilities. Therefore, they were informed that the aim was to gauge their understanding of DC circuits, and that while some of the questions may look similar to them, they should answer all the questions. They were also informed that if a student's answer was found to be interesting, not necessarily right or wrong, that student may be called for a personal discussion. It was urged that the students respond to each of the questions honestly, so as to maximize the capacity of the test to help students in achieving their goals in the course. Furthermore, a clear instruction was given to all students, at the beginning of the test, not to refer to the preceding or the following questions while answering the questions. However, they were allowed to make corrections after finishing all the questions. No time limit was given for the test. Nevertheless, the test was completed in 25 minutes. The analysis of the data is not presented here in detail, but summarised in Appendix 2.

2.2.4 Issues arising from the pilot study

The final instrument and the protocol used to carry out the study were informed by (a) observations made during the administration of the instrument, and (b) by the preliminary analysis of the data. The important observations were (i) students' engagement with the questionnaire – they appeared to be deeply involved with the questions; (ii) students' interaction with the researchers – they asked questions about the instrument; and (iii) the time spent on each question – many students spent, on average, three minutes on each question. Thus, the final version of the instrument was constructed.

A number of features were changed in the final instrument. First of all, three questions were added to make up a total of eight questions in the final questionnaire. This was necessary because the author decided to investigate a few more concepts, such as current in a light bulb, current in a heater and charge flow in a heater. The brief analysis of the pilot data showed that none of the students used the fifth option, and this led the author to drop that option in the final version. With regard to the schematic diagrams in the pilot questionnaire, the lines showing the connections from the positive terminal of the battery to the resistor and the heater were both at the side. These connections at the side of the elements prompted the students to answer "correctly"; the reasoning was: the side of the resistor/heater is insulated. To avoid this, a systematic connection arrangement was made; the elements were connected at the top and bottom (heater and resistor), and at the side and bottom of the light bulb, from a battery. Furthermore, in the pilot study, all connections were from the positive terminal of the battery. This was changed in one of the heater questions, i.e. in the vertical circuit, the negative terminal of the battery is connected to the bottom of the heater, and in the horizontal circuit, the positive terminal is connected to the heater. This change was made to check whether the terminals of the battery would influence the responses. The final version of the instrument was thus based on the version of the pilot study. In addition, the questionnaire was presented at local and international conferences, and the comments received from colleagues were considered. Before finalising the updated instrument, the instrument was circulated among the researchers at the University of Maryland, United States of America, and the author considered their opinions regarding randomising the numbers (1 – 4) of the answer choices.

2.3 Constructing final instrument: Aspects of Circuits Questionnaire (ACQ)

As noted in Section 2.2.4, three questions were added to the pilot instrument, in addition to the other changes that were discussed. Figure 2.3 shows the combination of circuits and phrases used in the construction of the final instrument, as a result of the pilot study. The final version of the instrument consisted of eight questions, designated the Aspects of Circuits Questionnaire (ACQ). A conceptual version of the eight questions used in ACQ is shown in Figure 2.3. (The full questionnaire is presented in Section 2.4.) To facilitate comparison, both across the rows and down the columns, the figures for each question are arranged as given below, i.e. the same element and different wordings across the rows; and different elements with the same wording down the columns (except in column 1, row 2).

Row 1 illustrates three questions using light bulbs. Each question offers the same circuit configuration, orientated vertically and horizontally, in which the positive end of a battery is connected to a light bulb with a single wire. In the vertical orientation, the battery is connected to the *bottom of the bulb*, while in the horizontal orientation, the battery is connected to the *side of the bulb*. The key variation in each question is the wording of the text. In Question 1, the wording is “will bulb light up?”; in Question 2, the wording is “will charge flow in bulb?”; and in Question 3, the wording is “will there be current in bulb?”.

Row 2 illustrates three questions using resistors. Each question offers the same circuit configuration, orientated vertically and horizontally, in which one end of a battery is connected to a resistor with a single wire. In both vertical and horizontal orientations, the battery is connected to the bottom of the resistor. The key variation in each question is the wording in the text. The reason for the greyed question in column 1 is that there is no text equivalent of “light-up” or “heat-up” in the case of a resistor. This is a deeper issue, as there is no directly observable sensory correlate, such as “heat-up” or “light-up”, in the case of a resistor.

Row 3 illustrates three questions using heaters. Each question offers the same circuit configuration, orientated vertically and horizontally, in which one end of a battery is connected to a heater with a single wire. In the vertical orientation, the negative end of the battery is connected to the bottom of the heater, while in the horizontal orientation (as in all other scenarios pertaining to the battery), the positive end of the battery is connected to the top of the heater. The key variation in each question is the text.

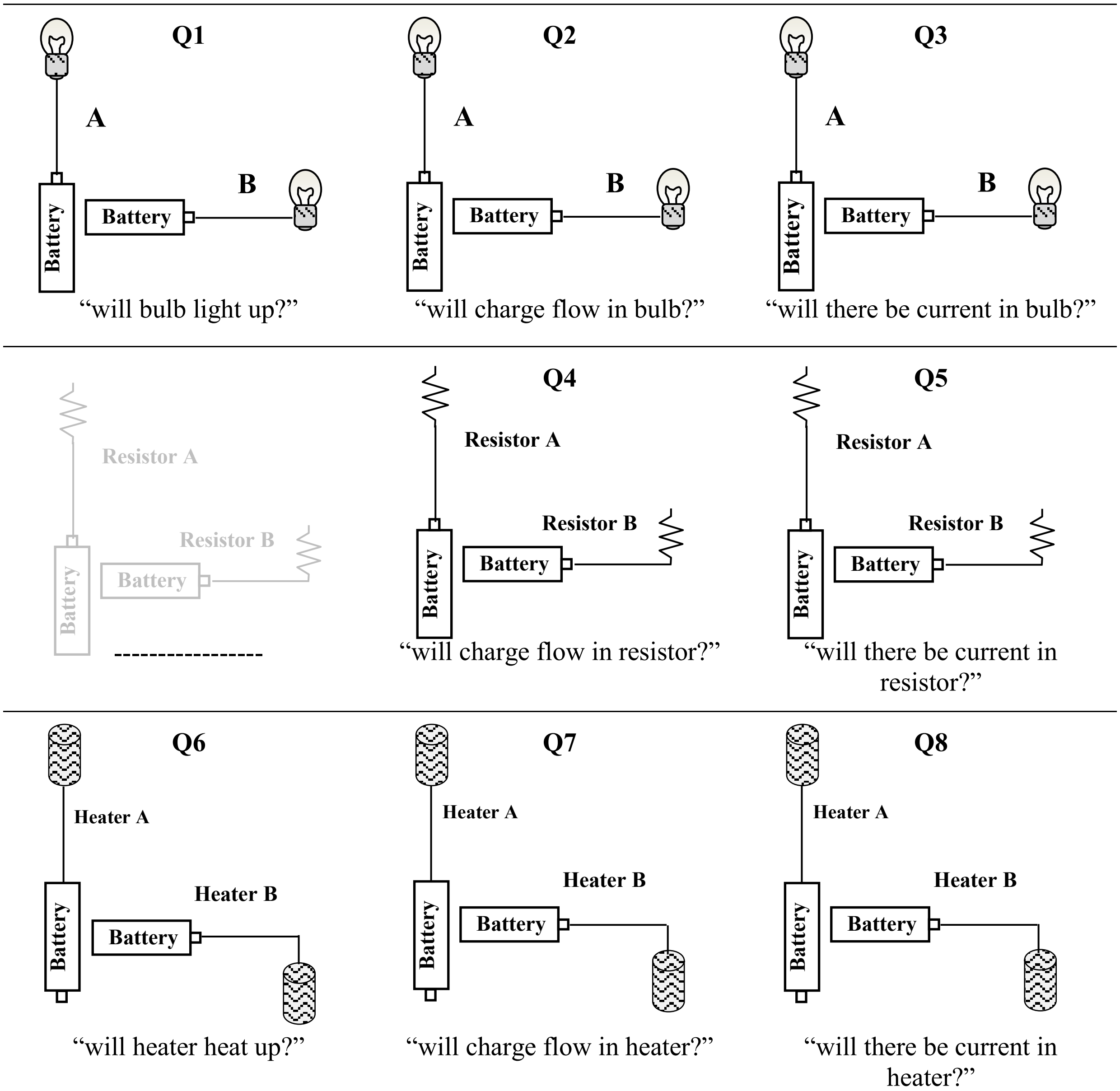


Figure 2.3: The combination of circuits and wordings used in the eight questions

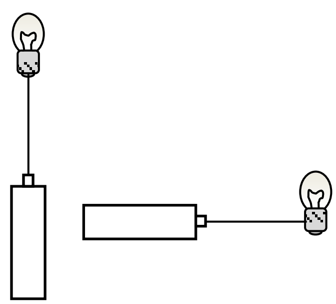
Column 1 illustrates one question using a light bulb and a heater, with the phrases "light-up" and "heat-up". As discussed, the resistor question in this context is non-existent. In the horizontal circuit, the point of connection to the circuit element varies from the middle (bulb) to the top (heater), while in the vertical circuit, the battery is connected from the positive terminal of the battery to the bulb, and from the negative terminal of the battery to the heater.

Column 2 illustrates three questions in which the wording “charge flow” is the same in each case, but the circuit element (bulb, resistor, heater) varies. In the horizontally orientated circuit, the point of connection to the element varies (middle – bulb, bottom – resistor, top – heater).

Column 3 illustrates three questions in which the wording “current” is the same in each case, but the circuit element varies (bulb, resistor, heater). In the horizontally orientated circuit, the point of connection to the element varies (middle – bulb, bottom – resistor, top – heater). Note that in all the circuits, irrespective of orientation, the circuit elements are always vertically orientated. In the horizontal orientations, the connections move from the side (light bulb), to the bottom (resistor), to the top (heater).

One student connects a light bulb to a battery, as shown in circuit **A**. Another student connects the light bulb to a battery, as shown in circuit **B**. The following discussion takes place among the students.

Student 1 says, “The bulb in circuit **A** will light up, but not the bulb in circuit **B**!”
Student 2 says, “No! The bulb in circuit **B** will light up, but not the bulb in circuit **A**!”
Student 3 says, “I disagree! Both bulbs will light up!”
Student 4 says, “No! None of the bulbs will light up!”
With whom do you most closely agree? Circle only one of 1, 2, 3, or 4.



1
2
3
4

Explain the reasons for your choice in detail below.

……

Figure 2.4: Format of the questions after the pilot study

The response choices were presented in a manner whereby the choice number (1 – 4) of the correct answer was not consistent among all eight questions. The final format of a question is illustrated in Figure 2.4. Each question consists of only four options, unlike the five options in the pilot instrument. Each question is presented as a hypothetical laboratory session in which a group of four students sets up an experiment using a light bulb, a single wire and a battery. A debate among them is presented as four options, from which the respondent has to select one and explain the reason for choosing that particular option. The final instrument developed is presented in the next section.

2.4 The Final Instrument: Aspects of Circuits Questionnaire (ACQ)

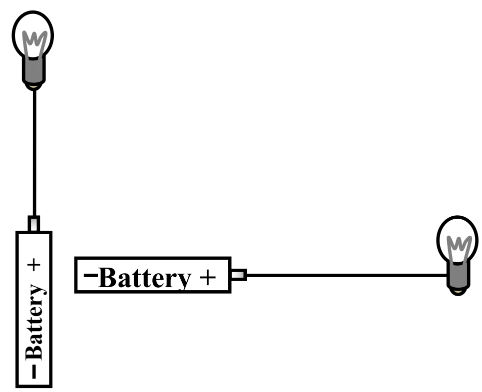
Although two questions are presented per page below, in the actual study, each question was printed on an A4 page and all questions were stapled together prior to administration.

Question 1
A student connects a light bulb to a battery as shown in figure **A**. Another student connects a light bulb to a battery as shown in figure **B**. The following discussion takes place among the students.

Student 1 says, “The bulb in figure **A** will light up, but not the bulb in figure **B**!”
Student 2 says, “The bulb in figure **B** will light up, but not the bulb in figure **A**!”
Student 3 says, “Both bulbs will light up!”
Student 4 says, “None of the bulbs will light up!”

With whom do you <u>most closely</u> agree? Circle <u>only one</u> of 1, 2, 3 or 4.

1
2
3
4



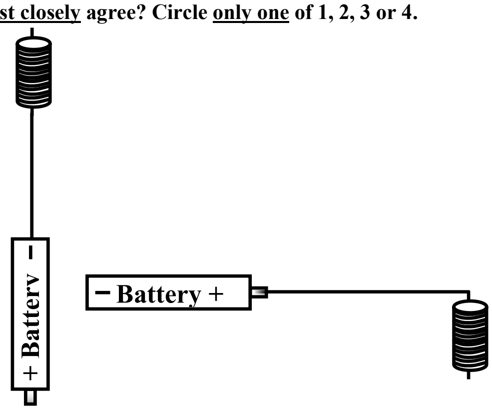
Explain the reasons for your choice in detail below.
……

Question 2
A student connects a heater to a battery as shown in figure **A**. Another student connects a heater to a battery as shown in figure **B**. The following discussion takes place among the students.

Student 1 says, “The heater in figure **A** will heat up, but not the heater in figure **B**!”
Student 2 says, “The heater in figure **B** will heat up, but not the heater in figure **A**!”
Student 3 says, “Both heaters will heat up!”
Student 4 says, “None of the heaters will heat up!”

With whom do you <u>most closely</u> agree? Circle <u>only one</u> of 1, 2, 3 or 4.

1
2
3
4

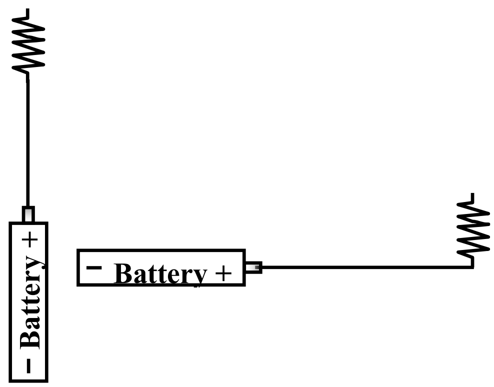


Explain the reasons for your choice in detail below.
……

Question 3
A student connects a resistor to a battery as shown in figure **A**. Another student connects a resistor to a battery as shown in figure **B**. The following discussion takes place among the students.

Student 1 says, "There will be a current in figure **A,** but not in figure **B**!"
Student 2 says, "There will be no current in any of these figures!"
Student 3 says, "There will be a current in both figures!"
Student 4 says, "There will be a current in figure **B,** but not in figure **A**!"

With whom do you <u>most closely</u> agree? Circle <u>only one</u> of 1, 2, 3 or 4.



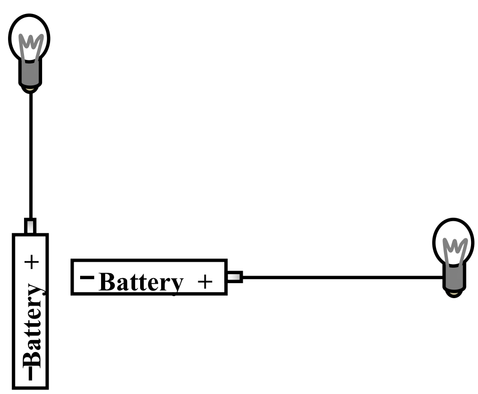
1
2
3
4

Explain the reasons for your choice in detail below.
……

Question 4
A student connects a light bulb to a battery as shown in figure **A**. Another student connects a light bulb to a battery as shown in figure **B**. The following discussion takes place among the students.

Student 1 says, "There will be a current in figure **A**, but not in figure **B**!"
Student 2 says, "There will be a current in figure **B**, but not in figure **A**!"
Student 3 says, "There will be no current in any of these figures!"
Student 4 says, "There will be a current in both figures!"

With whom do you <u>most closely</u> agree? Circle <u>only one</u> of 1, 2, 3 or 4.



1
2
3
4

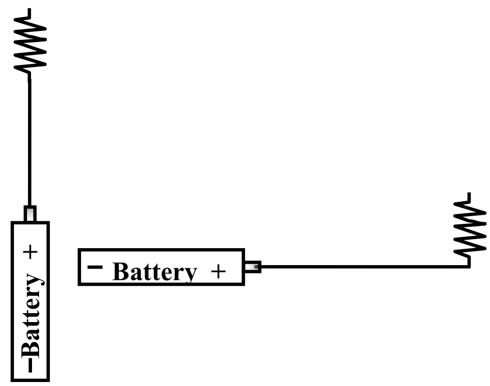
Explain the reasons for your choice in detail below.
………

Question 5
A student connects a resistor to a battery as shown in figure **A**. Another student connects a resistor to a battery as shown in figure **B**. The following discussion takes place among the students.

Student 1 says, “Charge will flow in figure **A,** but not in figure **B**!”
Student 2 says, “Charge will not flow in any of these figures!”
Student 3 says, “Charge will flow in both figures!”
Student 4 says, “Charge will flow in figure **B,** but not in figure **A**!”

With whom do you <u>most closely</u> agree? Circle <u>only one</u> of 1, 2, 3 or 4.

1
2
3
4



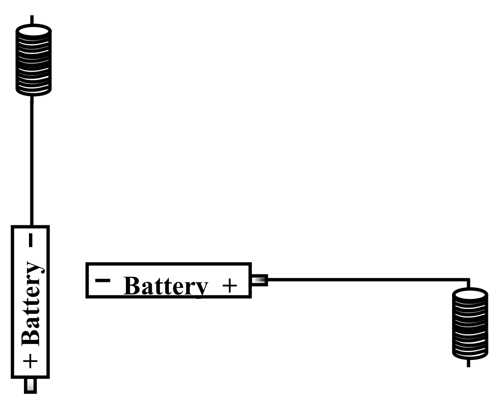
Explain the reasons for your choice in detail below.
……

Question 6
A student connects a heater to a battery as shown in figure **A**. Another student connects a heater to a battery as shown in figure **B**. The following discussion takes place among the students.

Student 1 says, “Charge will flow in figure **A,** but not in figure **B**!”
Student 2 says, “Charge will not flow in any of these figures!”
Student 3 says, “Charge will flow in both figures!”
Student 4 says, “Charge will flow in figure **B,** but not in figure **A**!”

With whom do you <u>most closely</u> agree? Circle <u>only one</u> of 1, 2, 3 or 4.

1
2
3
4



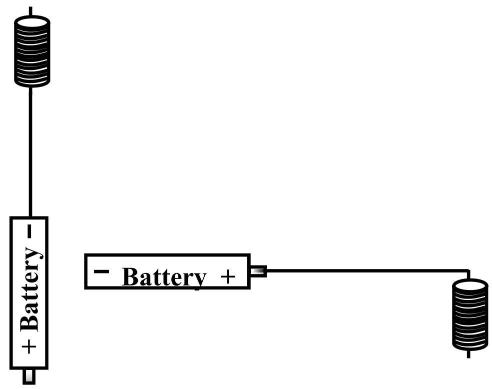
Explain the reasons for your choice in detail below.
………

Question 7
A student connects a heater to a battery as shown in figure **A**. Another student connects a heater to a battery as shown in figure **B**. The following discussion takes place among the students.

Student 1 says, "There will be a current in figure **A,** but not in figure **B**!"
Student 2 says, "There will be a current in figure **B,** but not in figure **A**!"
Student 3 says, "There will be a current in both figures!"
Student 4 says, "There will be no current in any of these figures!"

With whom do you <u>most closely</u> agree? Circle <u>only one</u> of 1, 2, 3 or 4.

1
2
3
4



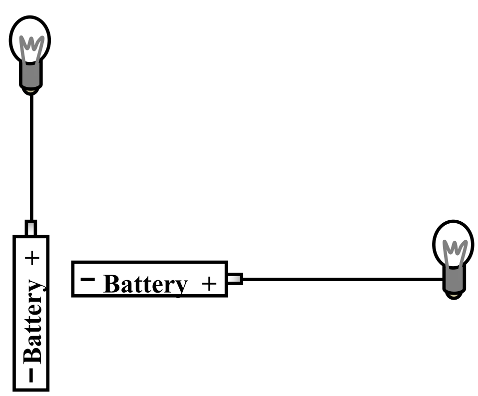
Explain the reasons for your choice in detail below.
………

Question 8
A student connects a light bulb to a battery as shown in figure **A**. Another student connects a light bulb to a battery as shown in figure **B**. The following discussion takes place among the students.

Student 1 says, "Charge will flow in figure **A,** but not in figure **B**!"
Student 2 says, "Charge will flow in figure **B,** but not in figure **A**!"
Student 3 says, "Charge will not flow in any of these figures!"
Student 4 says, "Charge will flow in both figures!"

With whom do you <u>most closely</u> agree? Circle <u>only one</u> of 1, 2, 3 or 4.

1
2
3
4



Explain the reasons for your choice in detail below.
……………..……

Figure 2.5: Aspects of Circuits Questionnaire

2.5 Main study

The main study was carried out in two phases on two separate, independent cohorts: UN1 and UN2, respectively. One of the main purposes of phase 1 was to explore the analysis framework, in particular, to develop a coding scheme based on the responses. This phase will be referred to hereafter as the Exploratory Main Study (EMS). Phase 2 of the main study was aimed at using the analysis framework that emerged from the EMS on an independent group of students (Confirmatory Main Study – CMS) and then to compare the two sets of findings (EMS and CMS) for consistency.

2.5.1 Samples used in the main study (UN1 and UN2)

UN1 consisted of a group of students from a university in the Western Cape, South Africa. These students were registered for a first year BSc degree. However, none of these students intended to major in physics, and therefore did not take the major physics course. The average age of the cohort was 18 years. All the students had done Physical Science in high school. Thus, they had encountered electricity, and in particular DC circuits, as part of their studies. All the students had passed their National Senior Certificate in Grade 12 with Physical Science as a subject, and this part of their curriculum had been included in the examination. The second group, UN2 cohort, was associated with a different university from that of UN1. These students were drawn from the same institution as cohort UNP (pilot) but were from a later group, i.e. while UNP were registered for first year in 2009, UN2 were registered for first year in 2012. For most of these students, English is a second or third language.

2.5.2 Administration of ACQ

The administration of the instrument was done according to the protocol defined in the pilot study. The ACQ was administered prior to instruction on electrical circuits. Students were not forewarned about the test; it was conducted as one of their random "surprise" tests. The author and a senior researcher were present during the test, before which the senior researcher had explained its purpose:

"This is a diagnostic test. You are from different schools, have been taught by different teachers, used different textbooks and different mediums of instruction." (In South Africa, a dual-medium system of instruction exists: English, a second language in the majority of schools; and Afrikaans. The cohort also consisted of other students who speak, among other languages, French.) *"We are planning to develop an appropriate curriculum for you. Therefore, we want to know what you know about simple DC electrical circuits. On the basis of this test, we will be developing the new curriculum. Your honesty is vital for the success of this project and your success in this course. For us to help you, you must help us by giving sincere answers to each of these eight questions. Please be legible in your explanations. After we have marked this test, if the answers are not clear to us or your answers are interesting - not necessarily right or wrong - we may call some students for personal interviews to get clarification of their answers and/or explanations."* (This was indicated to the students in an attempt to make them accountable for their responses.) *"Please read the questions carefully and answer all of them. Each question offers four optional answers, from which you have to choose one. You are also required to explain in detail, in the space provided, the reason for choosing that particular option. The questions may look the same for some of you, but answer all questions."*

Although no time limit was given, all students finished the test within half an hour.

Chapter 3
Data analysis

The sections below describe the different aspects of the data analysis in detail. Section 3.1 describes the analysis of the Exploratory Main Study (EMS) carried out on the UN1 cohort while Section 3.2 describes the analysis of the data collected for the Confirmatory Main Study (CMS) carried out on another independent cohort, UN2. The dataset from the EMS was analysed for both the Forced Choice Responses (FCR) and the Written Responses (WR). However, in the case of the CMS, the main purpose of the study was to establish whether the patterns of reasoning that emerged from the EMS were the same or different from the CMS. Therefore, only the WR are presented in detail in Section 3.2.

3.1 Exploratory Main Study (EMS) of UN1 Cohort

After the instrument was administered to the UN1 cohort according to the protocol (Section 2.5.2), the completed scripts were collected and organised for data entry. The questionnaire provided space for student numbers on each page, although most of the students only wrote their student numbers on the first page. For this reason, each answer set was kept together and the pages were not separated. Each answer set was examined and the number of correct answers was noted on the cover page. The answer sets were then grouped by number of correct responses, and the groups were ordered from "all correct" to "least correct". In order to enable student-by-student analysis, a unique "Respondent Identification Number" (RIN) was assigned and written on the front of each respondent set. The RIN was then copied to each page of the set. This was necessary to identify the scripts for future reference, particularly when the Written Responses (WR) were analysed. The Forced Choice Response (FCR) data and the Written Response (WR) data were then analysed as described in the following sections.

3.1.1 Analysis of Forced Choice Responses (FCR) for UN1 Cohort

As noted in the piloting phase, a spreadsheet was used to record the FCR responses. In this case, each row consisted of the RIN followed by eight numbers. Thus, the spreadsheet comprised 60 rows representing 60 students, and nine columns (RIN and eight questions). Since we have assigned different numbers (to avoid repetition bias) to each of the actual response, the spreadsheet of numbers required translation. For example, Table 3.1 shows the number assigned to the response "Neither circuit will activate" for each question.

Table 3.1: The choice "Neither circuit will activate" as assigned to each response number per question

Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
4	4	2	3	2	2	4	3

The data were thus transformed into a more descriptive mode using an alphabetic assignment as noted in Table 3.2 below, led to the spreadsheet summary of the data, as shown in Table 3.3.

Table 3.2: Response descriptions, alphabetic shorthand and corresponding colour code

Description of circuit action	Alphabetic assignment and colour codes
"Only **V**ertical circuit will activate"	**V**
"Only **H**orizontal circuit will activate"	**H**
"Both **V**ertical and **H**orizontal circuits will activate"	**VH**
"**N**either vertical nor horizontal circuit will activate"	**N**
Unanswered	**U**

Table 3.3 provides the translated dataset of Forced Choice Responses from all the students in the cohort UN1 in the order of the questions presented in the ACQ. Row-by-row entries provide the eight responses of a respondent as in the sequence of the ACQ. The last column provides the number of correct answers of each student. It is interesting to note that, while the first nine students answered all the questions correctly, the last ten students answered all the questions incorrectly; the middle two third selected different answer choices in different questions. The last row provides the total number (%) of students who answered each question separately and correctly. About half of the cohort answered each question correctly, except the questions relating to charge flow in a resistor and current in a heater. The lowest score was 38% in the question relating to charge flow in a resistor, and the highest score was 57% in the question relating to current in a heater. The possible reasons for these differences will be discussed in Chapter 5.

Table 3.3: FCR transformed to N, V, H and VH. Ref: Table 3.1 and Table 3.2 UN1 = 60

RIN	Light Bulb Light up	Heater Heat up	Resistor Current	Light Bulb Current	Resistor Charge flow	Heater Charge flow	Heater Current	Light Bulb Charge flow	# Correct Answers
101	N	N	N	N	N	N	N	N	8
102	N	N	N	N	N	N	N	N	8
103	N	N	N	N	N	N	N	N	8
104	N	N	N	N	N	N	N	N	8
105	N	N	N	N	N	N	N	N	8
106	N	N	N	N	N	N	N	N	8
107	N	N	N	N	N	N	N	N	8
108	N	N	N	N	N	N	N	N	8
109	N	N	N	N	N	N	N	N	8
110	N	N	N	N	N	VH	N	N	7
111	V	N	N	N	N	N	N	N	7
112	N	N	N	N	N	H	N	N	7
113	VH	N	N	N	N	N	N	VH	6
114	N	N	H	N	H	N	N	N	6
115	N	N	H	N	H	N	N	N	6
116	N	N	N	N	N	H	N	U	6
117	N	N	N	N	VH	N	N	V	6
118	N	N	N	N	N	VH	N	VH	6
119	VH	N	N	N	N	H	N	VH	5
120	N	V	VH	N	VH	N	N	N	5
121	N	N	VH	VH	N	N	VH	N	5
122	N	N	N	N	N	U	U	VH	5
123	N	N	V	V	V	N	N	N	5
124	V	N	H	N	V	N	N	N	5
125	VH	VH	VH	N	N	N	N	N	5
126	N	N	N	N	VH	VH	N	VH	5
127	N	V	N	N	VH	N	H	VH	4
128	VH	H	N	VH	N	N	H	N	4
129	VH	N	N	V	VH	N	V	VH	3
130	N	N	VH	H	VH	VH	VH	N	3
131	N	V	VH	VH	U	N	H	N	3
132	V	H	VH	V	VH	N	N	N	3
133	V	N	VH	V	VH	N	N	V	3
134	V	H	N	V	N	U	N	V	3
135	VH	VH	U	N	VH	VH	N	VH	2
136	V	N	VH	V	VH	H	N	V	2
137	V	U	H	V	VH	V	N	N	2
138	N	V	V	VH	VH	VH	N	VH	2
139	VH	VH	U	N	VH	V	N	VH	2
140	N	N	V	V	VH	H	H	V	2
141	N	N	VH	V	U	U	H	U	2
142	VH	VH	VH	N	VH	VH	VH	N	2
143	VH	VH	VH	N	VH	VH	VH	N	2
144	VH	VH	N	V	H	U	H	H	1
145	VH	VH	VH	VH	VH	VH	VH	N	1
146	V	VH	VH	V	VH	VH	N	VH	1
147	V	VH	VH	V	N	VH	VH	V	1
148	VH	H	VH	U	VH	VH	N	V	1
149	V	VH	N	V	VH	VH	V	V	1
150	VH	U	VH	VH	N	VH	VH	VH	1
151	VH	VH	VH	VH	VH	VH	VH	VH	0
152	V	VH	VH	V	VH	VH	VH	V	0
153	VH	H	VH	VH	VH	H	H	VH	0
154	V	VH	VH	V	VH	VH	VH	V	0
155	VH	H	VH	V	VH	H	H	V	0
156	VH	VH	VH	VH	VH	U	VH	VH	0
157	V	H	VH	VH	VH	H	H	VH	0
158	V	H	H	V	V	H	H	V	0
159	V	VH	VH	V	VH	VH	VH	V	0
160	V	H	VH	V	VH	H	VH	V	0
Correct Answers (%)	43 (26/60)	50 (30/60)	42 (25/60)	48 (29/60)	38 (23/60)	43 (26/60)	57 (34/60)	45 (27/60	

While the ACQ presented the questions in the order shown in Table 3.3, it is more convenient to group the questions along thematic lines. Thus, the questions were grouped together according to (i) circuit elements (three light bulb questions, three heater questions and two resistor questions; Figures 3.1 – 3.3); (ii) wording (light up, heat up, charge flow and current; Figures 3.4 – 3.6); and (iii) circuit orientations (vertical and horizontal; Figure 3.7). The first two graphs are presented as four sets of three colour bars, representing the four choices to the three questions. The third and fourth graphs are presented as four sets of two bars, and the last one is presented as eight sets of two bars. The sum of the numbers of each colour bar should total 100, however, since a few students did not answer all eight questions, the sum could be less than 100.

In order to discuss some of the features of the data, a series of bar graphs is presented. The aim of presenting these graphs is for qualitative analysis rather than for statistical analysis. Therefore, no error bars were determined from the frequencies of the choices in the graphs in Figures 3.1 – 3.7. The graphs are presented to illustrate the variation in student responses with respect to various fine-grained contextual changes in the questions.

3.1.1.1 Responses to Light bulb Circuits

Figure 3.1 illustrates the responses of students to the three questions relating to the light bulb (Figure 2.3, row 1). The four sets of three bars represent the four given choices in the three questions. The bars filled with yellow represent the "current" in the light bulb, the bars filled with red represent the "charge flow" in the light bulb, and the bars filled with blue represent the "light-up" of the light bulb. The first set represents the percentages of students who selected the correct answer choice. Approximately half of the students selected the correct choice (48% for the "current", 45% for the "charge flow" and 43% for the "light-up"). While the V(ertical) circuit was selected by a quarter of the students (32% for the "current", 23% for the "charge flow" and 28% for the "light-up"), the H(orizontal) circuit was selected by a negligible number of students (2% for the "current" and the "charge flow", and 0% for the "light-up"). Both V(ertical) and H(orizontal) circuits (VH) were selected by less than a quarter of the students (17% for the "current", 27% for the "charge flow" and 28% for the "light-up").

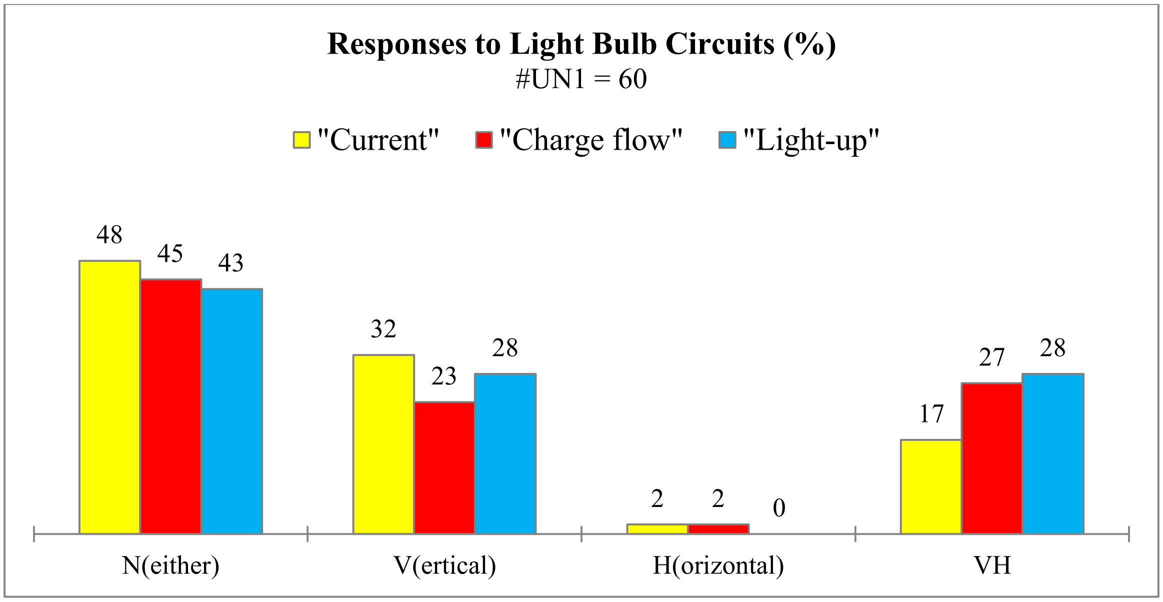


Figure 3.1: Students' responses to questions relating to light bulb. N = Neither circuit activates, V = Vertical circuit activates, H = Horizontal circuit activates, VH = both circuits activate. See text for details.

3.1.1.2 Responses to Heater Circuits

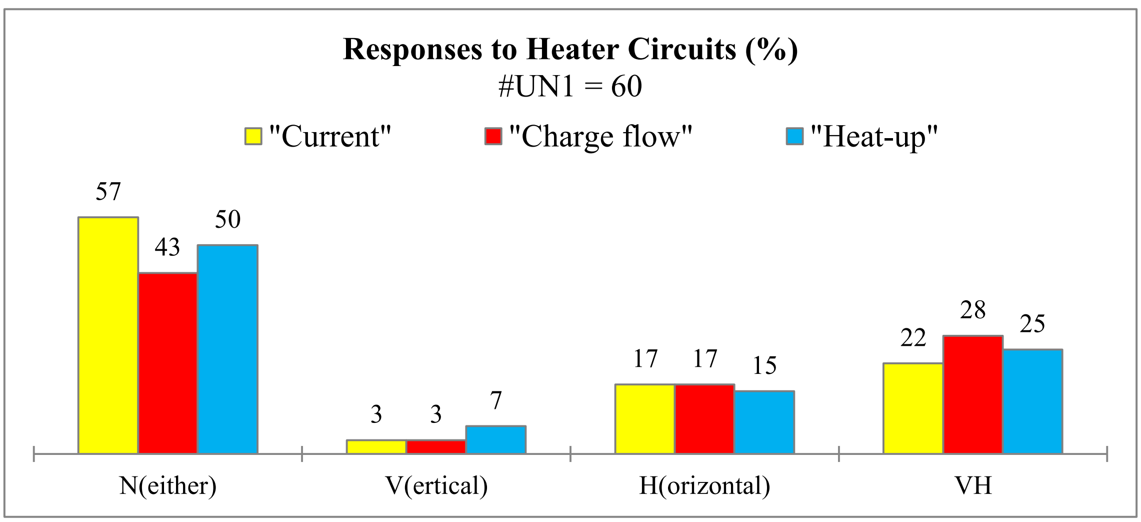


Figure 3.2: Students' responses to questions relating to heater. N = Neither circuit activates, V = Vertical circuit activates, H = Horizontal circuit activates, VH = both circuits activate. See text for details.

Figure 3.2 below illustrates the responses of the students to the three questions relating to the heater (Figure 2.3, row 3).

The four sets of three bars represent the four given choices in the three questions. The bars filled with yellow represent the "current" in the heater, the bars filled with red represent the "charge flow" in the heater, and the bars filled with blue represent the "heat-up" of the heater. The first set of bars represents the percentages of students who selected the correct choice. Approximately half of the students (57% for "current", 43% for "charge flow" and 50% for "heat-up") selected this choice. While the V(ertical) circuit was selected by 3% for "current" and "charge flow", 7% selected the same choice for "heat-up". The H(orizontal) circuit was selected by 17% for "current" and "charge flow", and 15% selected "heat-up". Both V(ertical) and H(orizontal) circuits (VH) were selected by a quarter of the students (22% for "current", 28% for "charge flow" and 25% for "heat-up").

3.1.1.3 Responses to Resistor Circuits

Figure 3.3 below illustrates the responses of the students to the two questions relating to the resistor (Figure 2.3, row 2).

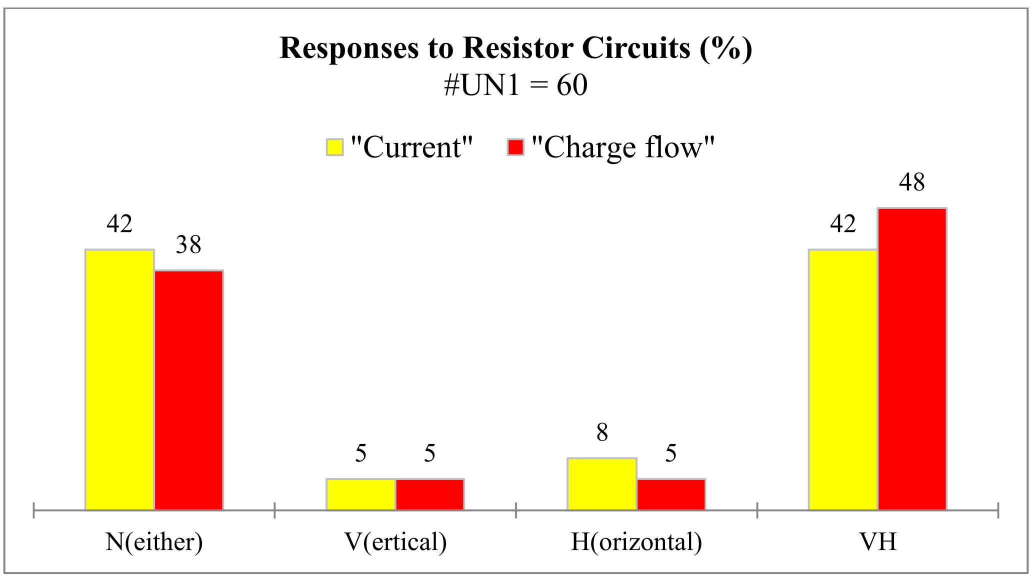


Figure 3.3: Students' responses to questions relating to resistor. N = Neither circuit activates, V = Vertical circuit activates, H = Horizontal circuit activates, VH = both circuits activate. See text for details.

The four sets of two bars represent the four given choices in the two questions. The bars filled with yellow represent the "current" in the resistor, and the bars filled with red represent the "charge flow" in the resistor. The first set represents the percentages of students who selected the correct answer, which constituted less than half (42% for "current", and 38% for "charge flow"). While the V(ertical) circuit was chosen by 5% for both "current" and "charge flow", the

H(orizontal) circuit was selected by 8% for “current” and 5% for “charge flow”. Both V(ertical) and H(orizontal) circuits (VH) were selected by 42% for “current” in the resistor and 48% for “charge flow” in the resistor.

3.1.1.4 Responses to Light-up and Heat-up

Figure 3.4 below illustrates the student responses to the two questions relating to the “light-up” of the light bulb and the “heat-up” of the heater (Figure 2.3, column 1). The four sets of two bars represent the four given choices in two questions. The bars filled with blue represent the “light-up” of the light bulb, and the bars filled with red represent the “heat-up” of the heater. The first

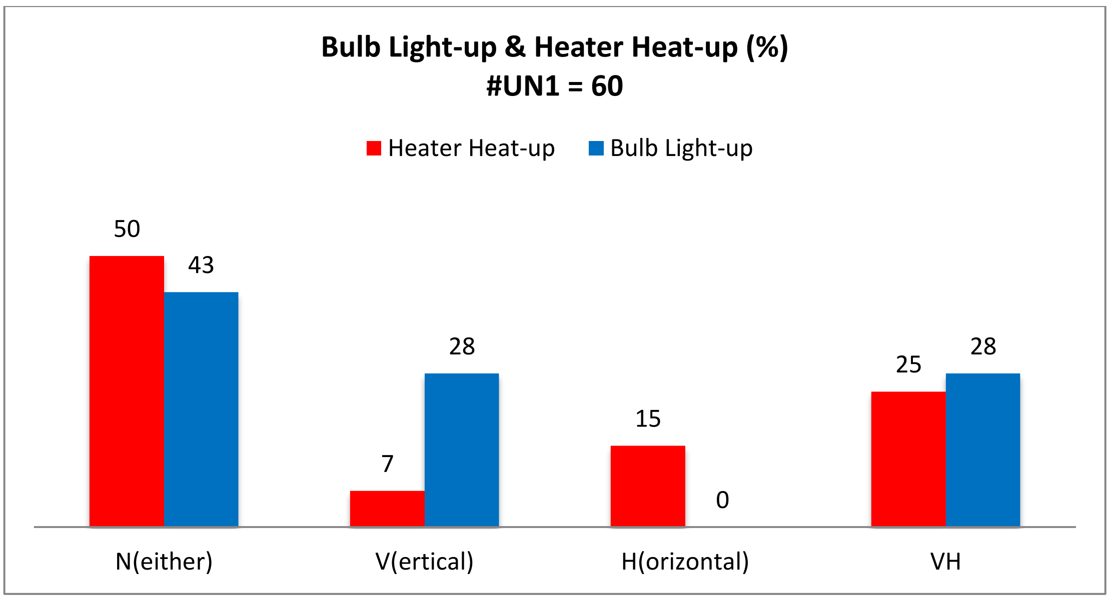


Figure 3.4: Students’ responses to questions relating to light bulb (blue) and heater (red). N = Neither circuit activates, V = Vertical circuit activates, H = Horizontal circuit activates, VH = both circuits activate. See text for details.

set of bars represents the percentages of students who selected the correct choice. The correct choice was chosen by less than half of the students (43% for the “light-up” of the light bulb, and 50% for the “heat-up” of the heater). While the V(ertical) circuit was chosen by 28% in the question relating to the light bulb, only 7% selected it in the question relating to the heater. While the H(orizontal) circuit was selected by 15% of the students in the question relating to the heater, none selected this choice in the question relating to the light bulb. However, both V(ertical) and H(orizontal) circuits (VH) were selected by approximately a quarter of the students (28% for the light bulb, and 25% for the heater).

3.1.1.5 Charge flow in Circuit Elements

Figure 3.5 below illustrates the responses of the students to the three questions relating to "charge flow" (Figure 2.3, column 2). The four sets of three bars represent the four given choices in three questions. The bars filled with yellow represent "charge flow in the light bulb", those filled with red represent "charge flow in the heater", and those filled with blue represent the "charge flow in the resistor". The first set of bars represents the percentages of students who selected the correct choice. Less than half of the cohort (45% for the light bulb, 43% for the heater and 38% for the resistor) selected the correct choice. While the V(ertical) circuit was selected by 23% in the question relating to the light bulb, only 3% selected this choice in the question relating to the heater, and 5% in the question relating to the resistor. The H(orizontal)

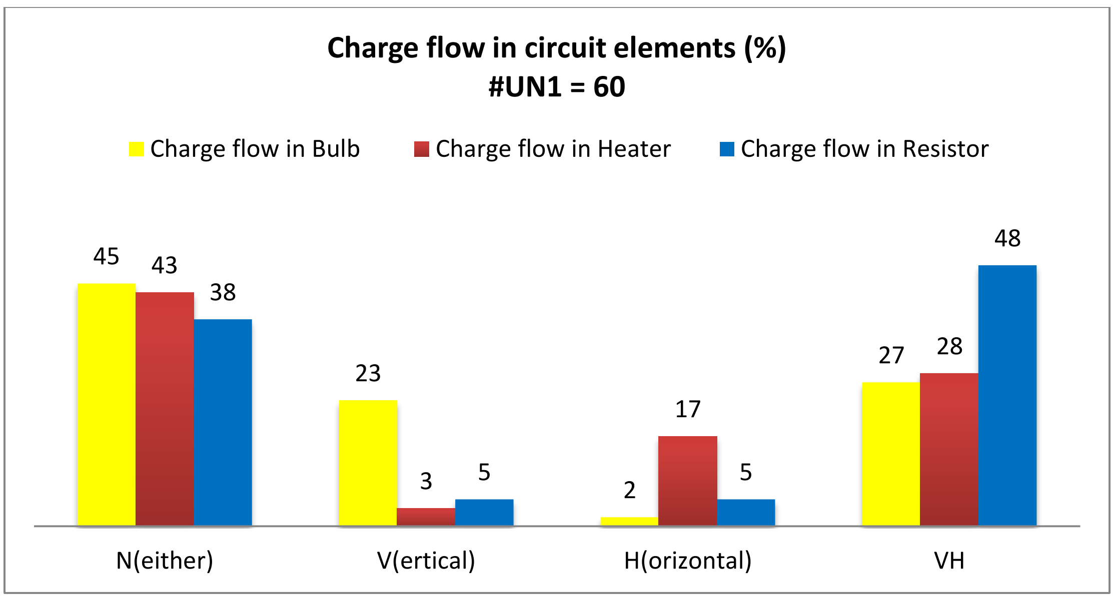


Figure 3.5: Students' responses to questions relating to "charge flow" in three elements. N = Neither circuit activates, V = Vertical circuit activates, H = Horizontal circuit activates, VH = both circuits activate (See text for details).

circuit was selected by 2% in the question relating to the light bulb, 17% in the question relating to the heater, and 5% in the question relating to the resistor. Both V(ertical) and H(orizontal) circuits (VH) were selected by 27% in the question relating to the light bulb, 28% in the question relating to the heater, and 48% in the question relating to the resistor.

3.1.1.6 Current in Circuit Elements

Figure 3.6 below illustrates the responses of the students to the three questions relating to "current" in three elements (Figure 2.3, column 3). The four sets of three bars represent the four given choices in three questions. The bars filled with yellow represent "current in the light bulb", those filled with red represent "current in the heater", and those filled with blue represent "current in the resistor". The first set represents the percentages of students who selected the correct choice. The correct choice was chosen by approximately half of the students (48% for the light bulb, 57% for the heater, and 42% for the resistor). The V(ertical) circuit was selected by 32% in the question relating to the light bulb, 3% in the question relating to the heater, and 5% in

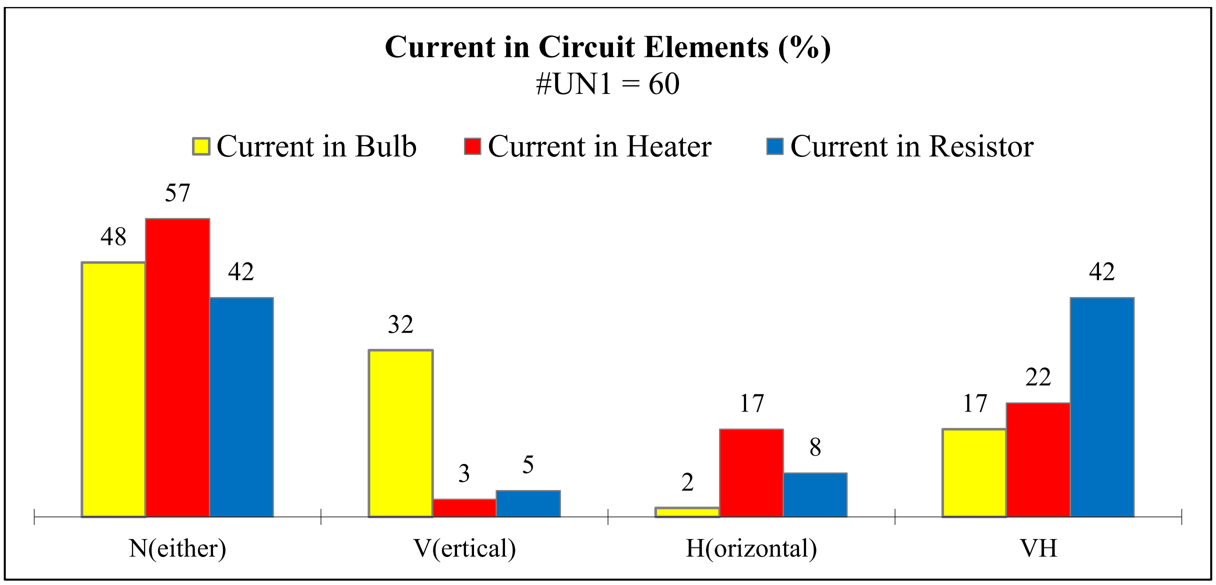


Figure 3.6: Students' responses to Q3, Q5 and Q8, relating to "current" in three elements. N = Neither circuit activate, V = Vertical circuit activates, H = Horizontal circuit activates, VH = both circuits activate. See text for details.

the question relating to the resistor. The H(orizontal) circuit was selected by 2% in the question relating to the light bulb, 17% in the question relating to the heater, and 8% in the case of the resistor. Both the V(ertical) and H(orizontal) circuits (VH) were selected by 17% in the question relating to the light bulb, 22% in the case of the heater, and 42% in the question relating to the resistor.

3.1.1.7 Responses to Circuit Orientations (Vertical and Horizontal)

Figure 3.7 below illustrates the responses of the students to the eight questions relating to the orientations of the circuits.

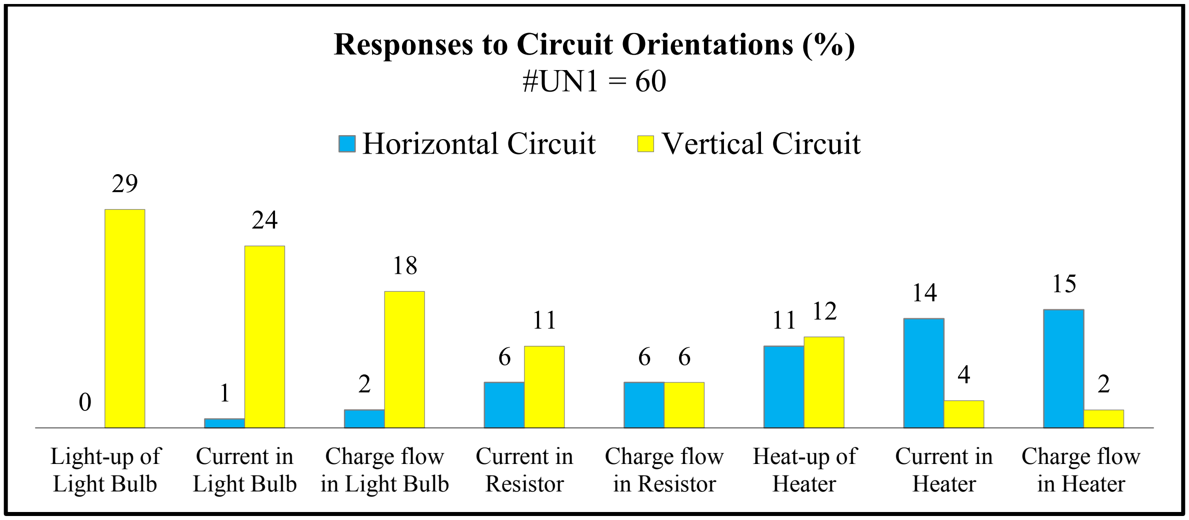


Figure 3.7: Students' responses to circuit orientations. See text for details.

The eight sets of two bars represent the eight questions and the two given choices ("only V(ertical)ly orientated circuit will activate" and "only H(orizontal)ly orientated circuit will activate"). The blue bars represent the percentages of students who selected the H(orizontal)ly orientated circuit, and the yellow bars represent the percentages of students who selected the V(ertical)ly orientated circuit. On the left of the graph, the yellow bars show that many students selected the V(ertical) circuit with regard to the light bulbs, while the blue bars on the right side indicate that many students chose the H(orizontal) circuit with regard to the heaters. The first three pairs (left side of the graph) represent the student responses to the questions relating to the light bulb (Figure 2.3, row 1). In these three cases, the majority opted for the V(ertical) circuit rather than the H(orizontal) counterpart, i.e. the majority of students selected the V(ertical) circuit for the light bulb related questions. In other words, the V(ertical)ly orientated light bulb circuit would activate, but the H(orizontal)ly orientated light bulb circuits would not.

The last three pairs of bars (right side of the graph) represent the questions relating to the heater (Figure 2.3, row 3). The blue bars indicate that the majority of students selected the H(orizontal) circuits with regard to the heater, i.e. the heater in the H(orizontal)ly orientated circuit would activate, whereas the heater in the V(ertical)ly orientated circuit would not.

The percentages of students who selected “charge flow in the resistor” were the same (6%) in both V(ertical)ly and H(orizontal)ly orientated circuits. The percentages of students who selected “current in the resistor” varied between 11% for the V(ertical) circuit and 6% for the H(orizontal) circuit. However, the percentages of students who selected “heat-up of the heater” for the V(ertical) and H(orizontal) circuits were almost the same; 11% for the H(orizontal) and 12% for the V(ertical) circuit.

3.1.1.8 Summary of FCR for UN1 Cohort

The figures in the previous sections are combined and presented in the graph in Figure 3.8. Eight sets of four bars, representing each question, are shown. The four bars in each set represent the four choices in each question. The solid grey-filled bars represent the percentages of students who selected the correct choice: “N(either) the vertical nor the horizontal circuit will activate”. The bars filled with yellow represent the choice: “only V(ertical) circuits will activate”. The bars filled with blue represent the choice: “only H(orizontal) circuits will activate”. Lastly, the bars filled with red represent the choice: “both V(ertical) and H(orizontal) circuits will activate”. Thus, if all students had answered all eight questions, the four bars (choices) in each colour would total 100%. Not all of the eight questions were, in fact, answered by all students, which led to a total of less than 100%.

On average, half the students selected the correct answer to each question separately; the other half was spread among the incorrect answers. Although half of the cohort opted to the correct choice separately in each question, these numbers were not the same in all questions. While more than half of the respondents chose the correct choice in the question relating to current in the heater, only more than a third selected the same choice to the question relating to charge flow in resistor. Similarly, a half selected both V(ertical) and H(orizontal) circuits to the question related to charge flow in the resistor, only a third selected this choice to the question related to charge flow in the light bulb. Furthermore, in the case of light up of the light bulb, a third selected the Vertical circuit but none selected the Horizontal circuit. Further, a third selected Vertical circuit to the question related to current in the light bulb, almost none selected Vertical circuit to the question related to current in the heater. Thus the students responded to various questions in accordance with the features in the question, including the students who answered correctly, separately, were not consistent with their choices.

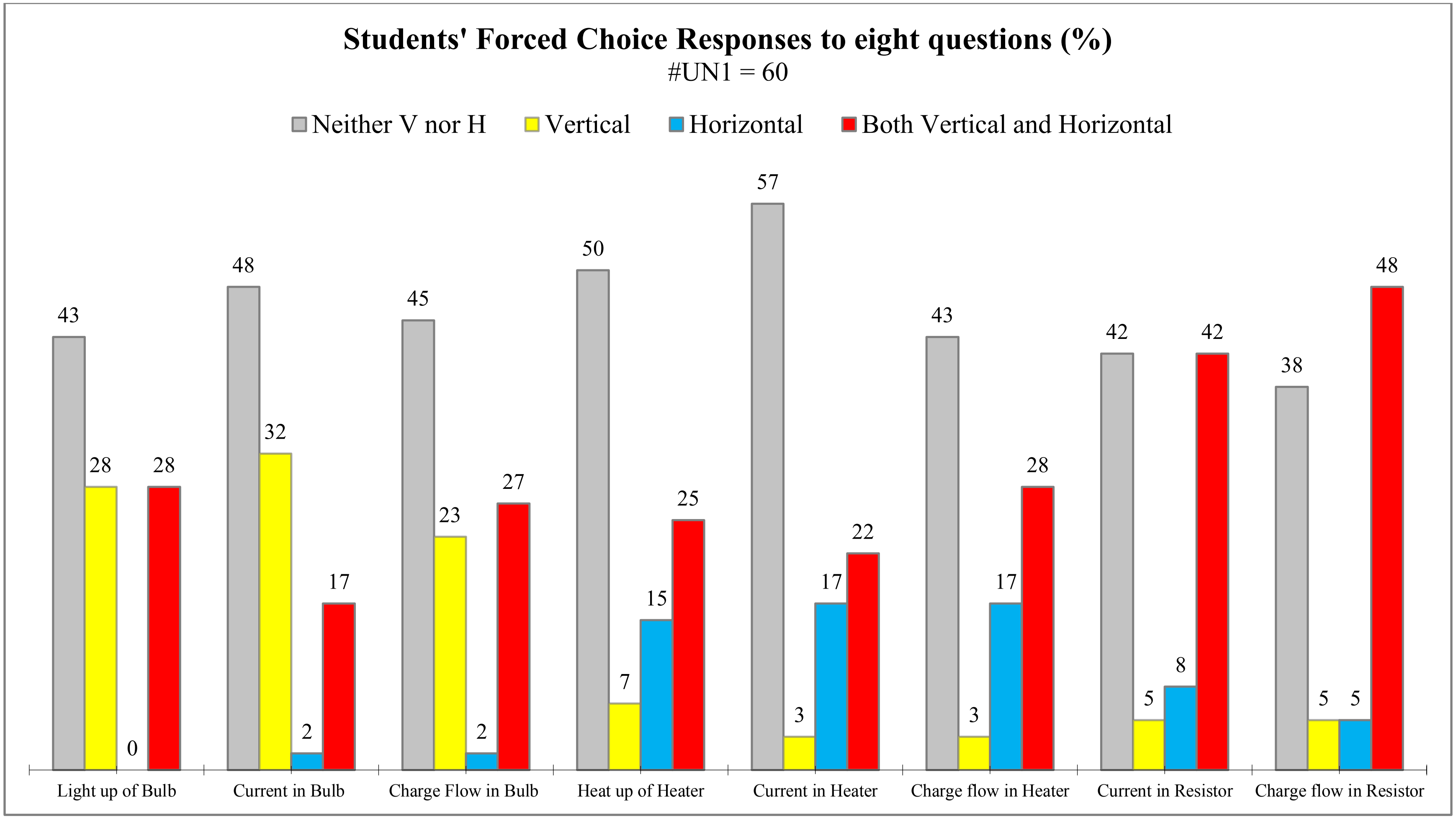


Figure 3.8: FCR responses (%) of the cohort UN1 in eight questions. Grey bars represent the correct responses to eight questions, yellow to that of the vertical circuits, blue to that of horizontal circuits and red to that of both vertical and horizontal circuits.

Table 3.4: Thematic ordering and colour-coding of FCR. Ref: Table 3.3 (UN1)

RIN	Light Bulb			Heater			Resistor	
	Light-up	Current	Charge flow	Heat-up	Current	Charge flow	Current	Charge flow
101	N	N	N	N	N	N	N	N
102	N	N	N	N	N	N	N	N
103	N	N	N	N	N	N	N	N
104	N	N	N	N	N	N	N	N
105	N	N	N	N	N	N	N	N
106	N	N	N	N	N	N	N	N
107	N	N	N	N	N	N	N	N
108	N	N	N	N	N	N	N	N
109	N	N	N	N	N	N	N	N
110	V	N	N	N	N	N	N	N
111	V	N	N	N	N	N	N	N
112	VH	N	VH	N	N	N	N	N
113	N	N	N	N	N	N	H	H
114	N	N	N	N	N	N	H	H
115	N	N	U	N	N	H	N	N
116	N	N	V	N	N	N	N	VH
117	N	N	N	N	N	H	N	N
118	N	N	VH	N	N	VH	N	N
119	VH	N	VH	N	N	H	N	N
120	N	N	N	V	N	N	VH	VH
121	N	VH	N	N	VH	N	VH	N
122	N	N	VH	N	U	U	N	N
123	N	V	N	N	N	N	V	V
124	V	N	N	N	N	N	H	V
125	VH	N	N	VH	N	N	VH	N
126	VH	V	VH	N	V	N	N	VH
127	N	H	N	N	VH	VH	VH	VH
128	N	N	VH	V	H	N	N	VH
129	VH	VH	N	H	H	N	N	N
130	V	V	N	H	N	N	VH	VH
131	V	V	V	N	N	N	VH	VH
132	N	N	VH	N	N	VH	N	VH
133	V	V	V	H	N	U	N	N
134	VH	N	VH	VH	N	VH	U	VH
135	N	VH	N	V	H	N	VH	U
136	N	VH	VH	V	N	VH	V	VH
137	VH	N	VH	VH	N	V	U	VH
138	N	V	V	N	H	H	V	VH
139	VH	V	H	VH	H	U	N	H
140	VH	VH	N	VH	VH	VH	VH	VH
141	V	V	VH	VH	N	VH	VH	VH
142	V	V	N	U	N	V	H	VH
143	VH	U	V	H	N	VH	VH	VH
144	V	V	V	N	N	H	VH	VH
145	VH	VH	VH	VH	VH	VH	VH	VH
146	V	V	V	VH	VH	VH	VH	VH
147	N	V	U	N	H	U	VH	U
148	V	V	V	VH	VH	VH	VH	N
149	VH	VH	VH	H	H	H	VH	VH
150	V	V	V	VH	VH	VH	VH	VH
151	VH	V	V	H	H	H	VH	VH
152	VH	V	V	VH	VH	VH	VH	VH
153	VH	VH	VH	VH	VH	VH	VH	VH
154	VH	VH	VH	VH	VH	U	VH	VH
155	V	V	V	VH	V	VH	VH	VH
156	V	VH	VH	H	H	H	VH	VH
157	V	V	V	H	H	H	H	V
158	V	V	V	VH	VH	VH	VH	VH
159	VH	VH	VH	U	VH	VH	VH	VH
160	V	V	V	H	VH	H	VH	VH

In anticipation of the analysis of the Written Responses (WR), the information in Table 3.4 is presented below. This information is grouped thematically in accordance with the series of graphs discussed earlier (Figures 3.1 – 3.7), as well as colour-coded to allow for WR coding to be superimposed on the FCR.

3.1.2 Analysis of Written Responses (WR) for UN1 Cohort

The analysis of the free writing responses elicited by the request for the students to provide detailed reasoning for their answer choices was performed using the approach suggested by Grounded Theory (Strauss & Corbin, 1990) and phenomenography (Marton, F. & Säljö, 1976).

The analysis proceeded as follows: each piece of writing was summarised in a short form that captured the essence of what the student had written without interpretation. This will be called a "Summarised Written Response" (SWR). This was necessary as the responses of the students were often difficult to read due to poor handwriting or use of language. However, one of the main reasons for this step was to separate what the student had written from the interpretation that would be made. It also simplified the analysis, at this stage, in that it was not necessary to return to the actual student scripts during the iterative process of developing the coding scheme. As noted in the follow-up study (CMS), once the coding had been developed, this step was not felt to be necessary and the codes were applied directly to the original responses in UN2.

This exercise was carried out by this researcher after which a random sample of ten students per question was selected, and the SWR was compared to the original student writing by the researcher's supervisor. In all cases, it was judged that the SWR correctly reflected the actual student writing. Some examples of the original student writings and the Summarised Writing Responses are illustrated below:

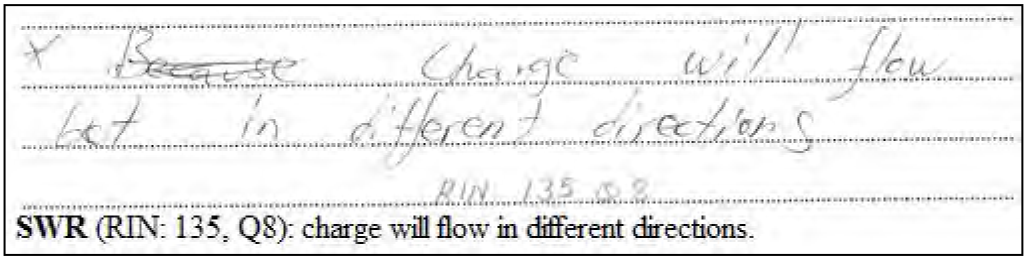

x ~~Because~~ Charge will flow but in different directions
RIN 135 Q 8
SWR (RIN: 135, Q8): charge will flow in different directions.

Figure 2.9a: Charge will flow in different directions

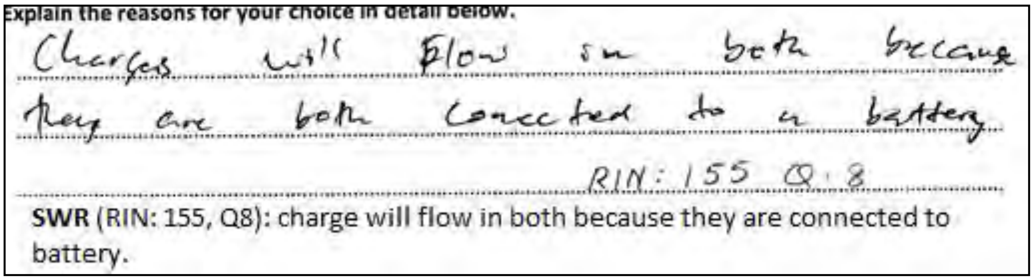

Explain the reasons for your choice in detail below.
Charges will flow in both because they are both connected to a battery
RIN: 155 Q: 8
SWR (RIN: 155, Q8): charge will flow in both because they are connected to battery.

Figure 3.9b: Charge will flow in both circuits because they are connected

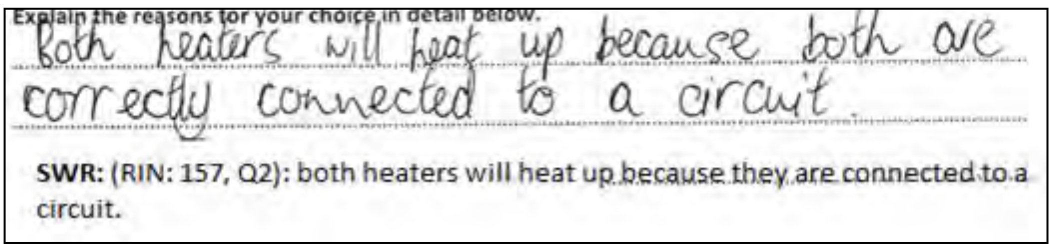

Explain the reasons for your choice in detail below.
Both heaters will heat up because both are correctly connected to a circuit.
SWR: (RIN: 157, Q2): both heaters will heat up because they are connected to a circuit.

Figure 3.9c: Both heaters are connected to circuits

The examples shown above (Figures 3.9a, b and c) are clear, short and well-written explanations. Figure 3.9d below shows a very long, but clearly explained sample with a unique idea. This pre-step also made it easier to identify the idea or ideas that were being expressed, and helped to avoid conflating the actual writing with the inferences.

None of them will heat up, because in A only the negetive side of battery is connected to the battery and in B only the positive side is connected. The idea/sugge I can give to this, is to combine the two sketchies and use one battery and one heat for both wires then the system will heat up.

SWR: (RIN: 136, Q2): none of them will heat up, because in A only -ve side of battery is connected and in B only +ve side is conneceted.

Figure 3.9d: Only one terminal is connected

There will be a current in bulb A but not in B because as I said in the just page I don't think bulb is connect if there is a battery that means there is a current because they are directly proportionat to each other.

SWR: (RIN: 149, Q1): there will be a current in bulb A, but not in B, ~~because bulb~~ is not connected; if there is a battery, there is current, because they are directly proportional to each other.

Figure 3.9e: Directly proportional

Explain the reasons for your choice in detail below.

Both heaters will heat up, They are both connected in a right way "positive and negative", I like charge attract each other unlike charge repel each other, in this case they match

SWR (RIN: 146, Q2): both heaters will heat up, they are not connected in right way. "+ve and -ve". Like charges attract each other, unlike charges repel each other.

Figure 3.9f: Like charges attract and unlike charges repel

The figures 3.9a-f illustrate the original student writing that was compared with the SWRs. Figure 3.9e and 3.9f are examples of long writing with more than one idea, which can be difficult to comprehend.

Appendix 8 shows the full response set of UN1 with FCR and WR after each written response had been formulated as an SWR. Each row represents the response of each student with FCR followed by the respective SWR for the eight questions, starting with the RIN in the first column.

The next step was to read each response (SWR) and to infer the intended meaning of each response. The interpretation of the writing was carried out by this researcher, and a sample of 20 was compared by the supervisor for Question 1. As noted, in some cases, the nature of the response made it easy to infer the idea being expressed while, in other cases, this was not easy either because the writing was of such a nature that it was difficult to extract the idea or because more than one idea was expressed. In order to facilitate the analysis, it was decided to allocate more than one idea code to a single response. It is interesting to note that the inter-rater agreement was only about 70% when only one code was allocated, but rose to over 90% when more than one code was used. The initial scheme was then applied to the other questions and the scheme was modified where required. A number of iterative cycles were required to arrive at an appropriate level of description. For example, in the first pass of the exercise, a more fine-grained scheme was developed. However, this did not turn out to be amenable to simple interpretation and was used to inform the next cycle. The results of the complete exercise, that included several cycles of engagement and interpretation, are summarised below.

It is clear that (from Appendix 8), at this level, there were a large number of different ideas (around 100) that were used in the 480 entries. However, many of these ideas could be grouped together, forming larger categories of 12-14 ideas (Appendix 11). Upon further grouping, six categories with subcategories emerged (Table 3.5) and are listed with examples in the following sections.

3.1.2.1 Description of Categories that emerged

Six main categories designated A, B, C, D, E and F emerged from the analysis described above. A brief description of each category (and its subcategories) is presented below. The last category U is for the ideas that could not be comprehended.

Category A: *Completeness or "closed-ness"* argument

The main idea in this category is that a circuit needs to be "complete" or "closed" in order to function. This category was easily identified as the words "complete" or "closed" appear explicitly in the SWRs. Five subcategories were introduced in order to code for further elaboration of this idea. These are noted below together with illustrative examples from the SWRs. It should be noted that the SWRs are quoted in full and that more than one code could be attached as indicated.

A10: No further elaboration

A30: Polarity mentioned

A40: Current mentioned

Examples of SWRs with [code(s) assigned with question number], followed by (RIN):

1. "must be complete circuit" [A10, Q2] (101)
2. "both terminals +ve and –ve connected to close circuit" [A30, Q1] (103)
3. "no complete circuit, there is no complete current flow" [A40, Q1] (101)

Category B: *Two-terminal* argument

The main idea in this category is that two terminals are needed in order for the circuit to function. This category was easily identified as the words "both ends" or "only one side" can be seen explicitly in the SWRs. Five subcategories were introduced in order to code for the reasoning behind this idea. These are noted below together with illustrative examples from the SWRs. It should be noted that the SWRs are quoted in full and that more than one code could be attached as indicated.

B10: No further elaboration

B30: Polarity mentioned

B40: Current mentioned

B50: Charge mentioned

B60: Energy or power or electricity mentioned

Examples of SWRs with [code(s) assigned with question number], followed by (RIN):

1. "only one side of battery connected" [B10, Q1- Q8] (108)
2. "both bulbs are connected to the +ve side of battery" [B30, Q1] (108)
3. "both terminals should be connected to heater, because current flows from –ve to +ve" [B40, Q2] (105)
4. "battery's end is connected to heater's end. There are +ve and –ve charges" [B50, Q6] (142)
5. "no energy transfer, only one pole connected" [B60, Q1] (113)

Category C: *Connected to a specified element* argument

The main idea in this category is that a circuit needs to be connected correctly to an element in order to function. This category was easily identified as the words "no proper connection" or "properly connected" appeared explicitly in the SWRs. Eleven subcategories were introduced in order to code for the reasoning behind this idea. These are noted below together with illustrative examples from the SWRs. It should be noted that the SWRs are quoted in full and that more than one code could be attached as indicated.

C10: No further elaboration

C21: Bottom of bulb mentioned

C22: Side of bulb mentioned

C23: Battery mentioned

C30: Polarity mentioned

C32: Polarity of bulb mentioned

C40: Current mentioned

C50: Charge flow mentioned

C60: Power or energy or electricity mentioned

C70: Insulator mentioned

Examples of SWRs with [code(s) assigned with question number] followed by (RIN):

1. "no proper connection between bulb and battery" [C10, Q1] (114)
2. "bulb connection is on the bottom not side, the pins of the holder are at the bottom" [C21, Q1] (155)

3. “connected to the centre of the bulb” [C22, Q1] (156)
4. “connected to the battery” [C23, Q1] (111)
5. “connected in charge (+ve and –ve)” [C30, Q1] (111)
6. “negative of bulb not connected to +ve of battery” [C31, Q1] (136)
7. “positive of battery is connected to –ve of bulb” [C32, Q1] (136)
8. “negative charge weaker than +ve charge, B may need –ve charge” [C50, Q2] (126)
9. “connected to covering of copper connection” [C70, Q1] (144)

Category D: *Absence of an element* argument

The main idea in this category is that a circuit requires elements (resistor, switch etc.) in order to activate. This category was easily identified as the words “no resistor” can be seen explicitly in the SWRs. Six subcategories were introduced in order to code for the reasoning behind this idea. These are noted below together with illustrative examples from the SWRs. It should be noted that the SWRs are quoted in full and that more than one code could be attached as indicated.

D71: Switch mentioned

D72: Resistor mentioned

D73: Ammeter mentioned

D75: Battery mentioned

Examples of SWRs with [code(s) assigned with question number] followed by (RIN):

1. “there is no switch” [D71, Q5] (146)
2. “there is no resistance” [D72, Q6, Q5] (122, 132)
3. “no device like ampere and resistor to assess the flow of energy” [D73, Q7] (124)
4. “if battery is functioning” [D75, Q1] (132)
5. “no conductor” [D76, Q4] (144)

Category E: *Current/charge/energy/electricity* argument

The main idea in this category is that a circuit needs to have a flow of charge or current or electricity in order to function. This category was easily identified as the words “no current transfer” or “energy transfer” can be seen explicitly in the SWRs. Three subcategories were introduced in order to code for the reasoning behind this idea. These are noted below together with illustrative examples from the SWRs. It should be noted that the SWRs are quoted in full and that more than one code could be attached as indicated.

E40: Current mentioned

E50: Charge mentioned

E60: Energy or power or electricity mentioned

Examples of SWRs with [code(s) assigned with question number] followed by (RIN):

1. “no current transfer” [E40, Q4] (123)
2. “charge flow with different magnitude” [E50, Q5] (135)
3. “they receive same amount of energy” [E60, Q1] (135)

Category F: *Series or parallel* argument

The main idea in this category is that a circuit is connected in series or parallel in order to function. This category was easily identified by the words used explicitly in the SWRs. Three subcategories were introduced in order to code for the reasoning behind this idea. These are noted below together with illustrative examples from the SWRs. It should be noted that the SWRs are quoted in full and that more than one code could be attached as indicated.

F80: Parallel and series mentioned

F81: Parallel mentioned

F82: Series mentioned

Examples of SWRs with [code(s) assigned with question number] followed by (RIN):

1. “They have to be placed in connection to each other in parallel or in series form” [F80, Q4] (112)
2. “They have to be connected in parallel to each other” [F81, Q3] (138)
3. “Current is more in B, because it is in series” [F82, Q5] (153)

Category U: Uncodeable – these are the ideas which could not be comprehended.

Table 3.5 summarises the final coding scheme that was developed over a number of cycles of passing through portions of the data.

Table 3.5: Categories and codes based on SWRs

Code	Category A Closed/open/complete/incomplete	Code	Category B Two terminals need to be involved
A10	No further elaboration	B10	No further elaboration
A30	Polarity	B30	Polarity
A40	Current	B40	Current
A50	Charge flow	B50	Charge flow
A60	Power/energy/electricity	B60	Power/energy/electricity
Code	Category C (In)correctly/(not)connected	Code	Category D Element present [absent]: activated [inactivated]
C10	No further elaboration	D10	No further elaboration
C21	Bottom of bulb	D71	Switch
C22	Side of bulb	D72	Resistor
C23	Battery/source of energy	D73	Ammeter
C30	Polarity	D75	Battery
C31	Polarity of battery	D76	Conductor
C32	Polarity of bulb		
C40	Current		
C50	Charge flow		
C60	Power/energy/electricity		
C70	Insulator/conductor		
C71	Vertical/horizontal		
Code	Category E Flow of …	Code	Category F General
E40	Current	F80	Parallel and series considerations
E50	Charge	F81	Parallel
E60	Energy/power/electricity	F82	Series
Code	Category U		
U00	No reason given/not attempted		
U10	Reason incomprehensible		

3.1.2.2 Results of applying coding scheme to the full set of UN1 responses

The coding scheme from Table 3.5 was applied to the full set of UN1 responses and resulted in Table 3.6. Thus, each respondent was assigned one or more code(s) per response with the total number of codes assigned being 487. It is interesting to note that only seven students had more than one code assigned and, in no cases, was it found necessary to assign more than two codes.

A more detailed analysis, in terms of the frequencies of code, is shown in Table 3.7. The highest frequency (70 responses) was for C10, which is associated with expressing the idea

"…connected to (not)…" without any further explanation. This category could be interpreted as correct reasoning, i.e. it is not connected properly, as a few students reasoned with the correct choice, while the meaning of proper connection is not clear at this stage. (The personal interview will shed more light on this category.)

Table 3.6: Category Codes assigned using Table 3.5 (UN1)

RIN	Light Bulb Light-up	Heater Heat-up	Resistor Current	Light Bulb Current	Resistor Charge flow	Heater Charge flow	Heater Current	Light Bulb Charge flow
101	A10	A10	A10	A10	A30	A10	A10	A10
102	B30, C32	B30	B30	B30	B30	B30	B30	B30
103	A30	B10	A30	A30	B10	B10	B10	B10
104	B30	B30	B30	B30	B30	B30	B30	B30
105	A10	A10	A10	A10	A10	A10	A10	A10
106	B10	B10	A10	A10	A10	A10	A10	A10
107	A10	A10	A10	A10	A10	A10	A10	A10
108	B30	B10	B10	B10	B10	B10	B10	B10
109	B10	A10	A30	A30	A10	A10	A10	A10
110	C21	B30	B30	B30	C10	C10	C10	C10
111	C23	E40	A10	A10	A10	E40	C10	C23
112	B30	B30	F81	B30	F81	B30	C10	C10
113	B60	B60	B10	B60	U10	B10	E60	E60
114	C10	C10	D72	C10	D72	C10	C10	U10
115	B30	B10	B30	B10	C10	B30	C50	C50
116	B30	B10	B10	B30	U10	E50	B30	U10
117	A30	B30	B30	E40	C10	B30	B30	C10
118	E60	B30	A10	U10	A10	A10	A10	A10
119	B30	U10	C23	A30	F40	F40	B10	A10
120	B30	B10	D72	C10	B10	B30	C23	U10
121	B30	A30	A10	A10	A10	U10	U00	A10
122	C30	C23	F81	E81	C31	D72	C23	F81,D72
123	C23	C23	C23	E40	E50	E60	E60	E60
124	C10	U10	E60	C22	C23	E60	D73	E60
125	B30	B30	E40	C32	C32	E40	E40	E40
126	B30	C50	C10	C10	C50	E50	C50	C10
127	E60	C31	E40	E60	E40	C31	C31	C23
128	E60	C31	C40	C10	E40	C10	C10	C30
129	U00	C23	C10	C10	C10	C10	C10	C10
130	A30	A30	A10	A10	C30	C30	A10	C30
131	C10	U10	U10	U10	U10	U10	C10	U10
132	D75	D75	U10	D72	D72	D75	D72	D75
133	B10	E60	F80	U10	E50	E50	C30	E50
134	B10	C23	E40	E40	E40	C23	C23	U00
135	E60	U10	U10	C10	E50	U10	C10	E50
136	B10,C32	B10	F82,E40	C32	F80	E50	E50	C10
137	B10	B10	U10	C10	B10	B10	B10	B10
138	C10	C23	F81	F81	C80	U10	C23	U10
139	D75	C23	U10	U10	A10	E40	U10	D75
140	C23	C70	U10	C22	U10	C10	U10	C10
141	C32	E60	C10	C10	C10	E60	E40	U10
142	C21	B10	C10	C21	E60	B30	B10	C22
143	U10	U10	U10	U10	U10	U10	U10	U10
144	C70	F80	F80	D76	E50	E50	C10	C70
145	A10	B10	E40	C10	E50	E50	E40	E50
146	E50	E50	U10	E50	D71	U10	U10	U10
147	E40	C31	C31	D72	C23	C10	C10	C31
148	C22	C23	U10	C22	C23	C23	C23	C23
149	C23	C10	U10	U10	C23	C23	C23	C10
150	F80	C60	F80	C22	F80	C10	C10	C22
151	U10	C23	C23	C23	C23	U10	U10	U20
152	C23	C23	C23	C23	U10	U10	U10	U10
153	F80	F80	F81	F81	F82	U10	C10	F81
154	C21	C10	U10	C10	U10	E40	C10	C10
155	C21	C10	F80	C23	C23	C10	C10	C23
156	C22	C31	C21	C21	U10	C23	U00	C10
157	C21	C10	U10	C21	U10	C10	C10	C21
158	D22	F81	E40	U10	U10	D72	D72	D72
159	C10	C23	C23	E40	E40	C10	C10	C10
160	C23,C60	C23,C60	C23,C60	C10	C10	C10	C60	C10

Table 3.7: Frequencies of Category Codes used in Table 3.6 (UN1)

Category Codes	Bulb Light-up	Heater Heat-up	Resistor Current	Bulb Current	Resistor Charge flow	Heater Charge flow	Heater Current	Bulb Charge flow	Total
A10	4	4	8	7	7	6	7	8	51
A30	3	2	2	3	1	0	0	0	11
B10	4	10	3	2	4	4	5	3	35
B30	10	7	5	5	2	7	4	2	42
B60	1	1	0	1	0	0	0	0	3
C10	5	5	4	11	6	11	16	12	70
C21	5	0	1	3	0	0	0	1	10
C22	3	0	0	4	0	0	0	2	9
C23	5	10	5	3	6	4	6	4	43
C30	1	0	0	0	1	1	1	2	6
C31	0	4	1	0	1	1	1	1	9
C32	1	0	0	2	1	0	0	0	4
C40	0	0	1	0	0	0	0	0	1
C50	0	1	0	0	1	0	2	1	5
C60	0	1	0	0	0	0	1	0	2
C70	1	1	0	0	0	0	0	1	3
D71	0	0	0	0	1	0	0	0	1
D72	0	0	2	2	2	2	2	1	11
D73	0	0	0	0	0	0	1	0	1
D75	2	1	0	0	0	1	0	2	6
D76	0	0	0	1	0	0	0	0	1
E40	1	1	5	4	4	4	3	1	23
E50	1	1	0	1	5	6	1	3	18
E60	4	2	1	1	1	3	2	3	17
F80	2	2	4	0	2	0	0	0	10
F81	0	1	4	2	1	0	0	0	8
F82	0	0	0	0	1	0	0	0	1
U00	1	0	0	0	0	0	2	1	4
U10	2	5	12	7	11	9	6	9	61

The second largest set of responses was A10 in which the idea of “closed/open/complete circuit” is expressed. The third largest category was C23, which expressed the idea: “connected to battery”. The fourth largest frequency was for B30: “two terminals with polarity”, and the fifth largest frequency was for B10: “two terminals” without mentioning polarity. It should be noted that, while both A10 and B10 are described as being without further elaboration, it could be argued that no further explanation is, in fact, necessary. However, C10 and C23 are somewhat different in that the nature of the "incorrectness" is not specified. Grouping the subcategories into their larger parent categories shows that categories C, B and A account for about two thirds of the responses (Table 3.8). It is of some methodological concern that 13% of the responses could not be coded, either because they were not understandable or because they were blank.

Table 3.8: Parent Categories and number of responses to each question (UN1)

Category	Bulb Light-up	Heater Heat-up	Resistor Current	Bulb Current	Resistor Charge flow	Heater Charge flow	Heater Current	Bulb Charge flow	Total	%
A	7	6	10	10	8	6	7	8	62	13
B	15	18	8	8	6	11	9	5	80	16
C	21	22	12	23	16	17	27	24	162	33
D	2	1	2	3	3	3	3	3	20	4
E	6	4	6	6	10	13	6	7	58	12
F	2	3	8	2	5	0	0	0	20	4
U	3	5	12	7	11	9	8	10	65	13

3.1.2.3 Analysis by combining Forced Choice Responses with Written Responses (UN1)

Each entry in Table 3.3 was colour-coded (using the colour codes from Table 3.2) for further analysis: the choices N, V, H and VH are colour-coded as grey, yellow, blue and red respectively, as presented in Table 3.4. The colour coding made it easier to view at a glance the degree of variations of student responses of the cohort in general and each student from each row.

The colour-coded FCR from Table 3.4 was combined with the assigned codes of Table 3.6, and then the responses are grouped in the order of the circuit elements (light bulb, heater and resistor) resulted in Table 3.9. The colour coding made it possible to add a last column with the number of reasons used by each student. This process made it easier to see the pattern of the dataset as a whole.

The first nine grey rows represent the nine students who answered all the questions correctly, while the last ten rows represent the students who answered all the questions incorrectly. The

Table 3.9: The FCRs and Category Codes rearranged in the order of Circuit Elements (UN1)

RIN	Light Bulb			Heater			Resistor		#reasons/student
	Light up	Current	Charge flow	Heat up	Current	Charge flow	Current	Charge flow	
101	A10	A10	A10	A10	A10	A10	A10	A30	1
102	B30, C32	B30	B30	B30	B30	B30	B30	B30	1
103	B30	B30	B10	B10	B10	B10	B30	B10	1
104	B30	B30	B30	B30	B30	B30	B30	B30	1
105	A10	A10	A10	A10	A10	A10	A10	A10	1
106	A10	A10	A10	B10	A10	A10	A10	A10	1
107	A10	A10	A10	A10	A10	A10	A10	A10	1
108	B30	B10	B10	B10	B10	B10	B10	B10	1
109	A10	A30	A10	A10	A10	A10	A30	A10	1
110	C22	B30	C10	B30	C10	C10	B30	C10	2
111	C21	A10	C23	E40	C10	E40	A10	A10	2
112	C23	B30	C10	B30	C10	B30	F81	F81	3
113	B60	B60	E60	B60	E60	B10	B10	U10	2
114	C10	C10	U10	C10	C10	C10	D72	D72	3
115	B30	B10	C50	B10	C50	B30	B30	C10	2
116	B30	B30	U10	B10	B30	E50	B10	U10	3
117	A30	E40	C10	B30	B30	B30	B30	C10	4
118	E60	U10	A10	B30	A10	A10	A10	A10	4
119	B30	A30	A10	U10	B10	F40	C23	F40	5
120	B30	C10	U10	B10	C23	B30	D72	B10	5
121	B30	A10	A10	A30	U00	U10	A10	A10	3
122	C30	E81	F81,D72	C23	C23	D72	F81	C31	4
123	C23	E40	E60	C23	E60	E60	C23	E50	2
124	C10	C22	E60	U10	D73	E60	E60	C23	3
125	B30	C32	E40	B30	E40	E40	E40	C32	3
126	B30	C10	C10	C50	C50	E50	C10	C50	3
127	E60	E60	C23	C31	C31	C31	E40	E40	2
128	E60	C10	C30	C31	C10	C10	C40	E40	2
129	U00	C10	C10	C23	C10	C10	C10	C10	1
130	A30	A10	C30	A30	A10	C30	A10	C30	2
131	C10	U10	U10	U10	C10	U10	U10	U10	2
132	D75	D72	D75	D75	D72	D75	U10	D72	2
133	B10	U10	E50	E60	C30	E50	F80	E50	5
134	B10	E40	U00	C23	C23	C23	E40	E40	3
135	E60	C10	E50	U10	C10	U10	U10	E50	3
136	B10,C32	C32	C10	B10	E50	E50	F82,E40	F80	3
137	B10	C10	B10	B10	B10	B10	U10	B10	3
138	C10	F81	U10	C23	C23	U10	F81	C80	3
139	D75	U10	D75	C23	U10	E40	U10	A10	4
140	C23	C22	C10	C70	U10	C10	U10	U10	2
141	C32	C10	U10	E60	E40	E60	C10	C10	3
142	C21	C21	C22	B10	B10	B30	C10	E60	3
143	U10	U10	U10	U10	U10	U10	U10	U10	1
144	C70	D76	C70	F80	C10	E50	F80	E50	4
145	A10	C10	E50	B10	E40	E50	E40	E50	4
146	E50	E50	U10	E50	U10	U10	U10	D71	2
147	E40	D72	C31	C31	C10	C10	C31	C23	3
148	C22	C22	C23	C23	C23	C23	U10	C23	2
149	C23	U10	C10	C10	C23	C23	U10	C23	2
150	F80	C22	C22	C60	C10	C10	F80	F80	2
151	U10	C23	U20	C23	U10	U10	C23	C23	2
152	C23	C23	U10	C23	U10	U10	C23	U10	2
153	F80	F81	F81	F80	C10	U10	F81	F82	3
154	C21	C10	C10	C10	C10	E40	U10	U10	3
155	C21	C23	C23	C10	C10	C10	F80	C23	2
156	C22	C21	C10	C31	U00	C23	C21	U10	2
157	C21	C21	C21	C10	C10	C10	U10	U10	2
158	D22	U10	D72	F81	D72	D72	E40	U10	3
159	C10	E40	C10	C23	C10	C10	C23	E40	2
160	C23,C60	C10	C10	C23,C60	C60	C10	C23,C60	C10	1

middle two thirds provided different answers to different questions. The white cells represent the absence of a response. While 11 students used only one reason to answer all the questions, others used up to four reasons. The first nine students, who used only one reason to answer all the questions, used either Category A or Category B to explain their choice in the FCR. However, two students (RIN 129 and 160) who used only one reason category C, they did not select the same answer choice in all questions (shown by different colour codes). Although these two students used the same category reason C, RIN 129 chose a few correct answer choices while RIN 169 chose none.

It is interesting to note that the three colours are concentrated in different columns i.e. yellow is more prevalent in the first three columns, blue is more prevalent in the following three columns and red is more prevalent in the last two columns. The inference from these observations is that, while more students opted for the V(ertical) circuit activation for light bulbs, the H(orizontal) circuit activation was chosen for heaters. However, both V(ertical) and H(orizontal) circuit activation (VH) was opted for with regard to the resistor circuits. A more detailed discussion will be presented in Chapter 5.

Table 3.9a illustrates the four sub-tables representing the four choices. As noted before (Table 3.2), the grey shaded cells represent the correct choice: “Neither circuits will activate”, and yellow, blue and red represent “Vertical circuit activation”, “Horizontal circuit activation” and “both Vertical and Horizontal circuit activation” respectively. The second and third sub-tables appear to be more interesting. While in the second sub-table, the yellow cells are densely populated in the first three columns (which are the responses to the light bulb-related questions), in the third sub-table, the blue cells are densely populated in the middle three columns (4, 5, 6) and these are the responses to the questions relating to the heater.

The first subset of data (grey fills in Table 3.9a) shows that the students who answered individual questions correctly are widely spread across the cohort. Interestingly, the next two sub-tables (yellow and blue) are polarised by elements. Yellow represents the students who opted for the choice “Vertical circuit activation”, i.e. yellow is prominent in the first three columns that represent the bulb questions. This provides strong evidence that, while the majority of students expected vertical bulb activation, they did not expect the horizontal bulb to be activated.

Contrary to this, most of the students expected the horizontal heater to be activated, but not the vertical heater (third set of data; blue). When comparing the yellow and blue, it is clear that the blue features predominantly in columns 4, 5 and 6, which represent questions relating to the heater, while the yellow dominant columns (1, 2 and 3) represent questions relating to the light bulb. With the last set of data, shaded red, the cells are spread across the three elements. This represents the students who opted for the choice “Both vertical and horizontal circuit activation”. However, when observing carefully, it is clear that there is a higher population of red in the last two columns, which represent questions relating to the resistor.

Table 3.9a: A subset of Table 3.9; grey represents the correct choice ‘no activation’, yellow represents the ‘vertical activation’, blue represents ‘horizontal activation’, and red represents ‘both vertical and horizontal activation’

Bulb			Heater			Resistor	
BL	BI	BQ	HH	HI	HQ	RI	RQ
Q1	Q4	Q8	Q2	Q7	Q6	Q3	Q5
A10N	A10N	A10N	A10N	A10N	A10N	A10N	A30N
B30N,C32N	B30N	B30N	B30N	B30N	B30N	B30N	B30N
A30N	A30N	B10N	B10N	B10N	B10N	A30N	B10N
B30N	B30N	B30N	B30N	B30N	B30N	B30N	B30N
A10N	A10N	A10N	A10N	A10N	A10N	A10N	A10N
B10N	A10N	A10N	B10N	A10N	A10N	A10N	A10N
A10N	A10N	A10N	A10N	A10N	A10N	A10N	A10N
B30N	B10N	B10N	B10N	B10N	B10N	B10N	B10N
	A30N	A10N	A10N	A10N	A10N	A30N	A10N
	B30N	C10N	B30N	C10N	C10N	B30N	C10N
	A10N		E40N	C10N	E40N	A10N	A10N
B30N	B30N	C10N	B30N	C10N	B30N		
B60N	B60N	E60N	B60N	E60N	B10N	B10N	U10N
C10N	C10N	U10N	C10N	C10N	C10N	D72N	D72N
B30N	B10N		B10N	C50N	B30N	B30N	C10N
B30N	B30N		B10N	B30N		B10N	
A30N	E40N	C10N	B30N	B30N	B30N	B30N	C10N
		A10N	B30N	A10N	A10N	A10N	A10N
B30N	A30N	A10N		B10N	F40N		
B30N		U10N	B10N		B30N		B10N
B30N	A10N	A10N	A30N	U00N	U10N	A10N	A10N
	E81N	F81N,D72N	C23N	C23N	D72N	F81N	
C23N	E40N	E60N		E60N	E60N		E50N
			U10N	D73N	E60N	E60N	
B30N	C32N	E40N	B30N			E40N	
B30N	C10N				E50N	C10N	
						E40N	E40N
		C30N		C10N			
			C23N	C10N	C10N	C10N	
A30N	A10N		A30N	A10N		A10N	
				C10N	U10N	U10N	U10N
	D72N					U10N	
B10N		E50N			E50N		E50N
B10N				C23N			
	C10N			C10N			
B10N,C32N			B10N				
B10N		B10N	B10N	B10N	B10N		B10N
					U10N	F81N	F80N
		C10N		U10N	C10N		
				E40N			
			B10N	B10N	B30N		
A10N		E50N	B10N		E50N		E50N
							D71N
				C23N	C23N		
		U10N					
					U10N		
						U10N	
							U10N

Bulb			Heater			Resistor	
BL	BI	BQ	HH	HI	HQ	RI	RQ
Q1	Q4	Q8	Q2	Q7	Q6	Q3	Q5
C22V							
C21V							
						F81V	F81V
		C50V					
			U10V				
C30V							C31V
	C22V	E60V					
			C50V				
E60V	C10V						
U00V	C10V	C10V					
C10V	U10V	U10V					
			E60V				
			C23V			E40V	
					U10V		
	C32V	C10V				F82V,E40V	
	C10V					U10V	
	F81V						
C23V	C22V		C70V				
C32V	C10V						
C21V	C21V	C22V					
C70V	D76V	C70V					
	C10V						
E50V	E50V	U10V					
		C23V					
C23V	U10V	C10V					
	C22V	C22V					
C21V	C10V	C10V		C10V			
C21V							
C22V	C21V	C10V					U10V
C21V	C21V	C21V					
C10V	E40V	C10V					

Bulb			Heater			Resistor	
BL	BI	BQ	HH	HI	HQ	RI	RQ
Q1	Q4	Q8	Q2	Q7	Q6	Q3	Q5
				C50H			
			C31H	C31H	C31H		
			C31H		C10H		
			U10H				
				C30H			
				E50H	E50H		
		U10H		C23H			
						U10H	
				E40H			
			C31H	C10H	C10H		
			C23H				
			C60H	C10H	C10H		
			C10H	C10H	C10H		
			C31H	U00H	C23H	C21H	
			C23H	C10H	C10H		
			C23,C60H	C60H	C10H		

Bulb			Heater			Resistor	
BL	BI	BQ	HH	HI	HQ	RI	RQ
Q1	Q4	Q8	Q2	Q7	Q6	Q3	Q5
C23VH		C23VH					
		U10VH			E50VH		U10VH
E60VH	U10VH						
						C23VH	F40VH
	C10VH			C23VH		D72VH	
			C23VH			C23VH	
C10VH							C23VH
				E40VH	E40VH		C32VH
		C10VH					C50VH
E60VH	E60VH	C23VH					
						C40VH	E40VH
							C10VH
		C30VH			C30VH		C30VH
D75VH		D75VH	D75VH	D72VH	D75VH		D72VH
	U10VH					F80VH	
	E40VH	U00VH			C23VH		E40VH
E60VH		E50VH	U10VH			U10VH	E50VH
							F80VH
C10VH			C23VH				
D75VH	U10VH	D75VH	C23VH	U10VH	E40VH	U10VH	U10VH
							U10VH
		U10VH	E60VH		E60VH	C10VH	C10VH
						C10VH	E60VH
U10VH	U10VH	U10VH	U10VH	U10VH	U10VH	U10VH	U10VH
			F80VH	C10VH	E50VH	F80VH	E50VH
						E40VH	
			E50VH	U10VH	U10VH	U10VH	
E40VH	D72VH	C31VH				C31VH	C23VH
C22VH	C22VH					U10VH	C23VH
			C10VH	C23VH	C23VH	U10VH	C23VH
F80VH						F80VH	F80VH
U10VH	C23VH		C23VH	U10VH	U10VH	C23VH	C23VH
C23VH	C23VH	U10VH	C23VH	U10VH	U10VH	C23VH	U10VH
F80CH	F81VH	F81VH	F80VH	C10VH		F81VH	F82VH
			C10VH		E40VH		U10VH
	C23VH	C23VH				F80VH	C23VH
			C10VH	C10VH	C10VH	U10VH	U10VH
D22VH	U10VH	D72VH	F81VH	D72VH	D72VH	E40VH	
						C23VH	E40VH
C23VH,C60V	C10VH	C10VH				C23,C60VH	C10VH

3.1.3 Summary of the Exploratory Main Study for the UN1 Cohort

The analysis of the dataset for UN1 shows that the students' responses depend on the context presented in the question. While about a third of the students were of the opinion that the vertical light bulb will activate, none chose the horizontal circuit. Contrary to this, in the case of the heater circuits, 17% opted for the horizontal circuit and only a few chose the vertical circuit. However, in the case of the resistors, about half of the students opted for the choice "Both vertical and horizontal circuits will activate", while only a few opted for vertical and horizontal circuits separately.

In individual questions, about half of the students chose the correct answer choice. Among them, the highest (57%) was for the question relating to current in a heater and the lowest (38%) was for the question relating to charge flow in a resistor.

Students used various written reasons to justify their answer choices; 70% of the reasons were not related to circuits, but were physical, element-related, experience based reasons. A third of the students used Category A and B together. These two categories can be combined because they express the same idea in different words. However, more than a third used Category C to explain their answer choices; and 13% of the reasons were uncodeable due to poor handwriting or incomprehensible reasoning.

In the case of light bulbs, the connectivity of the light bulb (whether connected to the side or the bottom) and the orientation of the circuit (horizontal or vertical) influenced the responses. Regarding the battery polarity, the students were divided in their understanding of current and charge flow. For many, current and charge flow were two different things, while a few perceived them as working together. Moreover, for a few students, the charge flowed from the positive terminal of the battery, while others perceived it as flowing from the negative terminal.

3.2 Confirmatory Main Study (CMS): UN2 Cohort

The main purpose of carrying out the CMS on UN2 was to establish to what extent the coding scheme, that emerged from UN1 (EMS), was applicable to an independent cohort of students from a different institution. Thus, the analysis (presented in detail below) consisted of using the coding scheme in question to categorize the Written Responses of the UN2 cohort.

3.2.1 Analysis of Forced Choice Responses (FCR) for UN2 Cohort

The FCR data were analysed in the same manner as detailed in 3.1.1. After collecting the data, a unique respondent identity number (RIN) was assigned to each student's script and entered the FCR on a spreadsheet. The results are presented in Table 3.10 corresponding to the UN1 results as shown in Table 3.4. Note that the same colour codes are used in both tables to facilitate inter-comparison. The grey represents the correct choice; yellow, blue and red represent the choices: V(ertical) circuit activation, H(orizontal) circuit activation and both V(ertical) and H(orizontal) circuit activation (VH) respectively. A few responses were left out, and are represented by the unfilled white cells. When the columns in the table were grouped in the order of the elements, it was observed that the allocated colours in the cells appeared to be gathered together in the columns relating to a particular element. This process helped to exhibit the contextual dependency of the student responses with respect to a particular element. Thus, the detailed graphical analysis of the FCRs (Sections 3.1.1.1 – 3.1.1.7) was not necessary as in the case of UN1 (EMS).

3.2.2 Analysis of Written Responses for UN2 Cohort

The analysis of the Written Responses was carried out as follows. After reading each Written Response carefully, a code from Table 3.5 was assigned to each response. Each code was written on the script. After the entire set of responses was dealt with in this way, the codes were entered into a spreadsheet. Table 3.11 shows the result of the exercise after grouping the questions by element. A sample of 20 sets of responses was coded by another independent coder. The initial agreement was above 90% and, upon further discussion, it approached close to 100%. It should be noted, and felt to be significant, that no new codes had to be added to the existing ones during the analysis of the full sample.

Table 3.12 shows the frequency of the six categories in UN2. The total number of responses in this data was 712 (89×8). The single largest category used by the students was Category C31 (15%); the second largest was Category C23 (10%); the third largest category was B30 (9%); the fourth largest category was A10 (7%); and the fifth was U10 (7%). However, the largest combined parent category was C (41%) and the second largest was B (15%). Categories A and B could be combined (24%) because these two categories could be argued as expressing the same idea, relating to the "closed circuit", which was the key idea used by the students who chose the correct choice. Approximately a third of the students used other

Table 3.10: FCR in Colour Codes. Thematically grouped: Light bulb, Heater and Resistor (UN2)

RIN	Light Bulb			Heater			Resistor	
	Light	Charge	Current	Heat	Charge	Current	Charge	Current
201	N	N	N	N	N	N	N	N
202	N	N	N	N	N	N	N	N
203	N	N	N	N	N	N	N	N
204	N	N	N	N	N	N	N	N
205	N	N	N	N	N	N	N	N
206	N	N	N	N	N	N	N	N
207	N	N	N	N	N	N	N	N
208	N	N	N	N	N	N	N	N
209	VH	VH	N	VH	V	N	VH	N
210	V	N	N	VH	N	VH	VH	N
211	N	VH	VH	N	H	H	VH	N
212	VH	VH	VH	H	N	H	N	N
213	VH	N	VH	V	N	H	N	VH
214	N	VH	VH	H	V	H	VH	VH
215	V	V	V	H	H	H	VH	VH
216	V	V	V	H	V	H	VH	VH
217	VH	N	VH	H	V	V	VH	VH
218	N	VH	VH	VH	N	VH	VH	VH
219	V	VH	VH	H	VH	H	VH	VH
220	N	VH	VH	H	H	H	N	N
221	VH	VH	VH	H	H	H	VH	VH
222	N	VH	H	H	N	H	V	VH
223	VH	V	V	VH	H	H	VH	VH
224	VH	VH	VH	N	N	N	VH	N
225	N	N	VH	N	N	H	H	VH
226	N	VH	VH	H	VH	N	VH	V
227	N	N	VH	N	N	VH	N	VH
228	N	VH	N	H	N	N	N	VH
229	N	V	N	H	H	N	N	N
230	N	VH	N	N	VH	N	VH	N
231	N	VH	N	N	H	H	VH	N
232	N	N	N	N	N	V	N	N
233	V	VH	V	VH	V	H	VH	VH
234	N	N	N	H	H	H	VH	V
235	N	VH	VH	N	N	N	N	VH
236	N	N	VH	N	VH	N	N	N
237	VH	N	VH	H	H	H	VH	VH
238	V	VH	V	VH	VH	V	VH	VH
239	VH	N	N	N	VH	N	N	VH
240	N	N	N	VH	H	VH	VH	VH
241	V	VH	VH	H	H	H	VH	VH
242		VH	V	H	H	H	N	N
243	VH	H	V	V	VH	V	N	VH
244	V	V	V	VH	N	VH	VH	V
245	VH	VH	V	H	VH	VH	VH	H
246	V	VH	VH	H	N	H		
247	VH	H	VH	VH	VH	VH	VH	VH
248	V	V	VH	VH	VH	VH	H	VH
249	N	V	V	N	VH	VH	VH	VH
250	V	N	V	H	H	N	VH	N
251	V	N	N	H	N	VH	VH	VH
252	VH	H	V	V	VH	V	N	VH
253	N	VH	N	N	N	N	VH	VH
254	N	VH	VH	N	V	N	VH	VH
255	VH	VH	VH	H	V	H	N	H
256	V	V	N	H	VH	N	VH	VH
257	VH	VH	VH	VH	VH	VH	VH	VH
258	VH	H	VH	VH	N	V	VH	H
259	V	V	VH	H	VH	VH	VH	H
260	N	N	N	N	H	N	N	VH
261	N	H	VH	H	H	N	VH	H
262	H	V	N	V	V	V	V	VH
263	V	VH	V	H	VH	H	VH	VH
264	VH	N	V	N	V	H	N	VH
265	V	VH	V	H	V	H	V	VH
266	V	V	VH	H	H	H	VH	VH
267	VH	VH	H	H	H	N	VH	VH
268	VH	VH	VH	V	V	VH	V	V
269	VH	VH	VH	VH	VH	VH	VH	VH
270	V	V	VH	H	H	H	VH	VH
271	VH	VH	VH	H	H	H	VH	VH
272	VH	VH	VH	H	H	H	VH	VH
273	VH	VH	VH	H	H	H	VH	VH
274	N	VH	VH	N	H	N	VH	VH
275	V		V	H	N		VH	VH
276	VH	VH	VH	H	H	H	VH	VH
277	VH	VH	VH	V	H	H	VH	N
278	N	VH	VH	N	VH	N	VH	VH
279	N	VH	N	N	N	V	VH	N
280	N	N	N	V	H	H	VH	VH
281	VH	VH	VH	N	H	H	VH	VH
282	VH	N	H	V	V	VH	N	N
283	N	VH	N	N	VH	N	VH	N
284	VH	VH	VH	H	N	H	V	VH
285	VH	VH	VH	VH	VH	VH	VH	VH
286		VH	VH	N	VH	N	N	VH
287	V	V	V	H	H	H	N	VH
288	VH	VH	VH	H	H	H	VH	VH
289	VH	VH	VH	H	V	VH	V	V

Table 3.11: Student Written Response Category Codes superimposed on FCR (UN2)

RIN	Light Bulb			Heater			Resistor		#Reasons/
	Light up	Charge	Current	Heat up	Charge	Current	Charge	Current	student
201	A30	A10	A10	A30	A10	A10	A60	A20	1
202	B30	A10	A10	A10	A10	A10	A10	A10	1
203	B30	B10	B10	B30	B10	B10	B10	B10	1
204	B30	B10	B30	B30	B30	B30	B30	B30	1
205	B30	B30	B30	B30	B30	B30	B30	B30	1
206	B30	B30	B30	B30	B30	B10	B30	B30	1
207	B10	B10	B10	B10	B10	B10	B10	B10	1
208	B30	B30	B30	B30	B30	B10	B30	B30	1
209	A10	A10	A10	A10	E50	U00	D72	C60	4
210	A10	U00	A10	A10	A10	A10	B30	A10	2
211	A10	U10	C30	A10	U00	A10	E40	C10	3
212	B30	C30	B30	C31	B30	B30	B30	E40	3
213	B30	C50	C31	C31	C31	C50	C31	F80	3
214	B10	E50	D75	D75	D75	D75	E50	U10	4
215	B30	C21	A10	C31	C31	C31	A10	A10	3
216	A30	E41	D72	C31	U10	D72	C31	A30	5
217	B30	C31	C31	B10	C31	C31	C31	B10	2
218	A10	C10	C23	A10	C30	A10	C30	C23	2
219	B30	E50	B30	B10	E50	B10	E50	B10	2
220	B30	C30	B30	B30	C30	B10	C30	B30	2
221	A10	C23	C30	B10	A10	C30	A10	A10	3
222	A10	C23	A10	A10	E50	C40	C23	A10	3
223	A10	A10	B40	A10	A10	C30	B30	B40	3
224	A10	A10	E40	C31	C31	C31	C31	A10	3
225	B30	B30	U10	B30	B30	B30	B30	C30	3
226	B10	B10	U10	B10	E50	B10	B30	B10	3
227	F80	B10	C40	C31	B10	C31	D72	D72	4
228	B30	C31	C31	C31	E40	E40	E40	C31	3
229	B40	C10	C23	E40	C10	C40	D72	C23	3
230	B60	B30	B10	E50	A50	E50	U10	U10	4
231	A10	C31	C23	C31	C31	C31	D72	D72	3
232	B30	C23	C23	C31	B30	C23	C23	C31	2
233	B40	C31	C23	A10	C31	B10	C60	C23	3
234	B30	C23	C23	B10	C10	C10	C23	C10	2
235	B30	E40	E50	B30	C10	E50	F82	U10	4
236	B30	C23	C10	B30	U10	E60	C23	U10	4
237	U00	U10	C21	U10	C23	C23	D72	D72	3
238	C10	A10	A10	C10	F82	F82	C10	A10	3
239	C23	C31	C21	C40	C31	C31	D72	F82	3
240	D76	E50	C10	A30	A10	A10	C30	C10	4
241	C21	U00	C21	C23	U00	U00	C23	C23	1
242	C10	U00	C21	U10	U00	U00	C10	U00	2
243	C10	C22	U10	C10	C23	U10	U10	C23	2
244	C10	C30	C10	E60	C30	C30	C10	C10	2
245	C30	C10	C10	U00	C30	C30	C10	U00	1
246	C22	C22	C22	C31	C31	C31	C31	C10	1
247	C21	C31	C10	C31	C23	C31	C23	F80	2
248	C30	C30	U00	C30	U00	U00	U00	U00	1
249	C60	E40	C60	C40	D78	C23	C23	E40	3
250	C23	U10	U10	C31	C31	C10	C31	C31	2
251	C23	C23	D72	C31	C31	C31	U00	U00	2
252	E50	U00	U10	C23	U00	U10	U00	U10	3
253	E40	B10	C10	E50	C31	A30	F82	A10	5
254	C21	B10	D72	U10	E40	D72	D72	U10	5
255	C22	C23	C50	C31	C23	C23	U10	C23	2
256	U10	U00	C31	C23	C31	U00	C31	C31	2
257	C23	C31	A10	C10	E50	D72	A10	A10	4
258	F82	U00	F82	C10	E60	U00	U10	U10	4
259	F81	E50	C30	C31	C31	U10	F81	F81	3
260	C60	C23	C23	C31	D76	C23	D76	U10	3
261	C23	C40	C40	C31	A10	C40	A10	E40	3
262	C23	E40	D71	C31	C30	C30	U10	U10	4
263	C31	C23	C10	D75	C31	C31	B10	C60	3
264	C23	E60	C21	C31	E60	U10	E60	U10	3
265	C31	E60	C31	C31	C31	C10	C31	C31	2
266	C23	C31	U10	C31	C31	C31	C31	C31	2
267	C23	A20	U10	D72	E50	C10	E40	E40	5
268	E60	C10	E60	C31	C10	C10	C10	U00	2
269	C23	C10	U00	C23	U10	C10	C10	C10	1
270	C31	U00	U00	U10	U00	U00	U00	U00	2
271	C23	C23	C23	C23	C31	C23	U00	C23	1
272	C31	C30	C30	C30	C30	C30	C30	C30	1
273	C31	C31	C31	C31	A10	C31	C23	C31	2
274	C31	C22	C21	C31	C31	C31	C31	F82	2
275	F81	F81	U10	F81	U10	U10	U10	U10	2
276	C32	E50	C21	E50	C30	C10	C10	D72	3
277	C30	C50	F82	C23	C31	U00	C31	C23	2
278	C23	E40	C23	D71	D75	D75	F80	F80	4
279	C31	C31	E40	C30	C30	D72	C30	U10	3
280	U10	U10	U00	U10	U10	U00	U10	U00	1
281	E40	U00	U10	E40	E40	E40	D72	D72	3
282	E60	E40	E40	C23	C31	C31	C10	C23	2
283	E40	E60	E40	E60	F82	D76	F81	U10	4
284	C23	E50	C30	E50	E50	E50	C23	A40	4
285	U10	U10	C30	C23	U00	U10	U10	U10	2
286	C23	C21	C21	C10	C23	U10	D72	D72	3
287	C23	C10	C30	C31	U10	C30	U00	C30	2
288	C32	E50	C21	E50	C30	C10	C10	D72	3
289	C30	C50	F82	C23	C31	U00	C31	C23	2

Table 3.12: Frequency of six categories from 712 responses (UN2)

Code	Light Bulb Light-up	Heater Heat-up	Resistor Current	Light Bulb Current	Resistor Charge flow	Heater Charge flow	Heater Current	Light Bulb Charge flow	Total
A10	9	8	10	7	5	6	4	4	53
A30	2	1	0	0	0	2	1	0	6
A40	1	1	2	1	0	0	0	1	6
A60	0	1	0	0	0	0	0	0	1
B10	3	5	6	4	3	3	7	7	38
B30	17	9	6	8	9	7	6	4	66
B40	2	0	0	0	0	0	0	0	2
B60	1	0	0	0	0	0	0	0	1
C10	4	5	6	9	7	4	7	6	48
C21	4	0	0	7	0	0	0	3	14
C22	2	0	0	1	0	0	0	3	6
C23	14	8	8	9	9	6	10	10	74
C30	2	3	2	5	3	6	4	1	26
C31	9	24	8	6	13	19	15	15	109
C32	0	0	0	1	0	0	0	0	1
C40	0	2	0	2	0	0	2	1	7
C50	0	1	0	1	0	0	1	2	5
C60	1	0	1	1	1	1	0	0	5
D71	0	1	0	1	0	0	0	0	2
D72	0	2	7	2	10	0	3	0	24
D73	0	0	0	0	0	1	0	0	1
D75	0	1	0	1	0	2	2	0	6
D76	1	0	0	0	1	1	1	0	4
E40	3	2	5	5	3	3	3	5	29
E50	1	3	0	1	3	5	3	7	23
E60	2	2	1	1	1	3	1	3	14
F80	0	0	3	0	1	0	0	0	4
F81	2	1	2	0	2	0	0	1	8
F82	1	0	2	2	2	1	1	0	9
U00	2	0	6	4	6	5	12	7	42
U10	2	6	13	8	8	8	3	4	52

categories in their arguments to justify their responses. A considerable number of student ideas were difficult to comprehend, either because of poor handwriting or poor explanations, and were grouped into Category U (13%). This appeared to be problematic, but not surprising, since a similar number appeared in UN1 as well.

An important observation was made from Table 3.11 that all the students who used Category A and Category B as their reasons to justify their FCRs, chose the correct choice (N), except for five responses. This observation supports the argument that the students used an idea related to the "closed circuit" and responded to the canonical expectation.

3.3 Sense-making issues

An important consideration during the study was to what extent students engaged in a serious manner with the instrument. In particular, to what extent the responses had come about as a result of trying to make sense of all the questions, rather than simply providing random responses. While it is not possible to be completely certain, two indicators of student sense-making were as follows:

Firstly, from both observation and interaction during the administration with the two cohorts UN1 and UN2, it appeared to be the case that students were trying to interpret questions meaningfully. Secondly, the analysis of the data appeared to indicate a similar engagement with regard to sense-making. However, a small subset of responses was not easy to understand: either the pattern of the responses from the FCR was not understandable, or the writing did not appear to make sense in itself or relative to the choice that had been made. In order to clarify whether these were in fact random writings or whether these students were trying to express ideas that were not easy to interpret, eight such students were chosen for interviews.

The interviews are detailed in the following chapter. However, it is important to emphasise that the purpose of the interviews was to determine to what degree the Written Responses were a poor expression of sense-making, misunderstanding on the part of the researcher, or whether they were nonsensical. The outcomes of these interviews (Chapter 4), together with the results presented previously, will be further discussed in Chapter 5.

Chapter 4
Interviews to Explore Sense-making

4.1 Interviewees

Based on the discussion in Section 3.1, eight students from the UN2 sample were selected for interviews. The students were selected on the basis of the issues identified in terms of the FCRs and WRs, for example, a student who answered two questions relating to a particular element "correctly" and a third question "incorrectly"; or a student who answered questions relating to a concept (charge flow/current) "correctly" and another question "incorrectly"; or a student using the reasoning "closed circuit" in a few questions and, in other questions, different ideas unrelated to the circuit. Based on such criteria, the eight students (the names are not their own, but their genders are kept) were selected as shown in Table 4.1 below. There were five male and three female students; five students with isiXhosa (an African language) as their home language, but the medium of instruction was English; and two with Afrikaans (another African language) as their home language. The French student received instruction at school in his home language. The ages of the students varied from 18 – 33.

Table 4.1: Details of the interviewees

No.	Name	Age	Gender	Home language	Medium of (school) instruction
1	Sherif	26	M	Afrikaans	English
2	Baba	24	F	Xhosa	English
3	Asie	18	M	Xhosa	English
4	Swala	18	M	Xhosa	English
5	Tishik	33	M	French	French
6	Pam	18	F	Xhosa	English
7	Leo	18	F	Afrikaans	Afrikaans
8	Siya	18	M	Xhosa	English

Figure 4.1 illustrates the FCRs in a graphical format with the summarised Written Responses (and the corresponding codes) of the eight interviewees. The unfilled (black) figures represent the inactivated elements (correct answer choice) and the filled (red) figures represent the activated elements (incorrect answer choice) in each question. The eight sets of pictures represent the eight-set-FCRs for the eight questions for each interviewee. It is clear that the red fillers are spread in an irregular fashion throughout the figure.

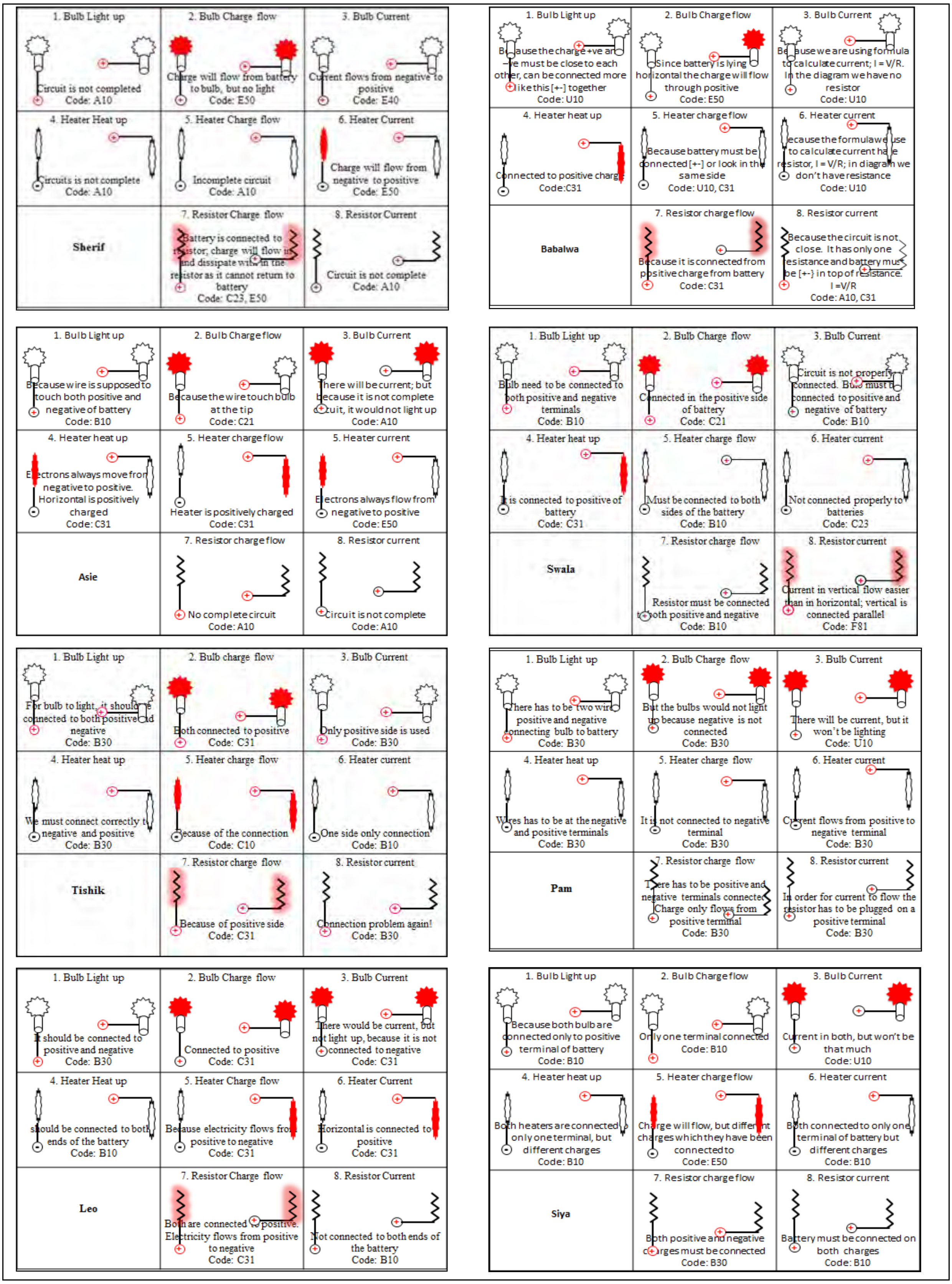


Figure 4.1: FCRs with the Written Responses and corresponding codes for eight interviewees. Red filled figures represent the activated elements and black unfilled figures represent the inactivated elements in each case. Details are given in the text.

This irregular activation of elements was the main reason for selecting these students as interviewees. More details about these students' FCRs and reasoning are given in the interview section of each case.

The venue was a small meeting room in their department. All interviews were conducted in the afternoon because most students were fully occupied in the morning. All students were registered for the first-year diploma in food technology.

4.2 The Interview Protocol

Both the researcher and the supervisor were present at the first three interviews. The subsequent interviews were conducted by the author himself. The interviews were conducted using the following protocol. Each student was seated and the purpose of the interview was clearly explained to each student as a diagnostic test with no correct or incorrect answers. It was also stressed that the interview would in no way affect their final mark or the relationship between the lecturer and the student. The purpose of the interview was explained in detail, emphasising that the reason for it was that their response was interesting (not that it was right or wrong).

To put the students at ease, the author also asked some background questions. These included:

- Why did you choose food technology as a course of study?
- When have you last done physics?
- Did you like physics at school? (Most of them replied "No")

The permission was sought to video-record the interview by asking the following questions:

- Are you happy to be recorded?
- Should we hide your face in the video or not?
- May we show the video to other research colleagues in the field?

In order to ensure that the students were fully engaged and thinking though the issues, the author suggested:

- Publicity on *YouTube*?

Without exception, however, they laughed and said no.

Although the interviews were planned for 15 minutes, they lasted much longer due to following up on interesting aspects as they occurred, leading to interviews of 45 minutes. While, in the initial session, the interviewer read out the original script of each student and asked them for clarification, this proved unsatisfactory because of three people (two interviewers and one interviewee) sharing one script. Subsequent sessions utilised a photocopy of the script for the two interviewers and the original for the student.

To refresh their memories, the interviewer summarised what the instrument had been about and then pinpointed specific questions about which they would be questioned further. They were then asked to read aloud their responses to those specific questions. This was necessary because the questionnaire had been completed by the students three weeks before the interviews.

Based on these responses, we asked, "What did you mean by this? Please explain further." We also assured the students that, if they no longer agreed with their earlier responses, they would later be able to tell us so and explain why. Some students changed their original answer choices during the interview. One of these students, Pam, when asked why she was changing her response, replied, "After the test I went and checked my high school book."

The words of the interviewer are paraphrased, with salient features recorded accurately, while the students' replies are reported verbatim. The ideas that emerged from the interviews of the eight students are described in the following section. However, only one of them is presented in detail with the full transcript. The other seven are described briefly with their FCRs and WRs in graphical format, and their explanations followed by the key ideas that emerged from the interviews. The full transcripts of the interviews are provided in Appendix 6.

4.3 Full Interview of Baba

Baba is a 24-year-old female student who had completed matric three years ago. She answered five of the eight questions correctly in the FCRs, but with different written reasons. The interview lasted 46 minutes.

Figure 4.2 shows the combination of FCRs and brief written responses and codes for her eight questions. The red represents the activated elements and the black represents the inactivated elements. The first row represents the questions relating to the light bulbs; the second row represents that of the heaters; and the third row represents that of the resistors.

Thus, it is clear that three cells are red and the rest are black. It is interesting to note that she answered five of the eight questions correctly, however with unexpected reasons. None of her reasons were related to the circuit, but were rather related to the battery, the physical appearances of the elements, and the equation from Ohm's Law. She chose correctly for two of the three light bulb-related questions.

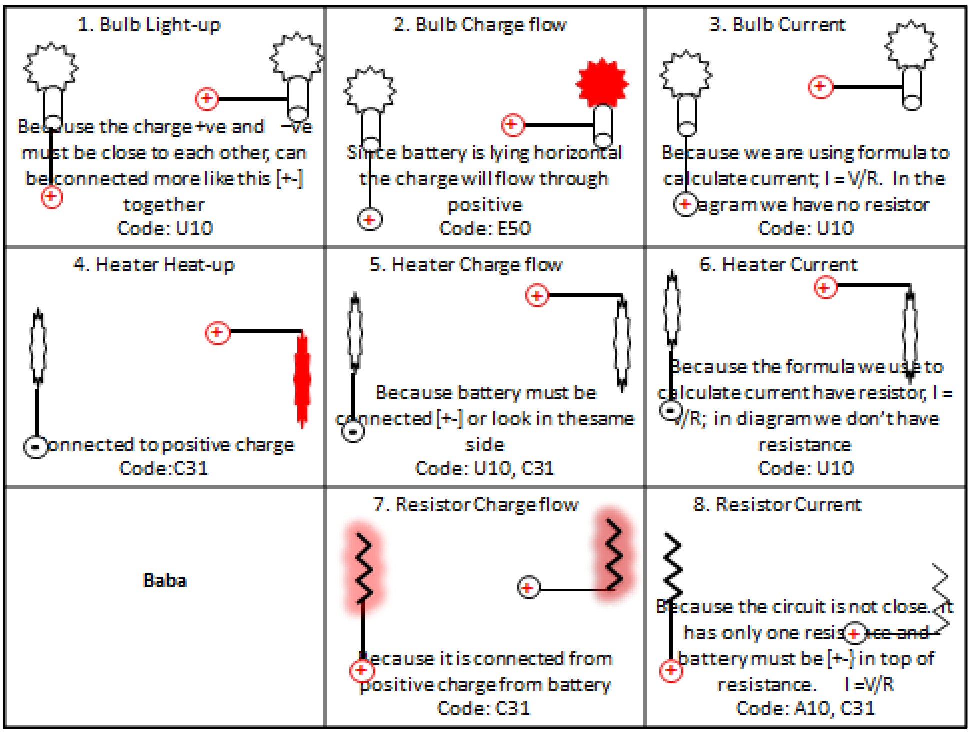


Figure 4.2: Baba's FCRs with the Written Responses and code(s)

Similarly, while two questions relating to the heater (Q5 and Q6) were answered correctly, Q4 was answered incorrectly with battery polarity as a reason. The equation for Ohm's Law was used for the three current-related questions, while the charge flow question was argued on the basis of the battery. Thus, her reasoning was incomprehensible, inconsistent and ambiguous, which led to a personal interview.

In the following interview sections, **I** represents the interviewer and **S** represents the student.

4.3.1 Interview

The interview started according to the protocol discussed above.

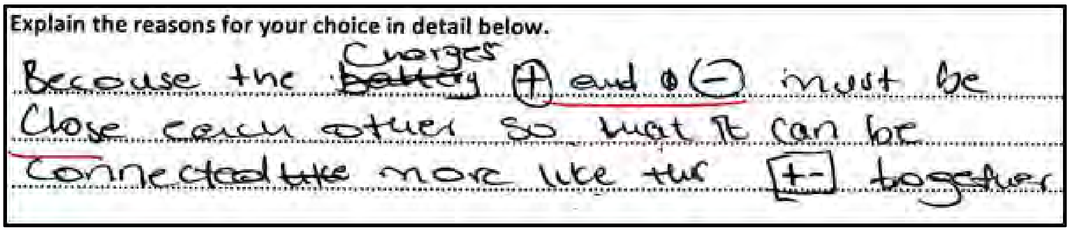
I: It is important to know what students know or think before teaching a certain topic. This is a diagnostic test, i.e. we would like to know what you know before we teach.

This is a follow-up of what you wrote in the test. Your response was interesting. Can you repeat it?

S: At the time we wrote the test, we were not aware of this test because it was done on the first day. So I wrote what I thought at the time. I wasn't studying anything. I finished it [matric] in 2007.

The test had been written in the first week of February 2012, on the first day of the semester. The interview was conducted on the 22nd of March.

I: Let us look at your answer to the question relating to the bulb. Just try to remember why you wrote it. Please read and explain what you wrote. You have a bulb, a battery, a heater and a resistor. Please go through your answer. In the first question related to the light-up of a bulb, you selected the choice "none of them will light up" and you gave the reason … please read.


Explain the reasons for your choice in detail below.

Because the ~~battery~~ charges + and − must be close each other so that it can be connected ~~like~~ more like this +- together

Figure 4.3: Baba's original Written Response to the question relating to light-up of a light bulb

S: "Because the charges positive and negative must be close each other so that it can be connected more like this … together" (Figure 4.3).

I: Please explain what you meant by this.

Baba held both hands vertically, parallel to each other, saying,

S: If we are connecting, positive must be like this and negative must be together.

I: Can you please draw what you are saying?

Having done her drawing (Figure 4.4), she explained,

S: For example, if you take a TV remote, open it, you will see the batteries are like this. If you connect the batteries one positive and the other negative together, it will not go on. You must connect one positive up and the other positive down if you want to [turn] on the TV remote.

Figure 4.4: Baba's illustration: connection of two batteries

I: So basically you are taking your experience from the ...

S: TV remote.

I: That is great. Because it is not something you learned from a book. You learned from your experience.

S: Yes.

I: If you wanted it to work, what would you do? Can you draw?

She illustrated as shown in Figure 4.5.

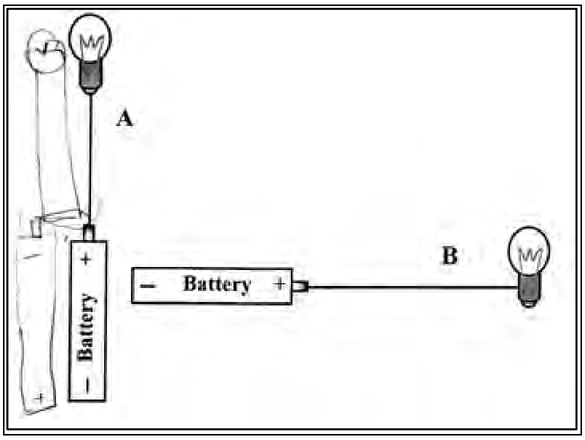


Figure 4.5: Baba's illustration: connection to light up a bulb

I: The key idea is that you would need two batteries?

S: Yes.

I: That is interesting. Let us turn to the next page. This is a question relating to the heat-up of a heater. You chose the option "the heater in Figure B will heat up but not the heater in Figure A". You gave the reason.

S: "It will heat up from Figure B because the heater is connected from a positive charge and, in Figure A, is connected from a negative charge."

I: Can you explain what you meant?

S: The reason is the heater A is connected to the body of the battery, not from the top. I don't know how to call…

I: Oh, that little protrusion?

She nodded her head as if to say, 'whatever you call it'.

I: What is different and what is common in a heater and a bulb? Because, in the bulb, you said the bulb will not light up, but in the heater, you said the heater in the circuit B will heat up. What is the difference?

S: No. There is no difference that much, Sir, because it is connected to the body of the battery.

I: So, as I understand it, the reason you chose a different answer is that one is connected to the flat part of the battery and the other to the little protrusion?

S: I think so.

I: If you were asked to answer this question now, what would you choose?

S: None of the heaters will heat up.

I: The same reason?

S: The same reason.

I: Let us turn to the next question. It is about resistors. Here, you chose "no current in any of the resistors". The reason given was …

The student read her script (Figure. 4.6).

I: Please explain.

S: I was not sure. The circuit is not closed.

I: How will you close it?

She tried to draw a closed circuit, but was not sure how to, and could not complete it.

S: But … I was not sure … here I have a formula, $I = V/R$.

I: How come you thought of the formula in this case [resistor] and you did not think of it in the case of the bulb and heater?

S: It just appeared. In Ohm's Law, we have ampere, resistor, battery is just V. Here is a resistance, I have a battery V, here is a … and I don't know where I can say this is the ampere.

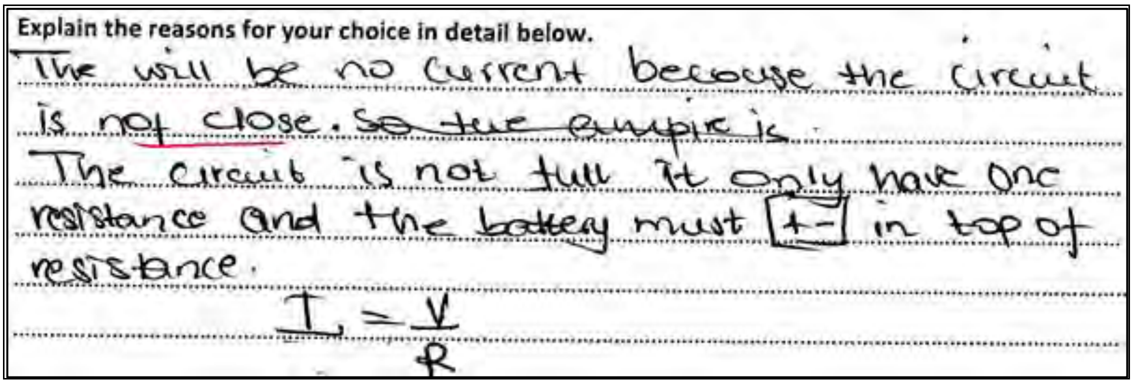

Explain the reasons for your choice in detail below.
The will be no current because the circuit is not close. ~~So the empipic is~~
The circuit is not full it only have one resistance and the battery must $\boxed{+-}$ in top of resistance.
$I = \frac{V}{R}$

Figure 4.6: Baba's original response to the question relating to resistor

I: What interests me is … would you use this formula in a bulb or heater?

S: No. I would not say that there is a resistor… bulb is not a resistor.

I: Okay. That explains it. It is very important for us to know how you see those different things. So, for the light bulb or the heater, you would not use the formula *R* = *V/I*, but for resistance, you would use it. That was really helpful.
What would you do to close the circuit?

S: No I don't want to do that.

I: Take it easy… When you said the circuit is closed, you had something in your mind.

S: Like the circuit is closed or not closed.

I: Yes – like the door is closed or not closed.

She drew a circuit with an open switch (Figure 4.7). She then added an "A" across the switch.

I: What does that "A" represent?

S: Ammeter.

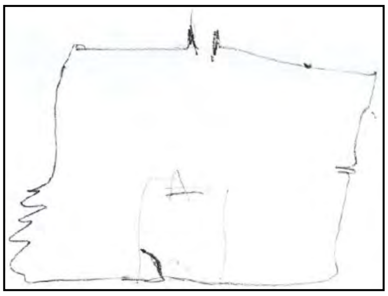


Figure 4.7: Baba's illustration: a closed circuit with a switch

By now, she appeared to be exhausted.

I: This is one of the best interviews I have ever had in my life. Because you have good reasons for what you have done. All the reasons you have given are valid. Okay. Let us turn to the next one. This is a question relating to current in a bulb. You chose the option "none of the bulbs will have current". Please read it aloud.

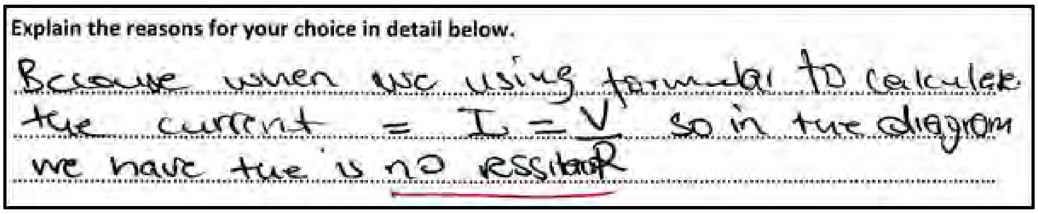
The student read her Written Response (Figure 4.8).

S: None of them will have current because there is no resistor. There is no current. I = V/R. We have V battery, but we do not have resistor R, therefore no current.

I: No resistor. So that, in essence, is related to what you said earlier. Is it not so? For I = V/R, you need an R. In the case of a bulb and a heater, there is no R?

S: Yes.

I: So if you wanted to explain it to somebody, what would you say?


Explain the reasons for your choice in detail below.

Because when we using formula to calculate the current = I = V so in the diagram we have the is no resistor

Figure 4.8: Baba's original Written Response to the question related to current in a bulb.

She put her hands on her forehead and asked,

S: How will I explain?

I: Please read aloud what you wrote.

The student did what she was asked to do (Figure 4.8).

I: In the diagrams, there is no resistor. For the current, you need a resistor. Is this true?

S: In the picture I don't see any resistor. Here we have a bulb and a battery.

I: So I can summarise. In this picture, there is voltage and a bulb but no resistor. In order to have current I, you need V divided by R. But there is no R in the given diagram. Therefore there is no current in any of these bulbs.

S: Yes.

I: If I said, "Baba said this," would you be happy?

S: Yes.

I: Okay. Let us move to the next question. This is a question relating to charge flow in a resistor. Please read your Written Response.

S: "Charge will flow because it connected from the positive charge from the battery."

I: Okay.

S: I will agree, I will not agree with my answer, because charge will flow from positive to negative.

She drew a circuit diagram with a resistor and a battery, and continued,

I would say no now. Because, in a circuit, charge will flow because we are having battery here, which is positive sign and negative sign.

Then she referred to the original question, saying,

But here, I said it is connected to a negative, no I mean positive of a battery … The final answer for me is, I would say, I would not agree with my answer. I think I would say no.

I: Which answer would you choose?

S: I would choose number 2.

I: “Charge will not flow in any of these resistors.” The reason would be …?

S: Because …

She shook her head in confusion and said,

I would choose … sorry Sir, I would choose number 3 … oh no …

I: Now you want to choose the original answer.

This caused general laughter.

S: The battery is connected vertical and parallel, but it is the same thing.

I: So let us start again. Which answer would you choose?

S: Number 2. No, number 3.

I: So, in other words, what you initially said was, “Charge will flow in both resistors.” The reason for this …?

S: No. It is the same battery which is connected … all over the circuit …

She was not sure and could not give any valid reason.

I: Okay. This looks a bit tricky. Let us move to the next question. Do you agree with your answer?

S: Yes.

She read her response,

“Charge will not flow in any of the heaters.” As I said before, the bulb would not light. Because of the battery not connected like the remote.

I: If we look at pages 8 and 9 together, the one is about charge flow and the other is about current. What is your understanding of current and charge flow? Are they related or not? Are they the same or different?

S: Sir, we are talking about a battery. For using a battery, we must have both … the other must lie positive and the other negative in order to connect. Otherwise it won’t.

I: Are you saying that there would be current, or no current?

S: Sir, can you remind me about current. Current is V over R.

I: To summarise, you say, for current, you need to have your R.

She nodded her head in agreement.

I: So, for charge flow, does it matter if you have an R or not?

S: I am trying to understand … when we are calculating …

I: How do you see current and charge flow? Is charge the same as current or are they different? Because, when you talked about charge, you mentioned about the connection and, in the case of current, you said you need R. Is that true?

S: Yes.

I: That is very clear. That is most fascinating; your answers are interesting and informative. Thank you very much for that. The last question relates to the charge flow in a bulb. You chose the option "charge will flow in bulb B, not in bulb A" (Figure 4.9). The reason given was "since the battery is lying horizontal the charge will flow horizontal through positive charge". Can you explain why it will not go up in A?

S: In Figure A, battery is …

She stopped, unable to explain.

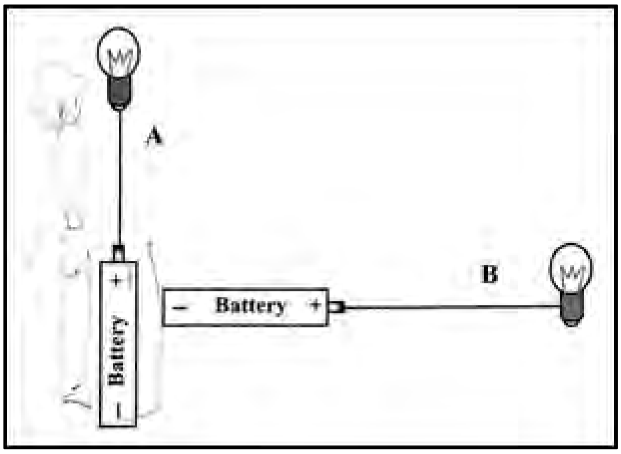


Figure 4.9: Baba's illustration: circuit for charge flow in a light bulb

I: Okay. Are you happy with the reason you have given?

S: I would say charge will not flow in any of the bulbs. There must be two batteries.

She added a battery to the given vertical circuit (Figure 4.9).

I: Okay. That is very clear.

I: One last question. If we have these three elements, a resistor, a heater and a bulb, the resistor has some resistance R …

S: Yes.

I: What would you say for the bulb and heater? You said neither of them has resistance R. Is that what you say?

S: Yes.

I: That is an important point. Do you see any difference between the resistance and a heater?

S: Sir, in resistance and a bulb, you know, sometimes you are given a resistance and a bulb and they ask, will the bulb light up? So there is a connection between bulb and resistance.

I: What do you think it is?

S: Because of the charges and electric wire …

I: Do you need a resistor in the circuit to light up a bulb, or not?

S: Yes.

I: If you take the resistor out, will the bulb light up?

S: No.

I: For the heater?

S: Heater won't heat up.

I: That is a clear statement. I am happy, and thank you very much.

4.3.1.1 Key Ideas from Baba's interview

Two batteries must be connected for the bulb to light up; one of them must be orientated (positive) up and the other (positive) down, like in a TV remote control (P98, L14-15, Figure 4.3, 4.4).

Her experience of the TV remote was used to answer the light bulb and heater questions (P94, L19-20).

There must be two batteries in order to produce a charge flow in a bulb (Figure 4.5, 4.9, P95, L1-5).

If the positive terminal of a battery is connected to the heater, the heater will heat up, but it will not heat up if connected from the negative terminal of the battery (P95, L10-16).

The resistor triggered the equation for Ohm's Law; she said, "it just appeared" (P96, L15-17, Figure 4.8).

The light bulb is not a "resistor" (P96, L19).

Without a resistor, there would be no current in the light bulb circuit because, to substitute in Ohm's Law $I = V/R$, there must be a R (resistor) (P97, L18 – 22, P98, L2-9)..

4.4 Summarised interviews

The following sections (4.4.1 – 4.4.7) present a brief description of the seven interviews. The full transcripts are provided in Appendix 6.

4.4.1 Interview of Sherif

The 26-year-old male student, who appeared to be confident, answered five of the eight questions correctly, with the same written reasoning “complete circuit”. However, the responses to the rest of the three questions did not follow the expected pattern of the correct five. These were the questions relating to charge flow in the resistor, charge flow in the light bulb and current in the heater. The interview lasted for 18 minutes. Figure 4.10 shows the combination of FCRs and brief Written Responses for the eight questions. The filled (red) figures represent the activated elements and the unfilled (black) figures represent the inactivated elements.

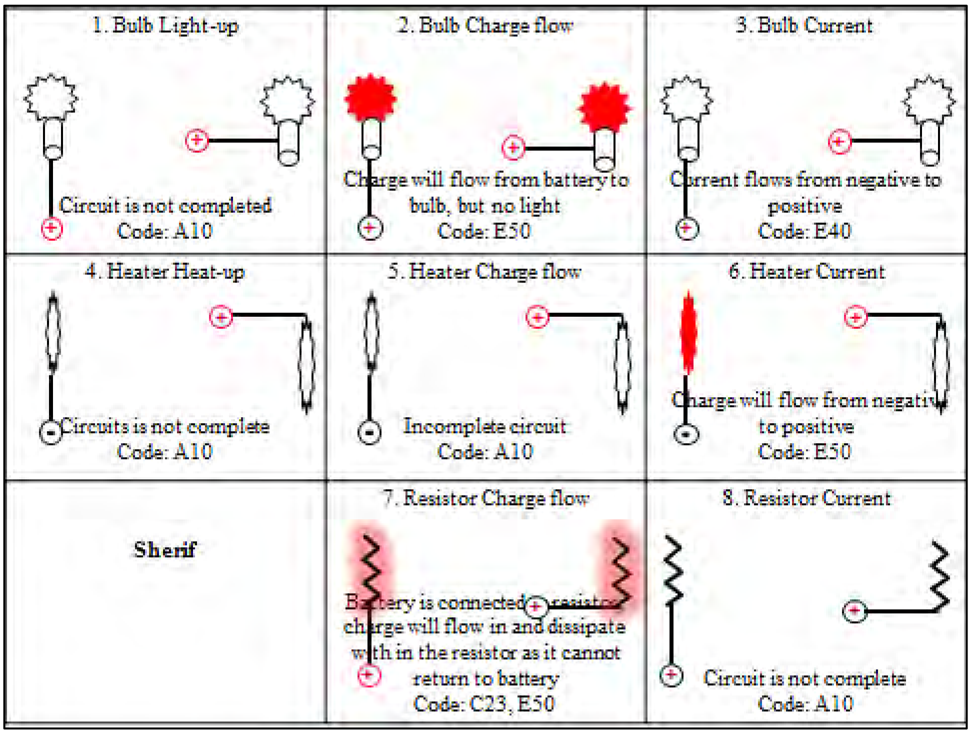


Figure 4.10: Sherif’s FCRs with the Written Responses and code(s)

The first row represents the questions relating to the light bulbs, the second row represents that of the heaters, and the third row represents that of the resistors. In each cell, the reason (SWR) used for answering each question is also given with the allocated code(s).

While he selected the correct answers for questions 1, 3, 4, 5 and 8, he did not select the correct answers in the other questions. Furthermore, he used the same circuit reason in four of these five responses, except in Q3. This question was answered using some ideas relating to current flow and the negative polarity of a battery. In the first row (light bulb), he answered two of the three questions correctly, but in the questions relating to charge flow, he selected the choice VH (both would activate), with an interesting reason, “charge will flow but it would not light up”. In the second row (last column), he opted for the choice V, with the reason, “charge will flow from negative to positive”; (it is to be noted that, in the given figure, the negative terminal of the battery is connected to the heater in the vertical circuit). In the last row (second column), he opted for the choice VH (both would activate), with the reason, “charge will flow in and dissipate within the resistor as it cannot return to battery”.

4.4.1.1 Key Ideas from Sherif’s interview

Based on his school experience, the bulb will not light up with one wire (P155, L19-21).
The resistor is not exactly the same as the bulb or heater. (P155, L26).
The current or charge dissipates in the resistor because there is no complete circuit (P155, L27).
The resistor is like an open cable. You will have electricity in the wire; you have a live wire (P156, L1-2).
Current is used for the unit to work (P156, L10 – 11); current is responsible for the light bulb to light up (L19 – 21).
Charge flow is a certain measurement; it is not responsible for the unit to work (P156, L10-11).
Current and charge work together (P156, L17).
The bulb and the battery are used to explain current; to explain charge he would use a meter (P156, L13-15).
The bulb has polarity (P157, L6-7, Figure 6.1).

4.4.2 Interview of Asie

This 19-year-old male student had studied in a village school where the municipal electricity grid was not available. This interview lasted for approximately 47 minutes.

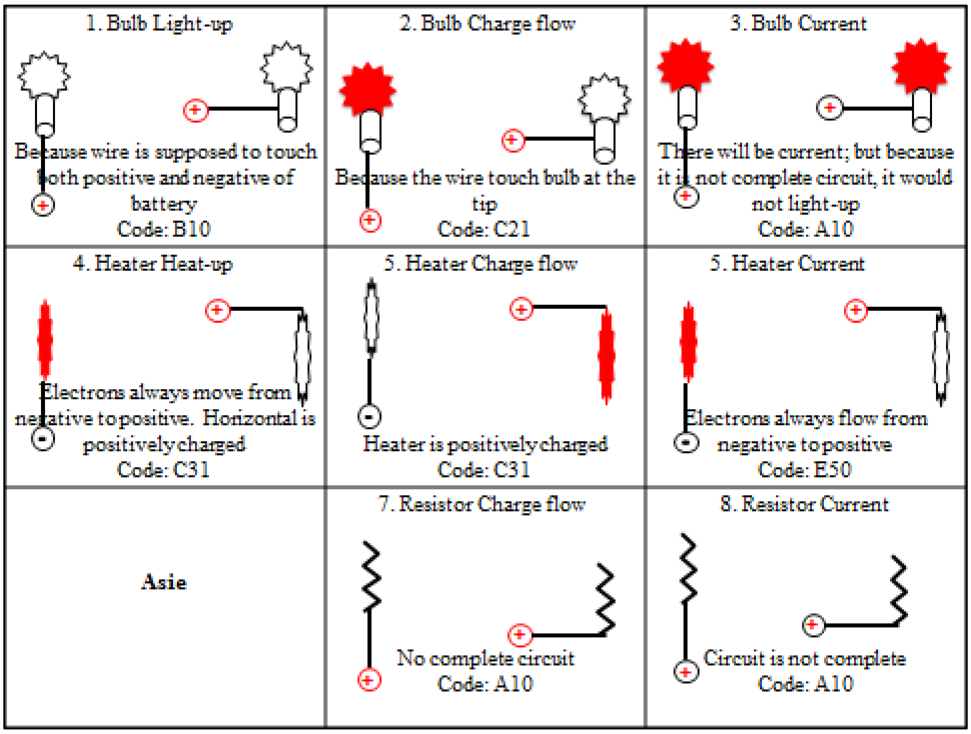


Figure 4.11: Asie's FCRs with the Written Responses and code(s)

Asie chose three of the eight correct choices in the FCRs and provided circuit reasons in all three. Figure 4.11 shows the combination of FCRs and brief Written Responses and the codes for the eight responses. The filled (red) cells represent the activated elements and the unfilled (black) cells represent the inactivated elements. The first row represents the questions relating to the light bulbs, the second row represents that of the heaters, and the third row represents that of the resistors. The reasons for each answer with the respective code(s) are also given in each cell.

Of the three light bulb questions, he answered only one correctly with a circuit reason. In the charge flow questions, he opted for the vertical activation with reasoning related to connecting terminals of the light bulb. However, in the current question, he opted for the VH option with interesting reasoning: "There will be current, but because it is not a complete circuit, it would not light up." Further, in the heater questions, he opted for the choice V in two questions and H for the other one. His reasoning for choice V was related to the positive or negative terminals of the battery and the charge flow; and was not related to the circuit.

4.4.2.1 Key Ideas from Asie's interview

A complete circuit is needed to light up a bulb (P157, L13-14, Figure 6.2).
There will be current in the bulb, even if the circuit is not complete, but it won't light up the bulb (P160, L11-13).
Current flows in a resistor only when there is a complete circuit (P159, L18-19).
The function of a resistor is to resist current (P159, L26).
The two reasons for current not flowing are: (i) circuit is not complete, and (ii) resistor resists current (P160, L1-4).
At the bottom of the bulb, there are two electrical contacts of the bulb. The bulb is supposed to be connected to the bottom part of the bulb (P160, L17-23).
The side of the bulb is just to hold the bulb (P161, L3-4, L16-18; Figure 6.4).
Electrons always flow from negative to positive (P162, L12-22).
Charge is the voltage of the battery or capacity (P164, L12-18).
When the mobile is flat, you charge the phone; it will work only if there is charge in the battery (P164, L20-22).
Charge is something that makes current flow (P164, L22-27).
Voltage is the power of the battery (P164, L30-31).
The light bulb has more resistance than the heater, because a bulb needs only a small current and a heater needs more current. The high resistance of a bulb limits the current in the bulb and the low resistance of the heater allows more current in the heater (P165, L1-11).

The full transcript of the interview can be found in Appendix 6.

4.4.3 Interview of Swala

Swala is an 18-year-old male student. The interview lasted for 38 minutes.

He answered five of the eight questions correctly in the FCRs with the correct circuit reason. Figure 4.12 illustrates the combination of FCRs and brief Written Responses with related code(s) for the eight questions. The filled (red) cells represent the activated elements and the (unfilled) black cells represent the inactivated elements. The first row represents the questions relating to the light bulbs, the second row represents that of the heaters and the third row represents that of the resistors. In each cell, the reasons used for answering each question are also given.

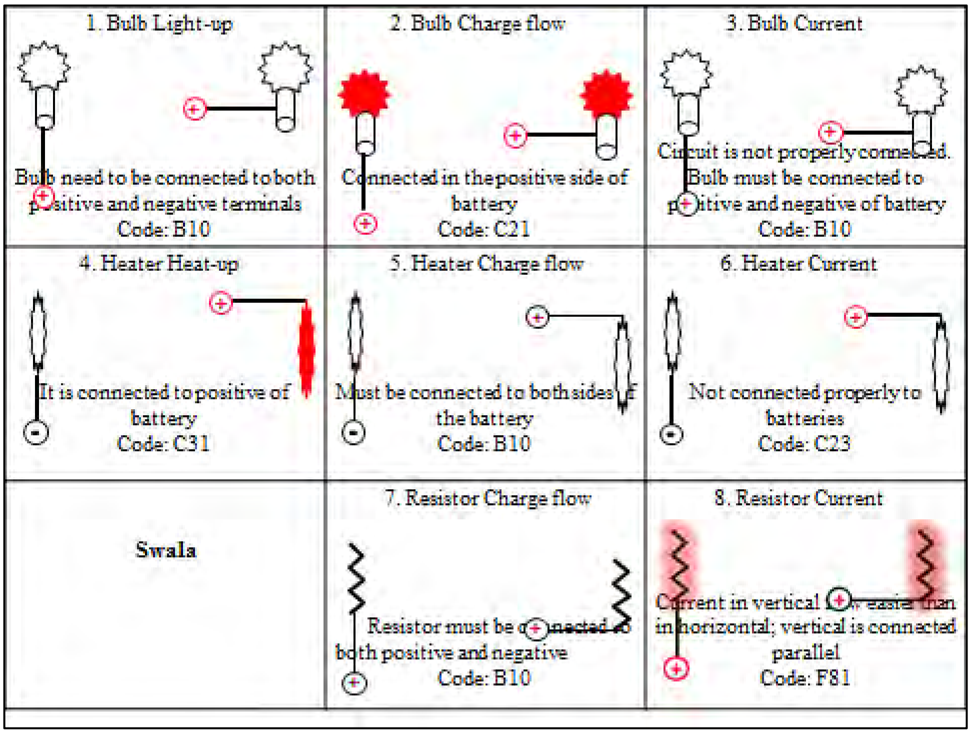


Figure 4.12: Swala's FCRs with the Written Responses and code(s)

While two of the three light bulb questions were answered correctly with acceptable circuit reasons, he opted for the choice VH in the case of the charge flow questions with a reason pertaining to the positive terminal of the battery. In the case of the heater questions, while two were chosen correctly with apparently acceptable circuit reasons, he opted for the choice H in the case of the heat-up, by providing "positive terminal of the battery" as the reason. Furthermore, only one of the resistor charge flow questions was answered with a circuit reason; and the current question was reasoned on the basis of parallel or series connection.

4.4.3.1 Key Ideas from Swala's interview

To light up a bulb, both positive and negative terminals of a battery should be connected (P1167, Figure 6.6, 6.7).

The connection can be to any part of a bulb (P168, L9-28, Figure 6.7).

If the positive terminal of a battery is connected, the heater will heat up (P169, L1 – 5).

If a resistor and a battery are drawn side-by-side, the resistor is connected in a parallel circuit, (P170, L4- 11, Figure 6.9).

In a parallel circuit, current flow is easier than in series (P170, L6).

When connected to the positive terminal of a battery, the positive charge will flow (P173, L13-15).

In an open circuit, charge will flow from the battery to the bulb, but it will stay off (P174, L1 – 7).

Only the positive charge will flow (P174, L8 – 12).

The bulb will have resistance only when it is connected to a circuit, and resistance can be calculated using the Ohm's Law equation; it depends on the voltage and current in the circuit (P175).

Charge and current are different because they are measured in different units (P177, L19).

4.4.4 Interview of Tishik

Tishik is a French-speaking 33-year-old student. This interview lasted for 27 minutes.

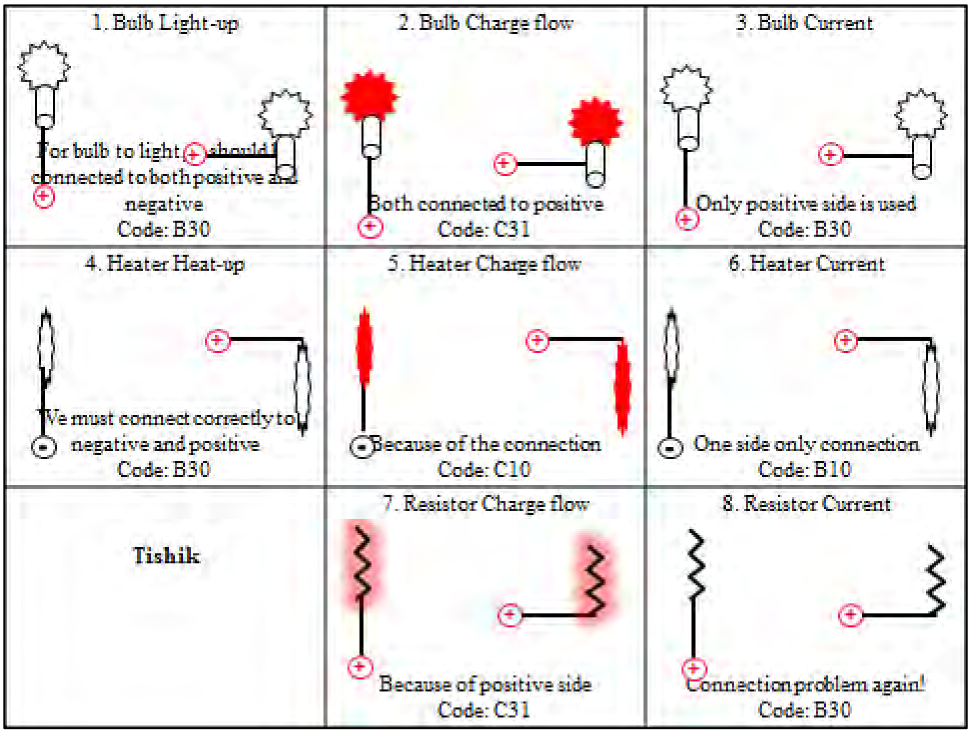


Figure 4.13: Tishik's FCRs with the Written Responses and code(s)

Figure 4.13 shows the combination of FCRs and brief Written Responses and code(s) for the eight questions. The filled (red) cells represent the activated elements and the unfilled (black) cells represent the inactivated elements. He answered five of the eight questions correctly with apparent circuit reasoning. However, in all the charge flow related questions (middle column), he opted for the choice VH (both will activate), with reasoning related to the positive terminal of the battery. Thus, the reasoning for the light-up of the light bulb, the heat-up of the heater and current in the elements, appears to be different to the charge flow in the same elements.

The full transcript of the interview can be found in Appendix 6.

4.4.4.1 Key Ideas from Tishik's interview

To light a light bulb, it should be connected to both positive and negative terminals of a battery (P187, L13 – 15, Figure 6.16).

Had experience with battery, bulb, and wire task, he was sure that if the positive terminal of the battery is connected to the convex part of the bulb, and the negative terminal of the battery is connected to the side of the light bulb, it will light up; but was not sure if the terminals of the battery were interchanged, (P187, L16 – P188, L14).

His reason was the same in the questions relating to current in a heater, resistor and light bulb. In the case of charge flow, he said charge will flow in a resistor because it is connected to positive terminal of the battery (P188, L23 – 24).

Charge will flow in an open circuit until the battery is not flat (charged) or runs out (P189, L1 – 9).

When there is a closed circuit (complete loop), there is current; with only one connection, charge will still flow. Current allows devises to work (P189, L14 – 24).

Electricity means: current, voltage etc., all of them; it is complex (P190, L7).

Charged means "enough electricity" in the battery (P190, L13 – 15).

4.4.5 Interview of Pam

Pam is a nervous 18-year-old female Xhosa-speaking student. This interview lasted for approximately 24 minutes.

Figure 4.14 shows the combination of FCRs and brief Written Responses and code(s) for the eight questions. The filled (red) cells represent the activated elements and the unfilled (black) cells represent the inactivated elements. The first row represents the questions relating to bulbs, the second row represents that of heaters and the third row represents that of resistors. In each cell, the reasons are given with the related codes. Thus, it is clear that five cells are filled (red) and the rest are empty (black). She chose six of the eight correct choices, all of them with apparent circuit reasons, "both terminals need to be connected".

The questions relating to the light bulbs were answered correctly, however, the questions relating to current and charge flow were not. In her opinion, there would be charge flow and current in the light bulb, but it would not light up; in order to light up there should be both positive and negative terminals to be connected. Her idea of charge flow and current without lighting up needed to be investigated in an interview.

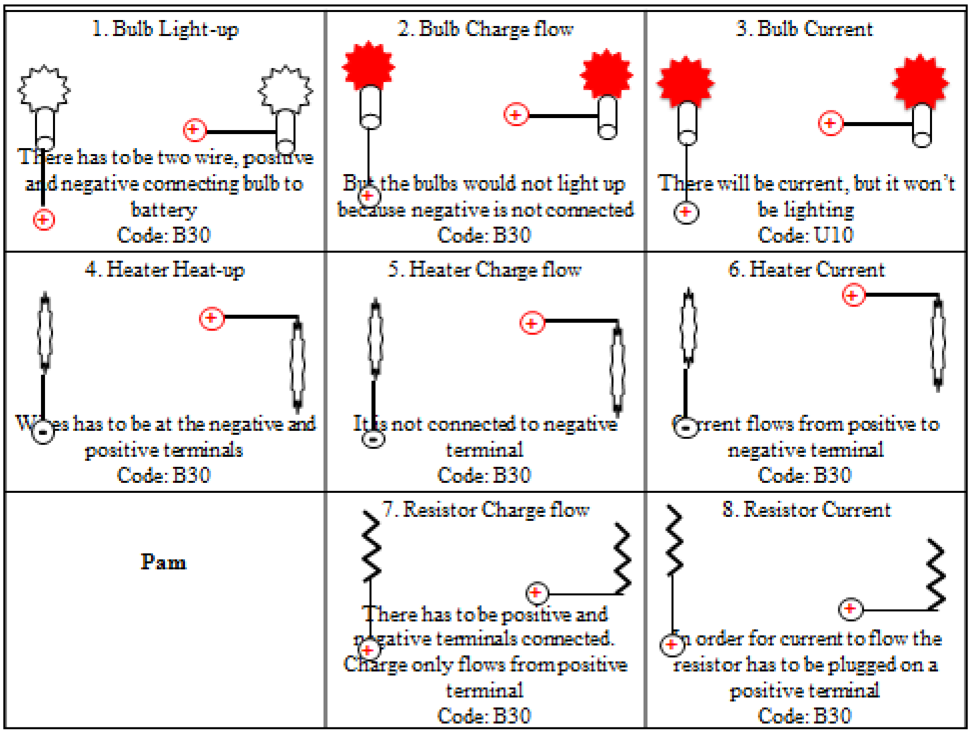


Figure 4.14: Pam's FCRs with the Written Responses and code(s)

4.4.5.1 Key Ideas from Pam's interview

Pam had no understanding of a resistor When asked about the resistance of each element (resistor, heater and light bulb), she was not sure of the resistance. However, during the interview, she learned that a resistor is something that resists the flow of charge in an electric circuit (P178, L25).

A battery has two charges, positive and negative. Both charges have to flow to the light bulb in order for it to light up (P178, L13).

From the interview, she learned that the charge flow and current are one and the same (P180, L19 – P181, L4).

After the test, she went home and read her textbook to check the answers she had written (P181, L8 - 14), and found that they were wrong. The test taught her something that she did not know before. In the interview, the reading prompted her to change her written answers to more acceptable answers (P180, L10).

4.4.6 Interview of Leo

Leo is an 18-year-old Afrikaans-speaking female student. The interview lasted for about 20 minutes.

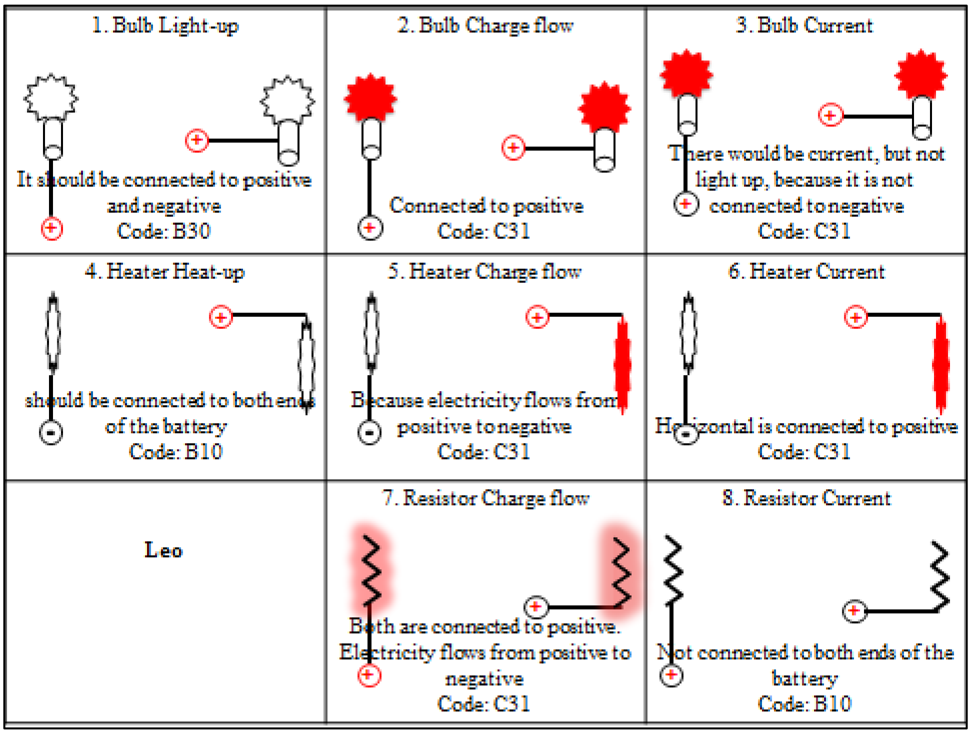


Figure 4.15: Leo's FCRs with the ideas in the Written Responses

Figure 4.15 shows the combination of FCRs and brief Written Responses and code(s) for the eight questions. The filled (red) cells represent the activated elements and the unfilled (black) cells represent the inactivated elements. The first row represents the questions relating to the bulb, the second row represents that of the heaters and the third row represents that of the resistors. In each cell, the reasons used and the corresponding code(s), for answering each question, are given. Thus, it is clear that five cells are filled (red) and the rest are empty (black).

In three questions, she opted for the correct choice with apparent circuit reasoning "both positive and negative need to be connected". However, she used this reason only in questions relating to the light-up of a light bulb, heat-up of a heater and current in a resistor. For the rest of the questions, she used battery and polarity-related reasons. In the questions relating to charge flow in a light bulb, her reason was "it is connected to positive", and her reason for current was interesting: "there would be current, but it would not light up because it is not connected to negative" (as well). In her opinion, for charge flow and current, only the

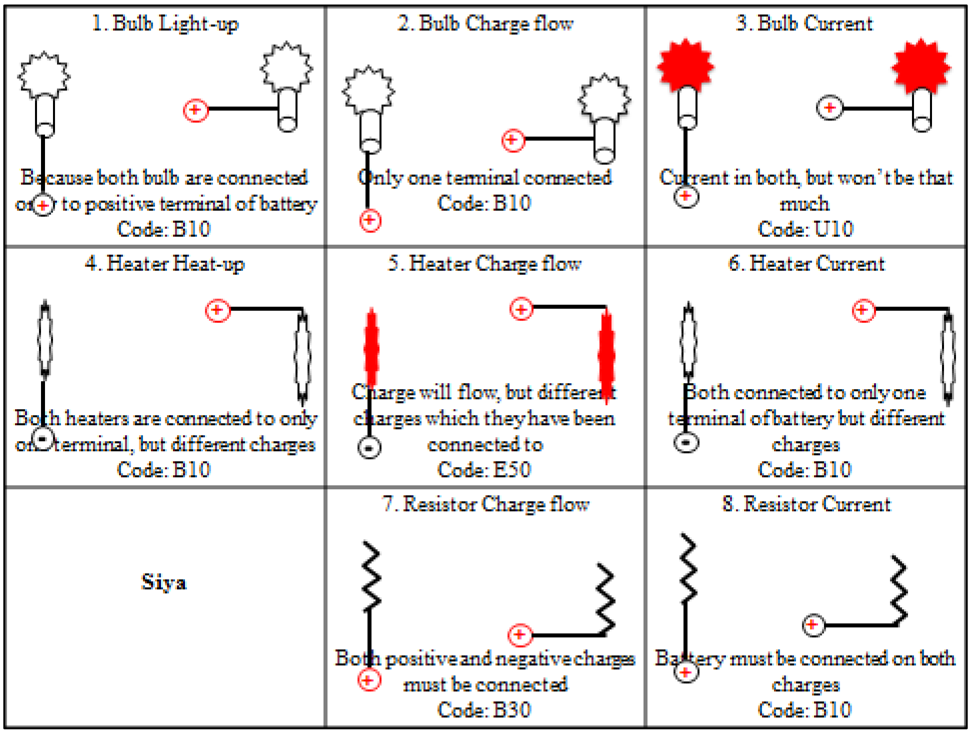


Figure 4.16: Siya's FCRs with the ideas in the Written Responses

positive terminal needs to be connected, but the light bulb would not light up and the heater would not heat up.

4.4.6.1 Key Ideas from Leo's interview

To light up a light bulb, there should be two wires connected from the battery to the light bulb, i.e. positive and negative terminals. However, Leo was not sure where or how these two wires have to be connected to the light bulb, i.e. the two terminal configuration of the light bulb was not familiar to her.(Figure 6.15, P184, L1 – 17; P185, L12).

Even if both terminals are not connected, there will be current, but the bulb would not light up (P184, L14 – 16).

If the light bulb is connected to the positive terminal of the battery, it will have charge flow although it will not light up (P183, L22 – 25).

She could draw a closed circuit correctly with a resistor, but not with a light bulb (Figure 6.15).

Only positive charge will flow (P185, L18-24)

4.4.7 Interview of Siya

Siya is an 18-year-old male student. He answered five of the eight questions correctly. The interview lasted 23 minutes. Figure 4.16 shows the combination of FCRs and brief Written Responses and code(s) for the eight questions. The filled (red) cells represent the activated elements and the unfilled (black) cells represent the inactivated elements. The first row represents the questions relating to the light bulbs, the second row represents that of the heaters and the third row represents that of the resistors. In each cell, the reasons used for answering each question are given. Thus, it is clear that six cells are red and the rest are black. Siya chose six correct choices from the eight questions and provided apparent circuit-related reasons. However, in the questions relating to current in the light bulb and charge flow in the heater, he opted for the choice VH (both would activate) with unexpected reasons.

4.4.7.1 Key Ideas from Siya's interview

The current will flow from both positive and negative sides of a battery to a light bulb in a closed circuit; in an open circuit, current will flow from only one terminal. Therefore, the bulb will not light up (P191, Figure 6.17)

The light bulb would not light up because there was only one connection. There must be two connections to get enough current from both sides to light up the bulb (P193, L13 - 31).

There must be two charges flowing in order to get current. Whatever is flowing is current when the circuit is complete, i.e. when both the charges from both sides flow, it is called current (P195, L15 – P196. L7).

He was visualising the light bulb circuit in order to answer the other (heater and resistor) questions.

4.5. Summary of the interview results

The summary of the ideas from the interviews is shown in Table 4.2. The interview results clearly demonstrate that the students were engaged in a sense-making exercise while answering each question in the situation. In Chapter 5, the results of Chapter 3 will be interpreted through a sense-making framework, since the interviews involved turned out to indicate a deep underlying mechanism of sense-making. All these interviews provided evidence of a sense-making exercise. As will be shown in Chapter 5, through the results of UN1 and UN2, these two datasets were regarded as statistically equivalent and used sense-making as a form of argument.

Table 3.2: Summary of interview results

Names	Key points from interviews	Experience-based reasoning
Sherif	The bulb will not light up, but it will have charge flow. Bulb has polarity. Resistor is not exactly the same as bulb or heater. Current or charge dissipates in the resistor. Current is responsible for a unit to work. Charge flow is a certain measurement; it is not responsible for the unit to work.	If you touch a live wire, you get electrocuted. When you reverse the battery in any devise, it will not work!
Baba	You need two batteries to light up a bulb and you need to put them in a typical configuration. No current in the bulb. Resistor triggered the equation. Heater would work if connected to +ve terminal.	In a TV remote control, there are two batteries. If you turn the battery around, it will not work. Bulb is not a resistor. When using eqn. $I=V/R$, from question, V = battery, but there is no resistor in the circuit, i.e. $R = 0$, therefore $I = 0$.
Asie	Bulb will not light up. Bulb has a high resistance and heater has a low resistance. There will be current in the open circuit, but bulb will not light up. Current flows in a resistor when there is a complete circuit.	The side of the battery is insulated (bayonet); you must connect both wires to the bottom of the bulb. The side of the bulb is just to hold the bulb. Resistor resists current. Since bulb needs only low current, high resistance of bulb prevents high current from entering the bulb. Since the heater needs more current, its low resistance helps it to get high current.
Swala	If there is no current in a circuit, there is no resistance; resistor is a dynamic element. Wire can be connected to any part of the bulb. If connected to +ve terminal, heater will heat up. Resistor and battery are connected parallel, if they are figuratively parallel. In an open circuit, charge will flow. Current and charge are different.	In equation $R = V/I$, if $I = 0$, then $R = 0$. Charge and current are measured in different units.
Tishik	If the +ve of battery is connected to bottom of bulb, it will light up with the –ve to the side. Charge will flow in an open circuit until the battery runs out.	Not sure about the reversal of polarity. He has done it in the first configuration.
Pam	In an open circuit, charge will flow but it will not light up. She went and referred to the book after the test; learned that she answered incorrectly in the test.	Because only one charge is flowing.
Leo	She knew that the bulb would not light up; there must be two wires connected. But she was not sure how to connect. She connected a short circuit.	The mystery of two terminal configuration of bulb. She could draw a closed circuit with a resistor; but with bulb, a short circuit.
Siya	The current will flow from both positive and negative sides of a battery to a light bulb in a closed circuit. In an open circuit, current will flow only from one terminal. If the light bulb is connected to only one terminal, there will be current, but it will not light up. Whatever is flowing is current when the circuit is complete, i.e. when both the charges from both sides flow, it is called current.	He was visualising the light bulb circuit to answer the other (heater and resistor) questions. The randomising of the answers produced repetitive bias. Thus, in certain cases, the selection of the choice and the written reasoning did not match. However, some of them changed the answer choices during the interview.

Chapter 5
Discussion

The results of the Forced Choice Responses in the Exploratory Main Study (Chapter 3) clearly show that the student responses were highly context dependent. This is consistent with the broad literature on KIP (diSessa 1993; diSessa 1988; Brookes & Etkina 2009). Furthermore, the analysis of the Written Responses indicates that a wide variety of ideas were used to answer the instrument. In order to confirm whether these might only apply to the group in question, a second study was done on a second cohort at a different university. The Confirmatory Main Study showed a similar pattern, in that there was a similar range of ideas associated with the changes in context. While the overall patterns of responses for UN1 and UN2 appear to be superficially similar, what is of importance is to what extent the reasoning patterns based on the Written Responses are equivalent, so that a single explanatory model might be proposed.

5.1 Establishing the "idea equivalence" of UN1 and UN2

In order to establish the level of "idea equivalence" of the two cohorts, their reasoning patterns were compared based on the coding of the ideas, assigned to the Written Responses. Table 5.1 shows a comparison of the frequencies that were obtained for the Emergent Categories (see Table 3.5) for UN1 and UN2 respectively. The table shows data based on the total number of responses to the eight questions per group, i.e. for UN1, 480 responses from 60 students and for UN2, 712 responses from 89 students.

Table 5.1: Comparison of frequencies (% of responses) of Emergent Categories for UN1 and UN2

#Responses	Emergent Categories						
	A	B	C	D	E	F	U
UN1=480	13	17	34	6	12	5	14
UN2=712	10	15	42	5	9	4	13

Thus, for example, 62 out of 480 responses (13%) of UN1 used the ideas associated with Category A to answer the questions. In order to make a simple statistical comparison between the two groups, 95% confidence intervals were calculated (Ref. Appendix 10). The data from Table 5.1 together with the 95% intervals are shown in Figure 5.1. The blue bars represent the frequencies of the dataset UN1 and the red bars represent that of UN2.

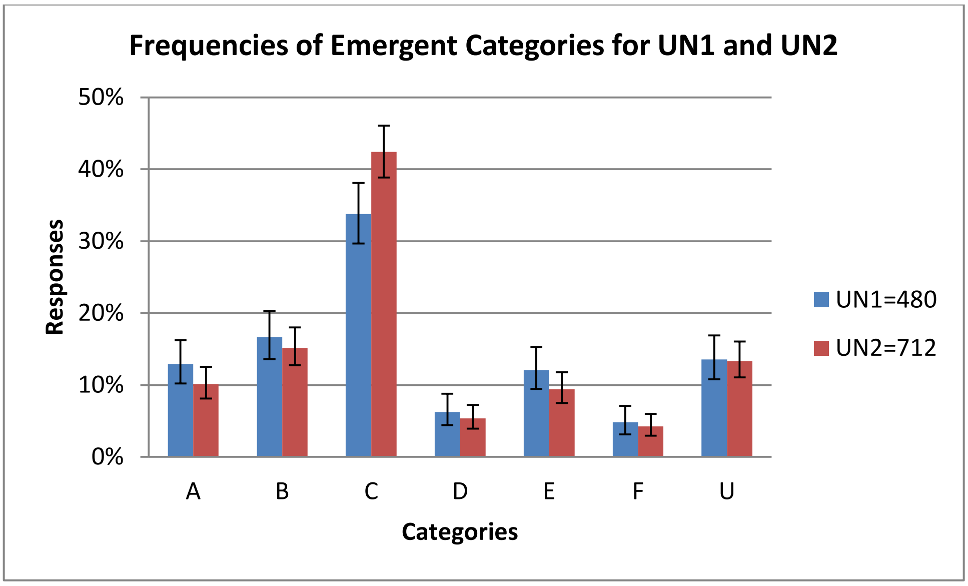


Figure 5.1: Percentage of frequencies of each category for the two groups UN1 and UN2. The error bars indicate the overlapping of 95% confidence intervals.

It is clear and striking that the results for each category are in agreement with each other. Thus, the students in both groups can be regarded as reasoning in the same way when presented with questions that are related to a DC circuit and where the context of the presentation changes.

5.2 The combined dataset

Based on the equivalence of the two groups, any subsequent analysis was done by combining the two cohorts into a single group. Table 5.2 shows the combined data at the level of the

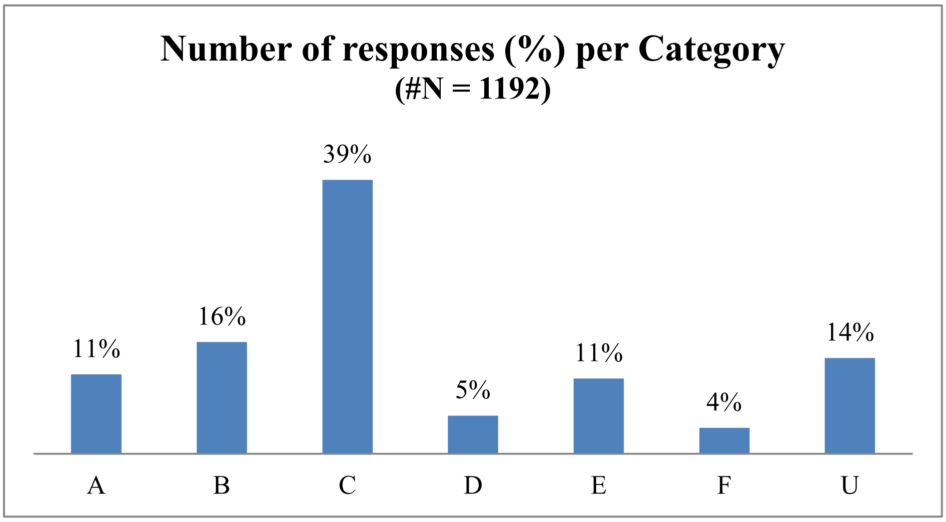


Figure 5.2: Frequencies (%) of reasoning categories of the combined group (UN1 + UN2)

Table 5.2: Frequencies of six Emergent Categories for the combined dataset (UN1 + UN2).

The total number of responses = 1192 (149 X 8).

Fine-grained Emergent Category	Light Bulb			Heater			Resistor		Frequency	Emergent Category	%
	Light-up	Current	Charge flow	Heat-up	Current	Charge flow	Current	Charge flow			
A10	13	15	13	9	17	11	15	16	**109**		
A30	5	4	0	2	1	1	2	3	**18**		
A40	1	1	1	0	2	0	1	0	**6**		
A50	0	0	0	0	0	0	0	1	**1**		
A60	0	1	0	0	0	0	0	0	**1**	135	**11**
B10	9	7	10	13	11	11	7	7	**75**		
B30	27	14	6	16	10	13	13	9	**108**		
B40	2	0	0	0	0	0	0	0	**2**		
B50	0	0	0	0	0	0	0	0	**0**		
B60	2	1	1	1	0	0	0	0	**5**	190	**16**
C10	9	16	18	12	22	18	13	10	**118**		
C21	9	3	4	0	0	0	8	0	**24**		
C22	5	4	5	0	0	0	1	0	**15**		
C23	21	11	14	20	14	14	15	12	**121**		
C30	3	3	3	3	3	5	5	7	**32**		
C31	9	25	16	17	9	16	7	21	**120**		
C32	1	2	0	0	0	0	1	2	**6**		
C40	0	2	1	0	0	2	3	0	**8**		
C50	0	1	3	1	2	1	1	1	**10**		
C60	2	0	0	2	2	0	1	1	**8**		
C70	1	0	1	1	0	0	0	1	**4**	466	**39**
D71	1	1	1	1	0	0	1	1	**6**		
D72	0	4	1	10	9	5	4	2	**35**		
D73	1	0	1	1	1	0	1	1	**7**		
D75	2	1	2	1	0	3	1	2	**12**		
D76	1	1	0	1	0	1	0	2	**6**	66	**5**
E40	4	6	7	4	8	8	11	8	**56**		
E50	2	4	10	4	1	9	1	10	**41**		
E60	6	3	6	3	3	4	2	4	**31**	128	**11**
F80	3	0	0	3	3	0	4	2	**15**		
F81	2	3	2	3	2	0	4	1	**17**		
F82	1	1	1	2	2	1	2	2	**12**	44	**4**
U00	3	2	8	6	8	12	4	5	**48**		
U10	4	13	14	13	19	13	21	18	**115**	163	**14**

fine-grained coding that was carried out on the Written Responses of the two cohorts. Thus, the total number of students is 149 (60 + 89); and the total number of responses is 1192 (149 X 8). The percentages shown in the last column (Emergent Category) correspond with the sum of the pairs of bars shown in Figure 5.1. Figure 5.2 is a graphical depiction of these results. For completeness, the main idea associated with each category is listed:

A = *Completeness or "closed-ness"*
B = *Two terminal argument*
C = *Connected to a specified element*
D = *Absence of an element*
E = *Current/charge/energy/electricity*
F = *Series and/or parallel*
U = *Uncodeable*

As is consistent with the individual datasets, the largest emergent response category was C. This is the category relating to the students who reasoned "connected to" any element or battery, or "not connected to" any element. The frequency of Category A was 11%, this is the category relating to the argument "completeness or closed-ness of the circuit"; the frequency of Category B was 16%, this is the category relating to the two terminal argument; and the frequency of Category C was 39%. The other categories relating to arguments such as absence of elements, presence of current, energy, charge and electricity amounted to 34%.

5.3 Findings from the combined dataset

The key findings from the data support the overall notion that context is a key factor in the student engagement in a DC circuit task (Finkelstein 2005). This is consistent with framework often referred as Knowledge in pieces (diSessa 1988; Scherr 2007; Hammer & Elby 2005; Wagner 2016). The data also indicate a number of interesting aspects which are described below. These relate in particular to the initial ideas that are triggered by the context. In turn these ideas relocate to prime experiential episodes that are drawn in order to make sense of the task in hand.

5.3.1 Foothold/main ideas based on the Written Responses

One of the intriguing features at the outset of the study (e.g. Tables 3.9 and 3.13) was that many students changed their ideas several times while responding to the questions. A minority of students appeared to stick with a single idea, while a few students appeared to use almost as many ideas as questions. In order to probe this further, the number of reasons used by an individual student was calculated in order to see whether the number of ideas used in reasoning across the ACQ could be related to the number of answers that were correct. Since each Emergent Category could be regarded as a broad umbrella for a similar set of ideas, the number of different Emergent Categories (A – F) that each student used in answering the ACQ was calculated. The combined results for UN1 and UN2 are shown in Figure 5.3 where the term "Reasoning Idea" is used as a shorthand term to indicate an idea that was used as the basis of the reasoning that was provided in support of the Forced Choice Responses.

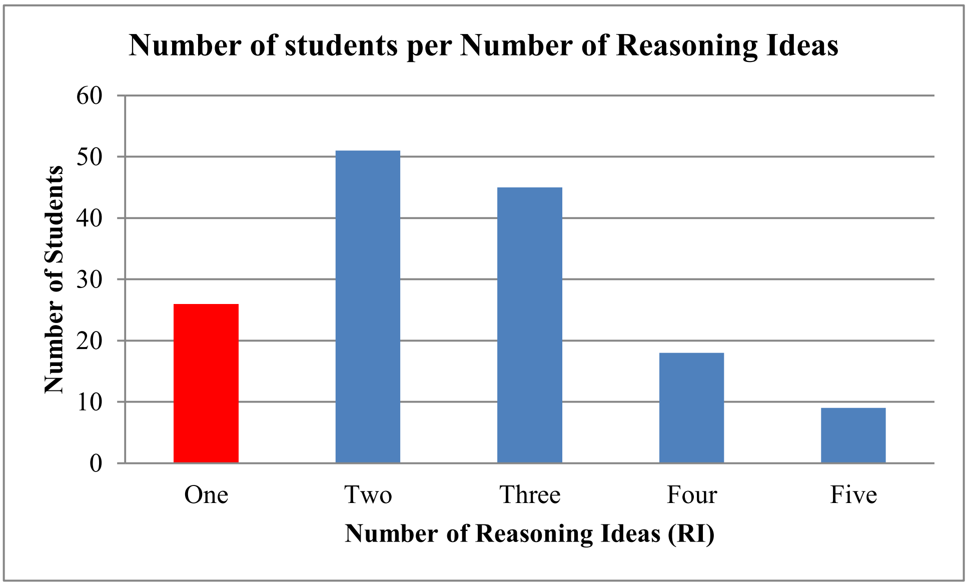


Figure 5.3: Distribution of students according to the number of Reasoning Ideas used in answering the ACQ

Along the x-axis, each bar represents a number of Reasoning Ideas (RI) ranging from one to five. The height of each bar shows the number of students in that category. Thus, 27 students used only one RI to answer all eight questions; 51 used two RIs; 45 used three RIs; 18 used four RIs; and nine students used five RIs to answer the eight questions. It was clear that hardly any students who used more than one RI answered all eight questions correctly, and that the highest proportion of students with all-correct answers were associated with the single RI category. A closer analysis of this category of 27 students shows that the actual Reasoning Idea that was used was distributed across the Emergent Categories as follows: A = 7, B = 10, C = 8 and U = 2. Figure 5.4 summarizes this distribution. In addition, the number of all-correct responses is shown in red.

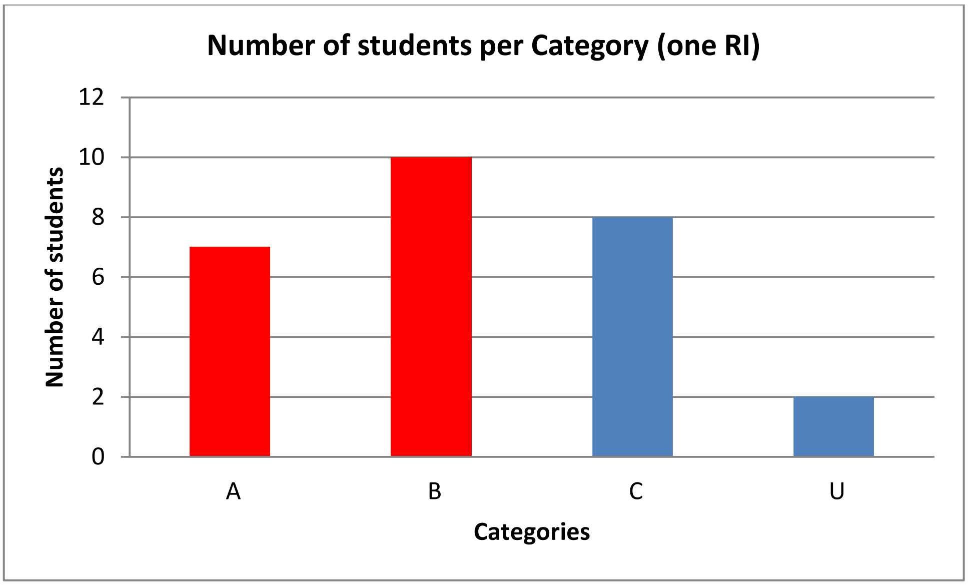


Figure 5.4: Detailed distribution of students (27) who used one RI to answer all ACQ questions.

The x-axis shows the letter representing the Emergent Categories. All students in Categories A and B answered all the ACQ questions correctly while none, among this group (one-reason), who used C did so. What is most interesting is that all students in the first two categories A and B (7+10) answered all the questions correctly. It is clear that the ideas expressed in A and B are key starting points (foothold ideas) that lead to correct outcomes in all cases. While the two categories A and B emerged separately from the data, as described in the analysis, it is clear that both can be regarded as subscribing to the same idea, namely that there needs to be an unbroken path all the way around the circuit in order for anything to work or flow.

It is also clear, however, that the context also primes a number of other ideas that form the footholds for subsequent reasoning. However, these foothold ideas are not productive in the sense that subsequent reasoning based on them does not lead to the correct outcomes. The way in which these ideas are triggered by the context is highlighted by the thrust of the findings from the interviews as discussed below.

5.3.2 Sense-making and the ambiguity of prior experience

While it was clear from the way in which the students had engaged with the ACQ that their responses were well considered (Section 3.1.2), the interviews (Chapter 4) were undertaken to probe a few cases in which sense-making did not appear to be evident. In all cases, the interviews indicated that, in the process of answering the questions, the students were trying to make sense given their prior experiences relative to the task. However, it became clear that reasoning correctly from experience did not always lead to the (canonically) correct conclusion.

The following is meant to illustrate such ambiguity, and the example comes from a close reading of some of the Written Responses: consider a flashlight with a (non-LED) light bulb. Experience shows that the flashlight will only work with the batteries inserted in one orientation, usually indicated by + and - signs in the battery compartment. Turn the batteries around and the flashlight will not work. A fair conclusion is that the bulb only works when the correct polarity of the batteries is observed. However, this is of course incorrect, as the reason for the flashlight not working is a mechanical one, not an electrical one. The interview episodes below, summarised from Chapter 4 and Appendix 6, capture this ambiguous feature of sense-making. In the first two examples, the RIs used <u>do</u> in fact lead to correct conclusions, but it is clear that the RIs, while clearly rooted in sense-making, are themselves incorrect.

In the case of Baba, she expressed that, in her experience, in order for a TV remote control to work, two batteries connected in opposing orientations were necessary. Baba then "transferred" (Kaminski et al. 2005; Kryjevskaia et al. 2013) this notion to the situation of a light bulb, which she perceived to be similar. Thus, she reasoned that the bulb would <u>no</u>t light up since, in the given circuit, there was only one battery. In this case, she came to the correct conclusion but for incorrect reasons. Thus, the battery was used as a "priming" agent to trigger resources that were then used to respond to the task. The number of batteries and the way they were configured, "one up and the other down" in her words, provided the main foothold for the reasoning that followed. However, using these RIs would, of course, not always lead to the correct conclusions in all cases, as is clear from the details provided in Chapter 4.

Another example is that Asie (Section 4.2; Appendix 6.2) correctly answered the question relating to the (non)-lighting up of the bulb. His reasoning was as follows: a bulb cannot work when the connection is to the side; for it to light up, a connection to the bottom of the bulb must be indicated. During the interview, it was revealed that he was only familiar with the bayonet-cap bulb, and not the screw cap bulb (see Figures 6.4 and 6.5 in Appendix 6.2). Thus, his RI was indeed consistent with his experience[1]. Furthermore, the way he reasoned could not be faulted. However, in this case, limited experience meant that the RI was not correct in the broader scheme of things, despite the reasoning.

A very interesting episode was presented by Sherif in that his Foothold Reasoning Idea was that a bulb has a polarity and that it would only work when the correct polarity was used, i.e. the positive terminal of a battery must be connected to the "negative" terminal of a bulb and the negative terminal of the battery to the "positive" terminal of the bulb, "otherwise it may burst". His RI was based on his experience that battery-operated devices would only work when the batteries were connected in a specific orientation. His RI is in fact mentioned in the illustrative example above.

Another interesting RI that he generated was based on his experience that touching the open end of an electrical cable resulted in people being electrocuted. Using this RI, he reasoned that there would be charge flow at the end of a resistor (a non-device similar to a cable), but that a device such as the bulb would not light up, as it needed a return path. Thus, his experience led him to distinguish between a resistor and a resistive device. A similar notion, based on experience, was expressed by Tishik who indicated that two wires from the battery needed to be connected to the element in order for it to work, but that there would be something at the end of the open circuit "to react with the other side of the battery". The other interviewees also tried to make sense in similar way.

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[1] Houses in South Africa usually only have one or the other type of fitting (bayonet or screw) and often, in rural areas, the bayonet caps are most widely used.

5.4 Toy Model of Task Engagement

The overall findings described in the preceding sections provide a basis for developing a model of student engagement which is described below. The previous sections provide evidence for two key mechanisms that appear to underlie the pattern of student responses. The first is that the context primed a wide range of ideas that were "spontaneously" generated. Secondly, even though the responses were incorrect, they did not appear to be random attempts at answer-making, but were reasoned from these initial foothold ideas. In order to describe and offer an explanation of the overall process from initial student engagement to the actual declared response, a "Toy Model" of task engagement and processing is proposed.

The main features of the Toy Model are depicted in Figure 5.7, in which the key stages in processing the task are shown. As shown in the figure an individual student is presented with a task, in this case, a question from the ACQ. The figure is divided into four large rectangles as follows: the top rectangle (yellow) indicates the external world in which the *task* and the *student responses* are exhibited. The remaining three rectangles show aspects of the internal, cognitive world of the student. The bottom rectangle denotes the world of *past experiences* (blue) that gives rise to a set of *resources* (bottom grey) derived from particular experiential episodes. Both past experiences and resources pertain to *long term memory* as shown. The second from top rectangle (grey) shows aspects of *working memory* that is used to process the task.

The essence of what happens in working memory, that is pertinent to the present study is described by using the Idea Space model (Allie & Demaree 2010). The IS model was developed to explain the impact of affective factors on students' engagement with a physics task at the level of "backstage cognition". As described in () the Idea Space is the set of resources that are triggered by a particular situation or task that can be used in the service of solving the problem at hand. Because working memory has a finite span, this set of resources is described by a geometrical metaphor, namely, a space that is bounded, and which is affected by several factors. For example, the "size" of the IS is affected (positively or negatively) by the way in which the task is presented, the "voice" of the task, monitoring activities, fear etc. However, for the purposes of the present Toy Model, these factors will be assumed to be of non-primary concern. Rather, the most important aspect of the IS that is relevant here is the fact that once resources are triggered / activated, the set is bounded and

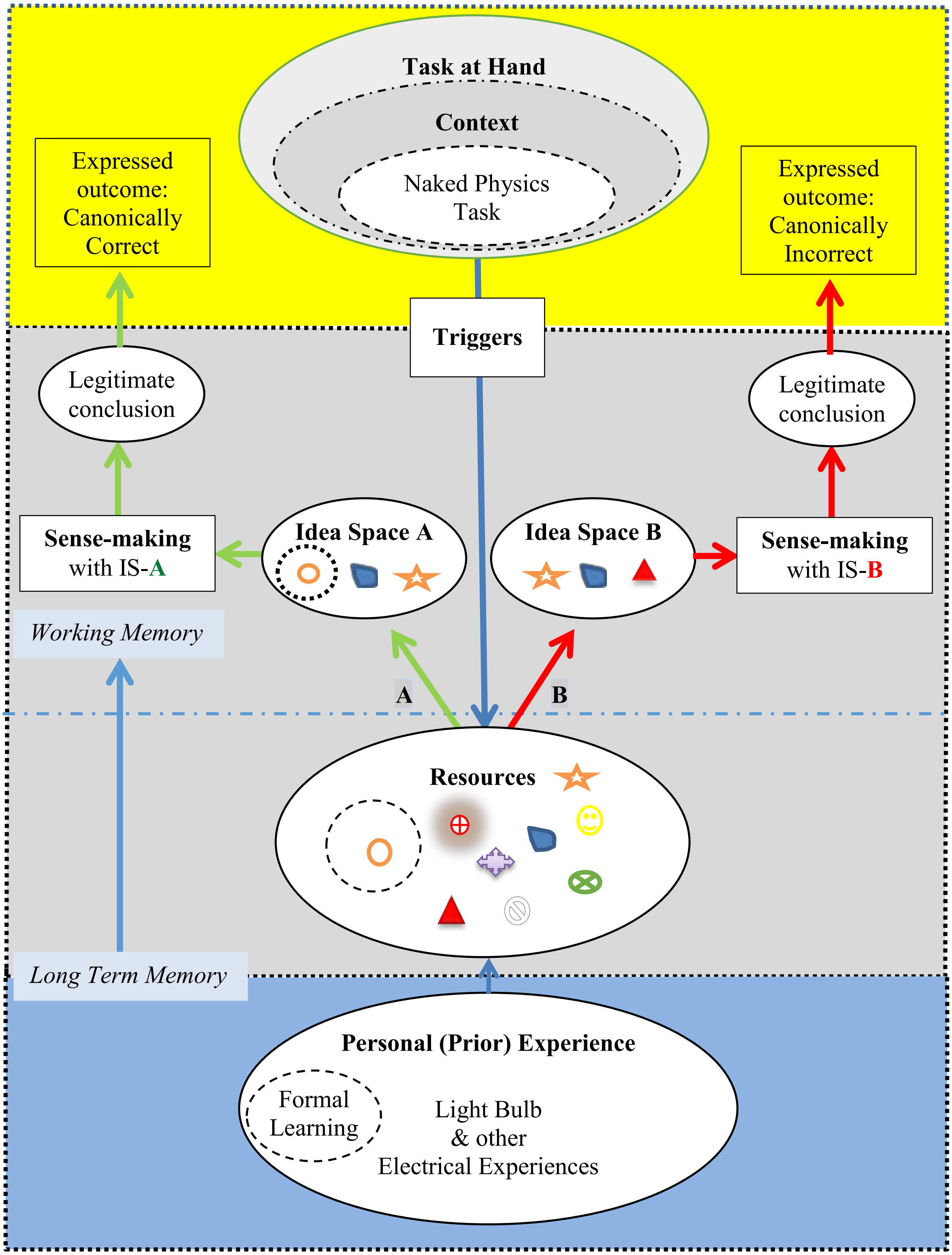

Figure 5.7: Toy Model of Task Engagement showing two pathways that could be followed by a particular student. Pathway A shows a sequence of events when the student has the resource of "loop continuity" available (circle enclosed within dotted circle), while B shows the sequence when the resource is absent. In both cases sense-making is applied. The third possibility which is

fixed for the step of reasoning and sense-making attempts. From a working memory perspective, using the model of Baddeley and Hitch (Baddeley, A.D. and Hitch 1974) and subsequently modified by Baddeley (Baddeley 2000); the latter can be thought of as being associated with the episodic buffer).

5.4.1 Functioning of Toy Model

The process depicted in Figure 5.7 can be described as follows: the physics task that is presented (top bright yellow rectangle) can be regarded as comprising a "naked physics task" clothed in a specific context. The term "naked physics task" (NPT) is used in the descriptions below in order to separate it from a question in which the physics concept is embedded in a more complex context. Thus, in the ACQ, the tasks with resistors would be NPTs while the light bulb and heater questions would not be. We suggest that the process of solving a given task follows the following sequence. When a student interacts with the given physics task (embedded in a real-time situation), it triggers the resources that have already been acquired from previous experience and the solution is found on the basis of a true-life situation. During this process, a student who has the naked physics resource (sense-making subset A in the Toy Model) identifies the physics situation embedded in the real-time situation, and finds the physics solution. On the other hand, a student who does not have the required canonical physics resources will use the available resources (sense-making subset B in the Toy Model) to solve the task at hand and will arrive at the wrong conclusion. For example, in this study, in a typical context of DC circuits, the overall instrument can be thought of as eliciting the responses that would, to an expert, be a single Naked Physics Task (NPT) namely, that for a current to pass through a resistive element, the circuit needs to be closed.

The NPT is then presented embedded within two contexts, that of the light bulb and that of the heater. The task that is presented at a given time triggers a set of resources that is primed to engage with the problem, and of which a subset is then used to process the problem to its answer. The resources that are triggered depend ultimately on prior experience.

It is important to note that model does not show an answer-making path to the correct canonical answer, which would simply a learned, rote response based on classroom experience. One reason for this is that the data show no significant such responses as has been argued in the previous sections. This is likely to be as a consequence of the fact that the instrument did not only require a forced choice response that could be answered intuitively but forced a degree of reflection to take place via the free writing that followed. Thus, unlike the descriptions provided by dual processing theories (Barrett et al. 2004), the responses appear to involve only the "slow thinking" (Kahneman 2011) part as described in such theories. The two paths shown in the Toy Model of Engagement emphasize the outcome of engaging in deliberate reflection but in which the correct answer cannot be obtained in this way.

5.5 Issues around prior experience

As noted earlier, in the area of mechanics all the resources required for successful engagement appear to be derivable by refining experience. In the present situation this does not appear to case, in particular, insofar as the critical resource of loop continuity is concerned. For example, in the case of the light bulb, students would have experienced the light bulb in a variety of ways in everyday life. These experiences include the following possibilities: a switch in one position turns the light bulb on, a switch in the opposite position turns the light bulb off; bulbs are screwed or fitted vertically into sockets in ceilings (in most cases); the bulbs appear to be hanging in a single cable from the roof; being further away from the bulb decreases the brightness of the bulb, while being closer increases the brightness; being further away decreases the heat of the bulb, while being closer increases the heat etc. However, nowhere in these experiences is there any evidence of the fact that a closed loop is required for functioning of a DC circuit.

Of the many experiences, one of the most likely experiences regarding light bulbs is that they are usually used in a vertical orientation, while bar heaters (the most common heater in South Africa) are used in a horizontal orientation. Thus, when confronted with these artefacts, the preferred orientation is likely to be primed, i.e. the students suggest that the light bulb will work when it is preferentially associated with a vertical bulb while, in the case of the heater, the preferred orientation is horizontal. From another perspective, students are unlikely to respond that a horizontal light bulb will not work or that a vertical heater will not work, as these ideas do not form part of the IS. Thus, the model (Section 5.4) would predict that the responses (FCRs and WRs in Sections 3.1 and 3.2) might reflect this in some way. On the other hand, insofar as the resistor is concerned, there is no such experience with regard to resistors, and it is likely that there will not be a difference in responses (vertical, horizontal). Two sets of analyses were carried out as described below in order to see to what extent these assertions might be true.

Based on the responses in Table 3.3 and Table 3.10, the first analysis was performed in which the responses to the horizontal and vertical orientations were compared to see if there was any association of the kind between light bulbs and heaters, as mentioned with regard to the phenomenological aspects, i.e. light-up or heat-up. Figure 5.5 shows the results of the exercise for the combined dataset of 149 students.

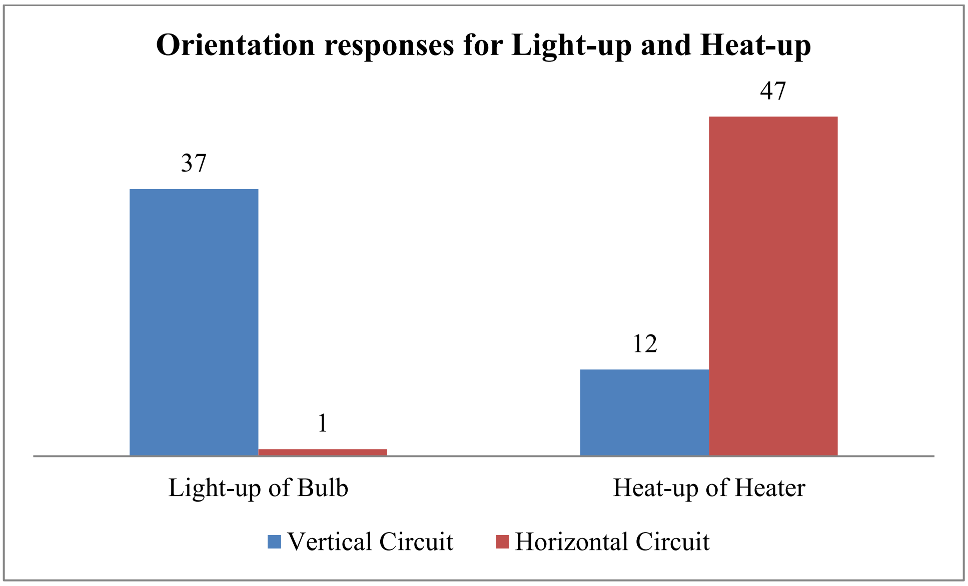

Figure 5.5: The number of students who indicated that (a) the light bulb would light-up and (b) the heater would heat-up, when each is in vertical or horizontal orientations, respectively.

The blue bars represent the number of students who suggested that the bulb or heater in the vertical circuit would activate; and the red bars represent the number of students who suggested that the bulb or heater in the horizontal circuit would activate. It is clear that there is a strong association with vertical bulbs lighting up and horizontal heaters heating up. Thus, while 37 students indicated that the bulbs in the vertical circuits would light up, only one student was of the same opinion in the case of the horizontal bulb. For the heater, on the other hand, 47 students suggested that the horizontal heater would heat up, while only 12 suggested that the vertical heater would heat up[2].

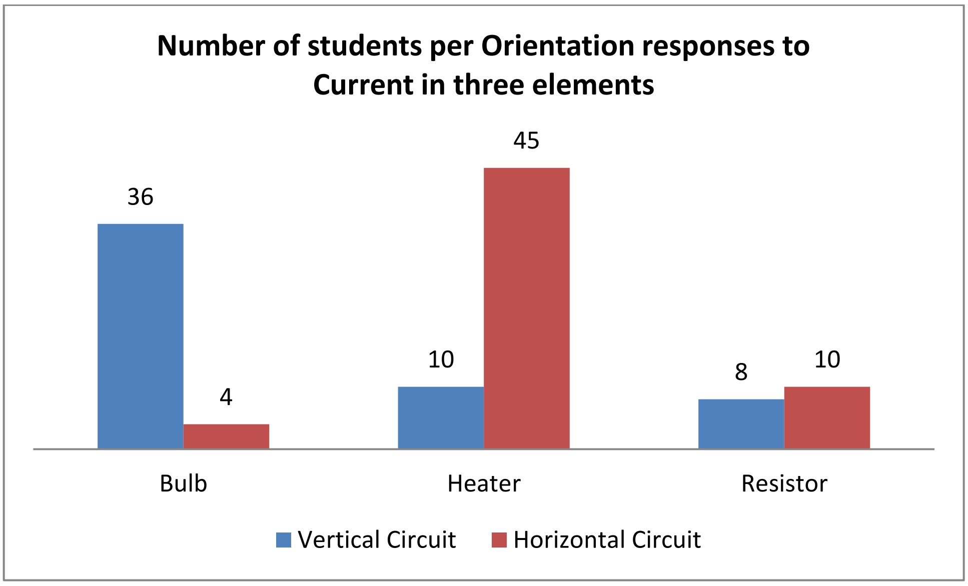

Figure 5.6: Student responses to the questions relating to current in vertical and horizontal circuits for the three elements.

A similar analysis was carried out to include the resistor, as the previous exercise did not have an equivalent for light-up and heat-up with regard to the resistor. Thus, the Questions 3, 5 and 8 (Figure 2.3), in which the presence of current was asked for all three elements was compared using the graph in Figure 5.6.

Figure 5.6 shows comparative responses to the questions relating to current in three elements. The three sets of two bars represent the number of students who responded to current-related questions for the three elements. The blue represents the vertical circuits and the red represents the horizontal circuits of each element. While 36 students suggested that the vertical light bulb would have current, only four suggested the same for the horizontal light

[2] Figure 5.5 represents the number of students who opted for the light-up and heat-up in the vertical and horizontal circuits only. Therefore, the sum of the numbers will not add up to 149, i.e. the rest of the students opted for the other two choices – both will activate and neither will activate, together this will add up to 149.

bulb. Conversely, while 45 students suggested that the horizontal heaters would have current, only ten had the same opinion in the case of the vertical heaters[3]. Thus, the results for the light bulb and the heater are consistent with those shown in Figure 5.5. However, the resistor shows two differing features. Firstly, the number of students who suggested that there would be a current in the resistor (18) was significantly lower than for either "current in the bulb" (40) or "current in the heater" (55). Secondly, there is no significant difference between the numbers in the results for the vertical and horizontal resistors. The 95% confidence interval with error bars is given in Appendix 9.

It is to be noted that, in the high school curriculum in South Africa, DC circuits are introduced using light bulbs, with special schematic symbol, a cross inside a circle.

5.6 Structural versus functional aspects of understanding

It has been suggested that the structure of the light bulb is not known to students, and therefore causes problems (Engelhardt et al., 2004). This may be true to a certain extent. However, it is not the structural aspect, but rather the functional aspect that needs to be understood. Consider a circular railway track that allows a train to go round and round. If a section of the track is stolen, then the railway line will be *closed* because there is an *open* section of the track. For the railway line to function again (i.e. to be *open*), the track must be fixed by *closing* the structural gap that is now there. Thus, the railway track needs to be structurally *closed* (*complete loop*) for the line to be *open* (functional again). However, in the case of the DC circuit, the physical path must be closed (close the switch; complete the circuit) so that the function of charge *flow* (current) can take place. However, in order to understand why the structural railway needed to be fixed (closed), the functional aspect first had to be understood. Thus, the notion of loop completeness or *loop continuity* precedes the

[3] Figure 5.6 represents the number of students who opted for the presence of current in vertical and horizontal circuits only. Therefore, the sum of the numbers will not add up to 149, i.e. the rest of the students opted for the other two choices – both will activate and neither will activate, together this will add up to 149.

structure of the light bulb. Therefore, understanding the structure of a light bulb needs to be preceded by the understanding of *loop continuity* – the path must exist.

However, in everyday situations, it is hard to come up with examples where the closure of a loop makes something work. Even rarer are direct experiences where the structural closure of a loop results in the dynamic functioning of some situation. When we switch on a device, the switch is up or down (left or right), is termed as on or off, and operates a device without any *closed loop* being apparent. [It should be noted that, in South Africa, most houses have ceiling lights with switches on a wall some distance away. Thus, young children are often intrigued by this "action at a distance" and persist in switching the lights off and on]. It is also unfortunate that the water analogy has the following issue: when the tap is "opened", there is flow and when it is "closed", the flow is prevented, which is seemingly the opposite to the switch, which is identified to be analogous to the electric switch.

Thus, it seems that, in the case of DC circuits, establishing the notion that loop closure is required for workability may be a good starting point and this is best done in the more abstract context of a resistor (and an ammeter, for example), rather than using artefacts that students have already experienced. This might appear to go against the usual way of teaching mechanics, for example, where concrete examples are refined and simplified until a model that is compatible with the Newtonian world is reached (Hestenes, 1987). However, it is clear that, in the latter case, prior experience can indeed be refined. However, "refining" in the absence of a Foothold Reasoning Idea (*closed loop*) that is derived from experience does not seem possible. Rather, as has been shown from the data, a less productive foothold idea will be primed for subsequent reasoning (Sloutsky et al., 2005; Kaminski et al., 2008).

The present work appears to show that, in the case of DC circuits, going from the abstract to the concrete might be a more beneficial teaching approach than the more well-known approach that starts with the concrete. Thus, the findings of the present study appear to support those of Kaminski et al. (2008, p 455) who noted the following:

> Our findings suggest that giving college students multiple concrete examples may not be the most efficient means of promoting transfer of knowledge. Moreover, because the concept used in this research involved basic mathematical principles and test questions were both novel and complex, these findings could likely be generalized to other areas of mathematics. For example, solution strategies may be less likely to transfer from problems involving moving trains or changing water levels than from problems involving only variables and numbers. Instantiating an abstract concept

> in a concrete, contextualized manner appears to constrain that knowledge and to hinder the ability to recognize the same concept elsewhere; this, in turn, obstructs knowledge transfer. At the same time, learning a generic instantiation allows for transfer, which suggests that such an instantiation could result in a portable knowledge representation. Compared with concrete instantiations, generic instantiations present minimal extraneous information and hence represent mathematical concepts in a manner close to the abstract rules themselves.

While the findings mentioned are in the domain of mathematics, it is suggested that DC circuits present a similar situation in physics.

5.7 Summary and Conclusions

The present work is the first systematic study, carried out in the area of direct current circuits, in which the role of context on student responses is carefully investigated.

In particular, the author studied the contextual dependence of students' responses at a fine-grained level. These contextual variations were made using an open circuit with only three components: a battery, a single wire and a resistive element. The battery and the wire were kept constant both in terms of written description and diagrammatically, while three aspects were varied as follows: three resistive elements were interchanged in questions (bulb, heater, resistor), two diagrammatic orientations were used (vertical and horizontal), and two different descriptions were used for the flow of charge (current and charge flow). Despite the relative simplicity of such a circuit, making the contextual variations mentioned led to a bank of 120 questions that could be used to make up an instrument. The format of each question was the same, namely, a question showing two configurations framed as a debate among students as to which of the resistive elements would "activate". Respondents then selected one out of a number of options (Forced Choice Responses – FCR) followed by a request for a detailed written explanation as to why a particular option had been selected.

The main study consisted of two independent cohorts: UN1 and UN2. The study consisted of three parts: (a) administering the ACQ to UN1, (b) administering the ACQ to UN2, and (c) interviewing eight students from the latter group.

The data analysis of the FCRs from both UN1 and UN2 showed that most of the students support the activation of the vertical bulb; contrary to this, most of them support the activation of the horizontal heater. Clearly, they do not treat these two elements as the same resistive elements in the same circuit.

The results from the two sets of data were then compared to establish to what degree these two datasets could be regarded as similar, both in terms of the tallies of the FCRs and in terms of the coded Written Responses. One measure of the latter was to compare the frequency of responses per (emergent) category for the two sets of data. These frequencies were shown as being in agreement with each other, based on overlapping 95% confidence intervals (Ref. Section 5.1; Figure 5.1). This was interpreted as indicating that the overall student reasoning for UN1 was not dissimilar to UN2, and that the two sets could be combined to for a single large dataset. Most importantly, it suggested that one explanatory model would suffice, even though the students came from different institutions.

It was observed from the data that all students who obtained correct answers for all eight questions had resorted to only one reason. Furthermore, this reason was associated with Categories A and B only. While Category A and Category B emerged by considering somewhat different criteria during the detailed (initial) coding exercise, the two categories can be considered to be different ways of expressing the same idea, namely, that *loop continuity* is required for the circuit to work.

One issue that was considered part of the work was to what degree the students had engaged with the questions in a sense-making manner. From the general pattern of the Written Responses, it seemed reasonable to assume that the majority of students had done so, based on the fact that the reasons provided for the answers appeared to align with the FCRs. However, in the case of few students' responses, the written reasons did not appear to make sense or were not aligned with the FCRs; while in other cases, the reasons provided were not acceptable given that the correct FCR had been chosen; yet in other cases, the reasons changed significantly from one context to another. This prompted further investigation into whether some of these students were simply providing reasons in order to write something, or whether there might be a level of sense-making at work that was not apparent.

There are two main implications that follow from the present work. Firstly, starting the instruction with light bulbs may be problematic in that no prior experience is likely to have led to students developing the notion that a closed, dynamic loop is required for workability (in any context, including non-electric circuits), and secondly, research findings – the student difficulties and the "misconceptions" for example - based entirely on questions or observations made from circuits involving light bulbs may, in some cases, require re-interpretation.

5.8 Future directions

One of the important directions for future work is to take the present findings and structure the instruction of introductory part of DC circuits around these. It seems interesting to pursue the line suggested by both the present findings and Kaminski et al. (2008) that the sequence should proceed from the abstract to the concrete. While the contexts for the latter study are mathematical, the abstract counterpart that is suggested is that of *loop continuity* as a requirement for continuous flow. Thus, the abstract concept needs to be introduced without reference to concrete instantiations that are liable to trigger inappropriate foothold ideas or resources. This suggests computer simulations as a possible entry point. Simulations in the area of DC circuits have already been studied by various groups. Of particular interest is the work of Finkelstein et al. (2005), which compared the differences in learning outcomes between groups of students who had done either simulations or real laboratory work. They stated their findings as follows:

> Students using the simulations learned more content than did students using real equipment. Notably, the results on the final examination demonstrate that the students who used the simulation had a better mastery of current, voltage, and resistance in basic dc circuits. No less significant, student facility in constructing real circuits is supported by the simulations. The data suggest that students who have worked with simulations are more capable at constructing and writing about circuits than their counterparts who have been working with the physical apparatus all along. In addition to more correctly and thoroughly writing about the circuits, the students take less time on average.

In both the studies of Kaminski et al. (2005; 2008), the statement appears to support a learning trajectory that starts with the abstract and leads toward the concrete. The present study offers the following: that the simulation allowed for the concept of *loop continuity* to be established, and thereby led to an effective understanding of the concepts mentioned, as well as an understanding of the correct functional aspects of concrete instantiations. However, the simulation was not purposefully directed at establishing *loop continuity* nor did it set out to minimize the concrete. A detailed study of the effect of these aspects on student learning will yield important information that can be used to develop curricula in this domain using the principles that are established from such studies. At the same time, it is clear that all previous studies that have been used to research student understanding need to be critically reviewed or repeated in order to establish the degree to which the results that have been stated are still valid.

One final point that relates to sense-making is alluded to by Finkelstein et al. in the same paper regarding the “invisible” aspects of circuits:

> A variety of visual cues in the computer simulations make concepts visible that are otherwise invisible to students. In the present study, most notably the simulation provides direct perceptual access to the concept of current flow. A visual representation of current is provided that allows students to study concepts that are otherwise hidden.

Thus, in order for sense-making to be complete, it would seem essential that some aspect of the simulations should be to relate students’ prior experiences of electricity to those of the abstract DC circuits by showing clearly how the invisible structures are indeed present and how experience can be correctly disambiguated. Perhaps some form of linguistic analysis should also be included so that the discussion regarding structural and functional is also reflected in the simulations. This could address the issue of open and closed as well as the fact that a “circuit” could indeed have no physical connections between the elements, but in a DC circuit, the loop is a physical one.

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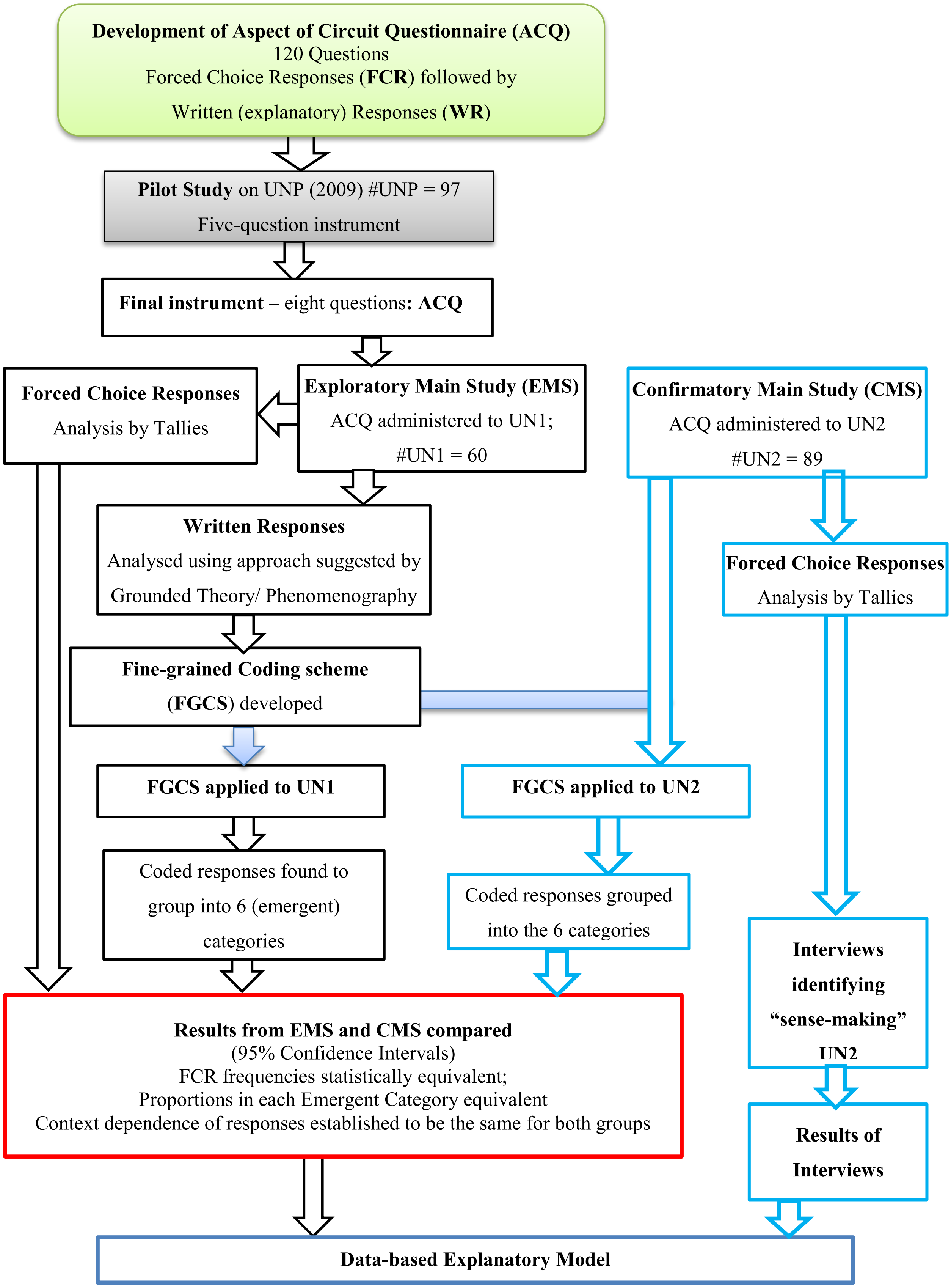
Appendix 1: Schematic diagram summarising the overall study



Appendix 2: FCRs from pilot study with five questions (#UNP=97)

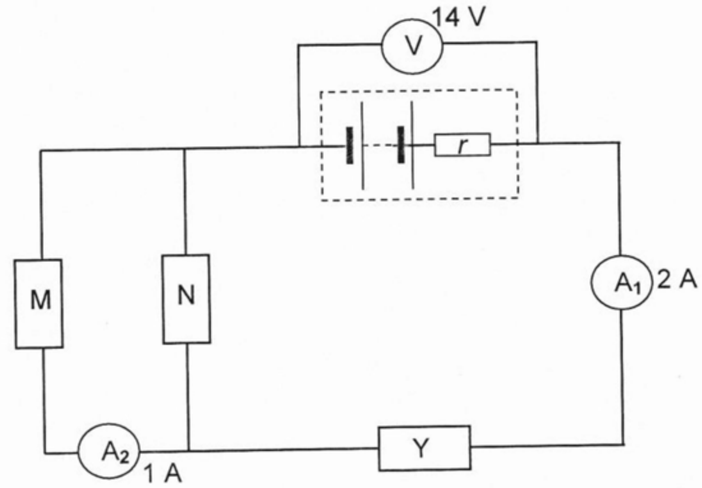
The yellow cells represent the correct answer choice. The other colours represent the incorrect answer choices.

Q1	Q2	Q3	Q4	Q5
1	3	1	3	3
3	3	3	3	3
1	1	4	3	4
3	3	3	1	3
1	1	3	1	3
1	1	1	1	1
4	4	5	1	1
4	2	3	4	3
3	1	3	3	3
1	1	1	1	1
4	4	2	3	1
4	4	4	4	4
4	4	4	4	4
3	3	3	3	3
4	4	1	1	1
1	3	3	3	3
1	1	1	1	1
4	4	4	4	4
4	3	1	1	1
3	1	1	3	4
1	1	1	1	1
1	1	3	3	3
1	3	1	1	3
1	1	1	1	3
1	1	1	1	1
1	1	3	4	3
3	3	3	3	3
1	3	3	3	3
3	3	1	1	3
3	3	3	1	3
3	3	4	1	3
1	1	2	1	2
2	3	1	3	5
3	3	3	3	3
3	3	2	4	2
3	3	3	3	1
4	4	4	4	4
4	4	4	4	4
3	1	3	1	3
2	3	4	3	5
1	2	1	1	1
3	1	1	3	1
3	3	1	1	1
3	3	1	1	3
3	1	3	1	1
3	2	1	1	3
1	1	5	4	3
1	1	3	1	3
3	1	3	1	1
1	3	1	1	1
3	1	3	1	1
4	4	3	3	4
4	4	4	4	4
1	1	3	3	3
3	3	3	1	5
3	1	1	3	3
5	3	3	4	3
4	4	4	4	4
1	1	3	1	3
4	4	4	4	4
4	4	1	1	1
4	4	4	4	1
1	1	1	1	1
1	4	5	4	4
1	4	5	4	4
4	4	4	4	4
4	4	4	4	4
4	5	4	3	4
1	3	3	3	3
1	1	3	1	1
1	1	1	1	3
3	1	3	1	2
1	3	4	4	4
1	1	1	1	1
3	3	3	3	1
4	3	1	1	1
4	4	4	4	5
4	4	4	4	4
4	3	3	3	4
3	2	3	5	2
4	4	4	4	5
3	3	3	3	3
1	1	1	1	4
4	4	4	4	4
1	1	1	4	4
4	4	1	1	1
1	1	1	1	3
3	3	3	2	3
1	1	3	1	1
2	2	3	1	2
5	5	3	3	5
1	2	1	3	3
1	3	1	2	1
1	3	1	3	1
3	2	3	1	3
3	1	3	3	4

Appendix 3: A sample question from Grade 12

QUESTION 11 (Start on a new page.)

The circuit diagram below shows a battery, with an internal resistance *r*, connected to three resistors, M, N, and Y. The resistance of N is 2 Ω and the reading on voltmeter V is 14 V. The reading on ammeter A_1 is 2 A and the reading on ammeter A_2 is 1 A. (The resistance of the ammeters and the connecting wires may be ignored.)



11.1 State Ohm's law in words. (2)

11.2 How does the resistance of M compare with that of N? Explain how you arrived at the answer. (2)

11.3 If the emf of the battery is 17 V, calculate the internal resistance of the battery. (5)

11.4 Calculate the potential difference across resistor N. (3)

11.5 Calculate the resistance of Y. (4)

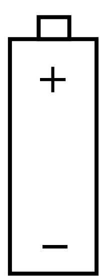
[16]

Please turn over

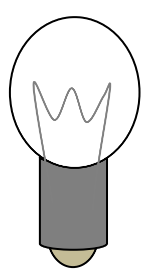
Appendix 4: Full questionnaire used in the Main Study (UN1 & UN2)

<table>
<tr><td colspan="3">Surname:</td><td colspan="2">Name:</td></tr>
<tr><td>Home Language</td><td colspan="4"></td></tr>
<tr><td>Name of school
& province</td><td colspan="4"></td></tr>
<tr><td>Year of passing
Grade 12</td><td></td><td>Age</td><td></td><td>Male/Female
(TICK ONE)</td></tr>
<tr><td rowspan="2">Grade 12 Marks %</td><td>English</td><td>Mathematics</td><td>Physics</td><td>Home language</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="5">Please read the flowing statements and tick the box that best describes your response</td></tr>
<tr><td></td><td>Strongly agree</td><td>Agree</td><td>Partially agree</td><td>Don’t agree</td></tr>
<tr><td>Electricity was
easy at school</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Looking forward
to study @CPUT</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="5">Please answer all Eight questions.
All answers may be different for some students and may be the same for other students.
All batteries, heaters, resistors and bulbs are identical and connected with identical electrical wires.</td></tr>
</table>

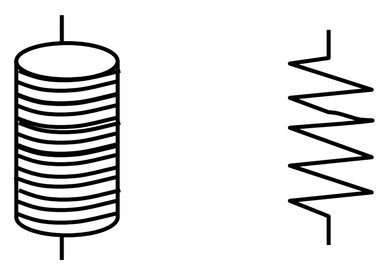
Battery



Light Bulb



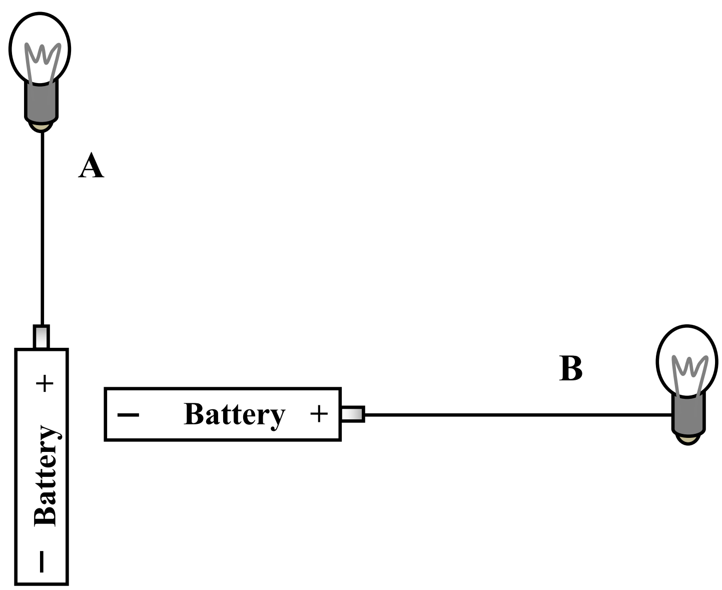
Heater



Question 1

A student connects a light bulb to a battery as shown in figure **A**. Another student connects a light bulb to a battery as shown in figure **B**. The following discussion takes place among the students.

Student 1 says, "The bulb in figure A will light up, but not the bulb in figure B!"
Student 2 says, "The bulb in figure B will light up, but not the bulb in figure A!"
Student 3 says, "Both bulbs will light up!"
Student 4 says, "None of the bulbs will light up!"
With whom do you <u>most closely</u> agree? Circle <u>only one</u> of 1, 2, 3 or 4.



1
2
3
4

Explain the reasons for your choice in detail below.

…………..………………………………………………………………………………………

…………………………………………………………..……………………………………

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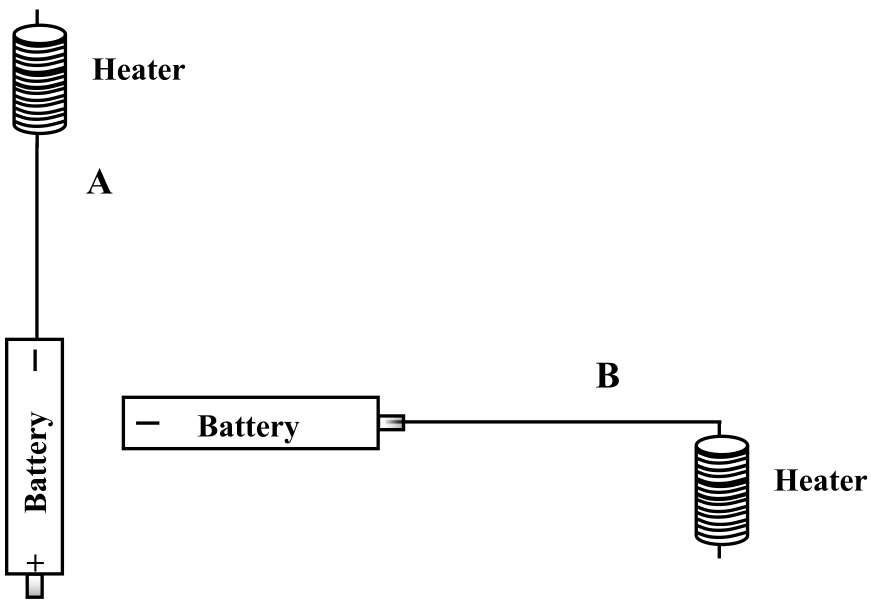
……………………………………………………………………………………………………

Question 2

A student connects a heater to a battery as shown in figure **A**. Another student connects a heater to a battery as shown in figure **B**. The following discussion takes place among the students.

Student 1 says, “The heater in figure A will heat up, but not the heater in figure B!”
Student 2 says, “The heater in figure B will heat up, but not the heater in figure A!”
Student 3 says, “Both heaters will heat up!”
Student 4 says, “None of the heaters will heat up!”
With whom do you most closely agree? Circle only one of 1, 2, 3 or 4.



1
2
3
4

Explain the reasons for your choice in detail below.

…………………………………………………………………………………………………
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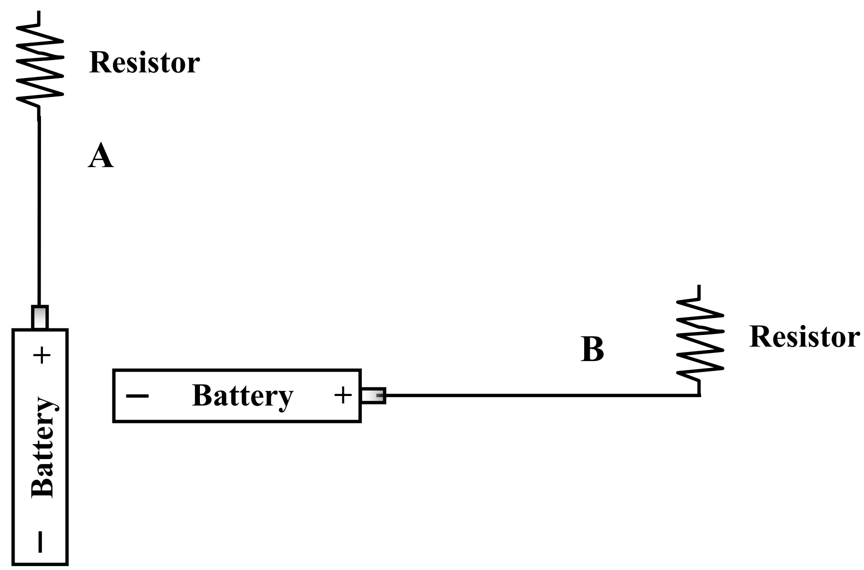
Question 3

A student connects a resistor to a battery as shown in figure **A**. Another student connects a resistor to a battery as shown in figure **B**. The following discussion takes place among the students.

Student 1 says, “There will be a current in figure A, but not in figure B!”
Student 2 says, “There will be no current in any of these figures!”
Student 3 says, “There will be a current in both figures!”
Student 4 says, “There will be a current in figure B, but not in figure A!”
With whom do you most closely agree? Circle only one of 1, 2, 3 or 4.



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Explain the reasons for your choice in detail below.

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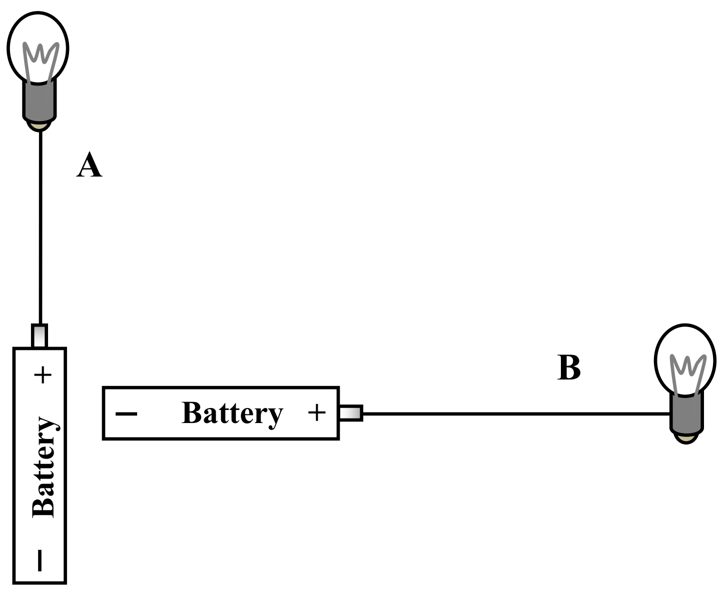
Question 4

A student connects a light bulb to a battery as shown in figure **A**. Another student connects a light bulb to a battery as shown in figure **B**. The following discussion takes place among the students.

Student 1 says, “There will be a current in figure A, but not in figure B!”
Student 2 says, “There will be a current in figure B, but not in figure A!”
Student 3 says, “There will be no current in any of these figures!”
Student 4 says, “There will be a current in both figures!”
With whom do you <u>most closely</u> agree? Circle <u>only one</u> of 1, 2, 3 or 4.



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Explain the reasons for your choice in detail below.

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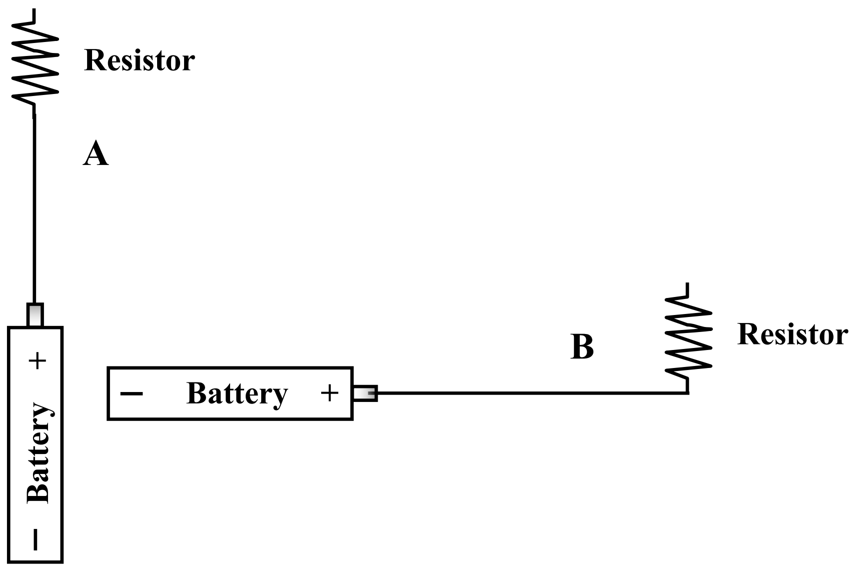
Question 5

A student connects a resistor to a battery as shown in figure **A**. Another student connects a resistor to a battery as shown in figure **B**. The following discussion takes place among the students.

Student 1 says, “Charge will flow in figure A, but not in figure B!”
Student 2 says, “Charge will not flow in any of these figures!”
Student 3 says, “Charge will flow in both figures!”
Student 4 says, “Charge will flow in figure B, but not in figure A!”

With whom do you most closely agree? Circle only one of 1, 2, 3 or 4.



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Explain the reasons for your choice in detail below.

Question 6

A student connects a heater to a battery as shown in figure **A**. Another student connects a heater to a battery as shown in figure **B**. The following discussion takes place among the students.

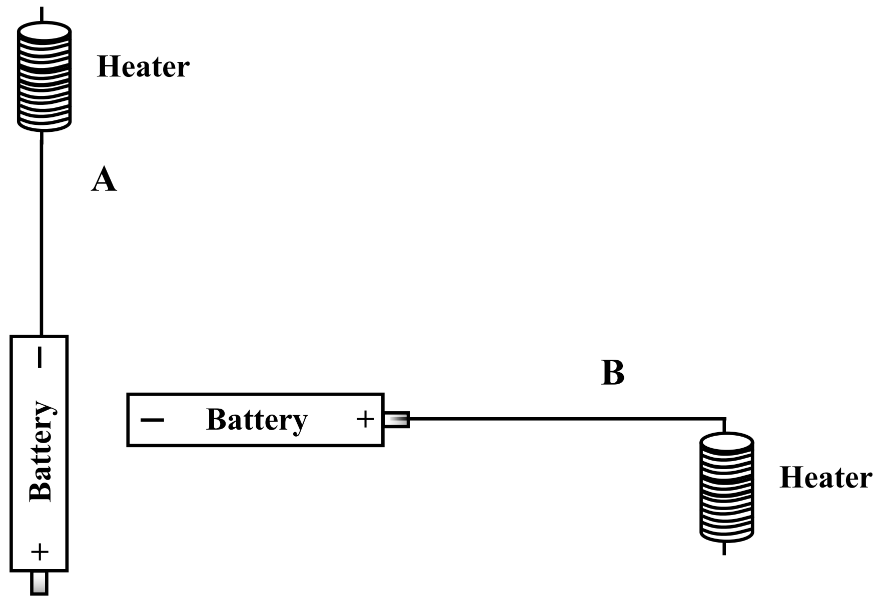
Student 1 says, “Charge will flow in figure A, but not in figure B!”

Student 2 says, “Charge will not flow in any of these figures!”

Student 3 says, “Charge will flow in both figures!”

Student 4 says, “Charge will flow in figure B, but not in figure A!”

With whom do you <u>most closely</u> agree? Circle <u>only one</u> of 1, 2, 3 or 4.



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Explain the reasons for your choice in detail below.

Question 7

A student connects a heater to a battery as shown in figure **A**. Another student connects a heater to a battery as shown in figure **B**. The following discussion takes place among the students.

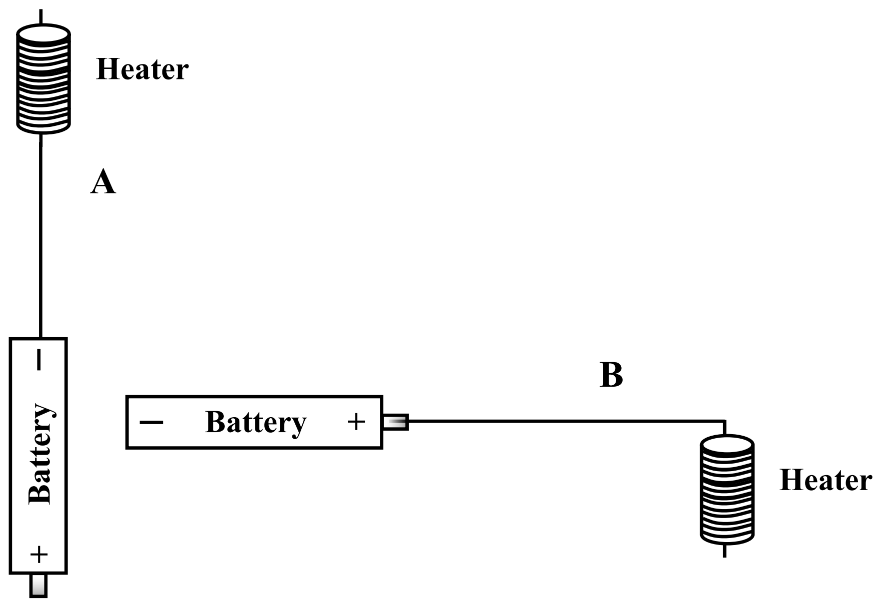
Student 1 says, "There will be a current in figure A, but not in figure B!"

Student 2 says, "There will be a current in figure B, but not in figure A!"

Student 3 says, "There will be a current in both figures!"

Student 4 says, "There will be no current in any of these figures!"

With whom do you most closely agree? Circle only one of 1, 2, 3 or 4.



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Explain the reasons for your choice in detail below.

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Question 8

A student connects a light bulb to a battery as shown in figure **A**. Another student connects a light bulb to a battery as shown in figure **B**. The following discussion takes place among the students.

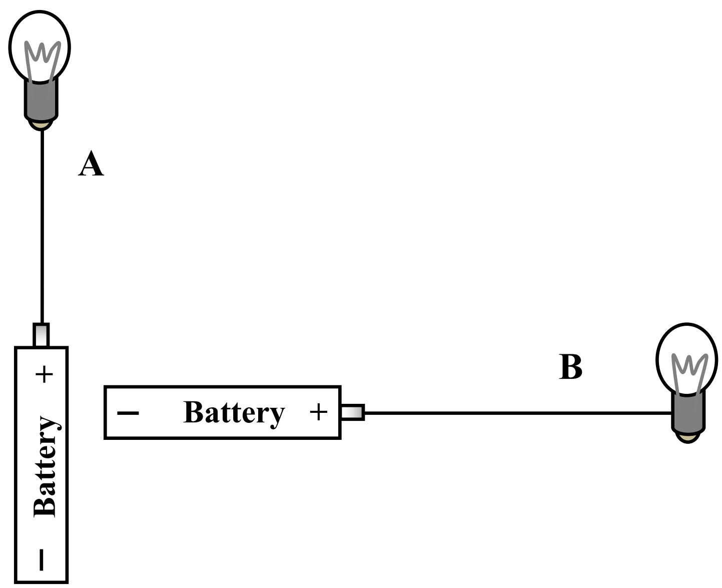
Student 1 says, “Charge will flow in figure A, but not in figure B!”

Student 2 says, “Charge will flow in figure B, but not in figure A!”

Student 3 says, “Charge will not flow in any of these figures!”

Student 4 says, “Charge will flow in both figures!”

With whom do you <u>most closely</u> agree? Circle <u>only one</u> of 1, 2, 3 or 4.



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Explain the reasons for your choice in detail below.

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Appendix 5: Students' original responses from FCR results (UN1)

RIN	Q1 Light Bulb Light-up	Q2 Heater Heat-up	Q3 Resistor Current	Q4 Light Bulb Current	Q5 Resistor Charge flow	Q6 Heater Charge flow	Q7 Heater Current	Q8 Light Bulb Charge flow
101	4	4	2	3	2	2	4	3
102	4	4	2	3	2	2	4	3
103	4	4	2	3	2	2	4	3
104	4	4	2	3	2	2	4	3
105	4	4	2	3	2	2	4	3
106	4	4	2	3	2	2	4	3
107	4	4	2	3	2	2	4	3
108	4	4	2	3	2	2	4	3
109	4	4	2	3	2	2	4	3
110	1	4	2	3	2	2	4	3
111	1	4	2	3	2	2	4	3
112	3	4	2	3	2	2	4	4
113	4	4	4	3	4	2	4	3
114	4	4	4	3	4	2	4	3
115	4	4	2	3	2	4	4	U
116	4	4	2	3	3	2	4	1
117	4	4	2	3	2	4	4	3
118	4	4	2	3	2	3	4	4
119	3	4	2	3	2	4	4	4
120	4	1	3	3	3	2	4	3
121	4	4	3	4	2	2	3	3
122	4	4	2	3	2	U	U	4
123	4	4	1	1	1	2	4	3
124	1	4	4	3	1	2	4	3
125	3	3	3	3	2	2	4	3
126	3	4	2	1	3	2	1	4
127	4	4	3	2	3	3	3	3
128	4	1	2	3	3	2	2	4
129	3	2	2	4	2	2	2	3
130	1	2	3	1	3	2	4	3
131	1	4	3	1	3	2	4	1
132	4	4	2	3	3	3	4	4
133	1	2	2	1	2	5	4	1
134	3	3	5	3	3	3	4	4
135	4	1	3	4	5	2	2	3
136	4	1	1	4	3	3	4	4
137	3	3	5	3	3	1	4	4
138	4	4	1	1	3	4	2	1
139	3	3	2	1	4	U	2	2
140	3	3	3	4	3	3	3	3
141	1	3	3	1	3	3	4	4
142	1	5	4	1	3	1	4	3
143	3	2	3	5	3	3	4	1
144	1	4	3	1	3	4	4	1
145	3	3	3	4	3	3	3	4
146	1	3	3	1	3	3	3	1
147	4	4	3	1	5	5	2	5
148	1	3	3	1	2	3	3	1
149	3	2	3	4	3	4	2	4
150	1	3	3	1	3	3	3	1
151	3	2	3	1	3	4	2	1
152	3	3	3	3	3	3	3	3
153	3	3	3	3	3	3	3	3
154	3	3	3	4	3	U	3	4
155	1	3	2	1	3	3	1	1
156	1	2	3	4	3	4	2	4
157	1	2	4	1	1	4	2	1
158	1	3	3	1	3	3	3	1
159	3	5	3	4	2	3	3	4
160	1	2	3	1	3	4	3	1

Appendix 6: Transcripts of Seven Interviews

6.1 Sherif's Interview

I: represents the interviewer

S: represents the student

The interview lasted for approximately 18 minutes.

I: While teaching the course, we leave you behind if you don't understand. Some students will understand and others will not. We are not sure why some students understand and others do not. Therefore, we would like to know why you answered these questions in the way you did. We want some clarification on your written answers.

The interviewer read out the answers from the student's script. This was done to refresh the student's mind about the questions and answers, because the test had been written three weeks before.

I: In the question relating to bulb light-up, you chose the correct answer choice, i.e. "none of the bulbs will light up". The reason you gave was that "the bulbs will not light up because the circuit is not complete".

This student had used the same reason in the questions relating to the heater and resistor.

I: In the question relating to the current in the light bulb, your reasoning was "as current flows from negative to positive". Why did you give that reason?

S: I actually used (at school) bulb and battery, and touched the bulb one end, it will not light up. That means it will not light up, means no current will pass … also current will flow from negative to positive.

I: In the question relating to charge flow in the resistor, you chose the option "charge will flow in both resistors". The reason you gave was "one terminal of the battery is connected to the resistor, meaning charge will flow into the resistor and dissipate within the resistor as it cannot return to the battery". Can you explain?

S: Okay. The resistor is not exactly the same as the bulb or heater in other questions … it is basically current or charge is flowing in but dissipating in the resistor, because no complete circuit.

I: To get your model correctly, are you saying that when it is connected, something happens at the beginning and then stops there at the end?

S: Yes, it is like an open cable … still it is connected … you will have electricity in the wire, you have a live wire.

I: In the question relating to current in the heater, you chose the option "there will be current in the vertical heater, but not in the horizontal heater". Your reasoning was "charge will flow from negative to positive".

In the vertical figure of the given question, the negative of the battery had been connected, and in the horizontal figure, the positive of the battery had been connected to the resistor.

I: What is the relationship between charge and current? How are they related?

S: Okay, current is like, it is used for the unit to work … charge is a flow of certain measurement … it is not responsible for the unit working.

I: How would you explain to a child? What is current?

S: I would set up something [gestured to suggest a circuit] and, to explain current, I will connect a battery and a bulb and show him … To explain charge, I would connect a meter of some sort.

I: How are they related?

S: They are working together, they are separate things … working in conjunction with each other.

I: What would be responsible for the light-up of the bulb? Current or charge flow?

S: Current … definitely.

I: You reasoned in four questions that the circuit is not "complete". Can you show how to make a "complete" circuit?

The interviewer offered a pencil to the student. The student drew a line, on the horizontal circuit, starting from the bottom of the bulb to the negative terminal of the battery and said,

S: That would basically be a closed circuit.

I: Can you connect this as well?

The interviewer pointed to the vertical circuit. The student moved to the vertical circuit, and replied,

S: I am not sure of this … it will work same as this circuit, because this is connected to the side.

He was pointing to the bulb in the horizontal circuit B (Figure 6.1).

I: Why are you not sure about the horizontal circuit?

S: Like I said, I am sure **A** will work, definitely … but not sure of **B**. Because … I think … in a light bulb, there are two points on the bulb … which is here and here.

He pointed to the two terminals, one at the side of the bulb, the other at the bottom (convex part).

I: Can you explain?

S: The bulb has both positive and negative points, so you can’t have the positive attached to the negative, because a short in the bulb … or the bulb itself will burst.

I: What you are saying is, this is the positive side of the bulb?

The interviewer pointed with a pencil to the bottom of the bulb.

S: No, no, no, this is the negative side of the bulb.

The student corrected with confidence.

I: So, maybe I can mark this as positive and the other as negative?

The interviewer marked as shown in Figure 6.1.

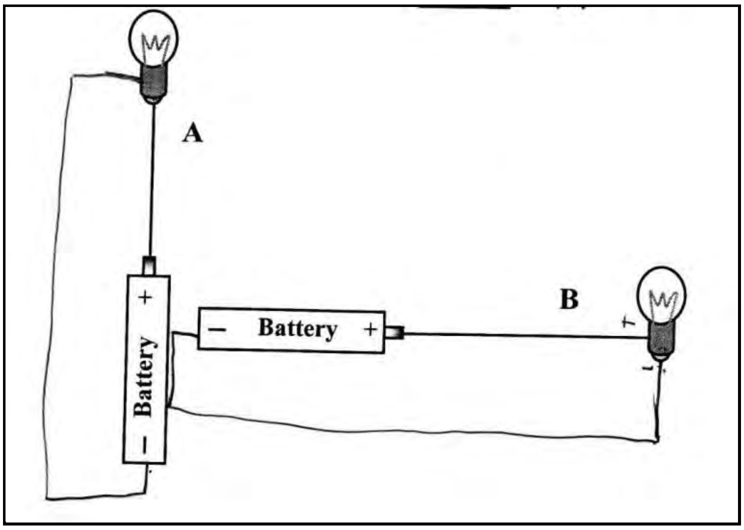


Figure 6.1: Sherif’s illustration: positive and negative terminals of a bulb

S: Exactly.

I: Okay. That was extremely useful. Thank you.

6.2 Asie's Interview

The interview started according to protocol.

I: While the course is being taught, it is not unusual that some students will follow, while others will not. It is unclear why this is. We are therefore keen to know why you answered these questions in the way you did, and would like some clarification regarding your written answers. Please read aloud the answers from your script.

The student was given the original script and the interviewer kept a copy. This was done to refresh the student's mind about the questions and answers, since the test had been written three weeks earlier.

I: In the first question, you chose "none of the bulbs will light up".

S: None of the bulbs will light up.

I: Can you read your explanation aloud?

S: "Wire supposed to be connected to both negative and positive that of battery." In other words, it means in order to light up, there must be a complete circuit.

He described a complete circuit with both hands, saying,

S: Here, we can see that there is no complete circuit.

I: Can you show, with this pencil, what you mean by a "complete circuit"?

S: I am not sure about this circuit…

He pointed at the circuit on the question paper, then started drawing a schematic diagram to the side of the given circuit, with a light bulb and battery, saying,

S: Let us say there is a switch here, let us forget about the resistors and whatever.

He finished his "complete circuit" with an open switch (Figure 6.2) and continued with his explanation:

S: If the switch is open, there will be no current flowing towards the bulb. The switch is supposed to be closed, so the current can flow from the battery to the bulb, so that the bulb can light. If the switch is opened, current will not flow...

Pointing at the switch,

S: … but it will not pass this part …

Pointing at the left side of his circuit, which he had connected directly from battery to bulb,

S: … it will pass only this side.

He then pointed to the vertical circuit, and continued:

S: Here, the battery is connected to the positive side and to the bottom of the bulb. There was supposed to be a wire maybe …

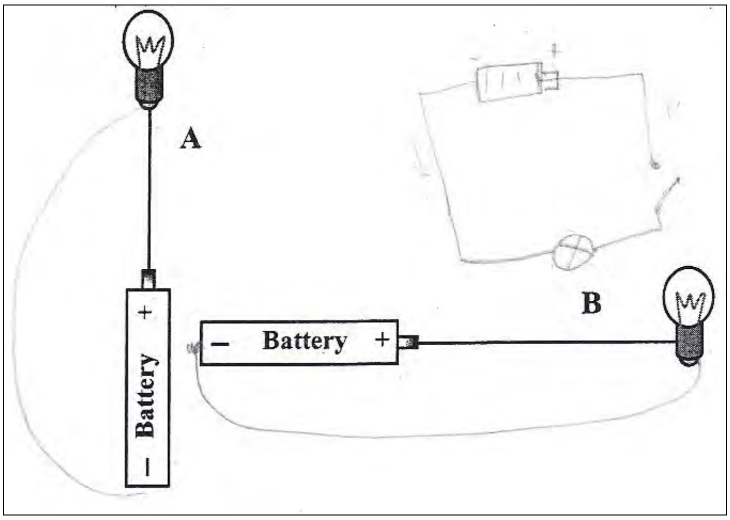


Figure 6.2: Asie's illustration: a 'complete circuit'

He carefully drew a line from the negative terminal of the battery to the bottom of the bulb, alongside the first wire, without allowing them to touch each other, saying,

S: Now the current can flow from both sides.

I: You said the current is flowing from both sides. Do you mean it is coming from both sides?

The interviewer pointed at the two wires starting from the battery to the bulb.

S: Yes.

The student was confident about the complete circuit with his own schematic diagram, but was not sure of the given bulb circuit.

I: What must you do to light up this bulb?

The interviewer pointed at the horizontal circuit.

S: Take another wire and connect it.

The student drew a connection from the negative terminal of the battery to the bottom of the light bulb, saying,

S: So that's a complete circuit.

I: So basically, we need a "complete circuit" for the bulb to light up?

S: Yes.

I: If there is a switch and the switch is open, will the bulb light up?

S: No light.

I: When you are drawing a circuit, is it compulsory that there must be a switch?

After some thought, he replied,

S: No, don’t think it is compulsory. The purpose of the switch is to turn on or off.

I: Okay. Let us look at the next question. It is about the heating up of a heater. You chose the option “the horizontal heater will heat up, but not the vertical heater”.

The student read his answer and said,

S: Oh, I am not sure. There is something about the AC generator and DC generator … I think … when the current pass through the coiled wire, it will generate heat … like the bulb becomes hot when the bulb lights up.

I: Yah … even an ordinary fan, after some time, it will be warm or hot … but … why did you say that the horizontal heater will heat up and not the vertical heater?

S: Because the vertical heater is connected to the negative.

I: You mean the current is flowing from positive, not from negative?

S: Yes.

I: Okay. Let us move to the next question. It is about the resistor. You chose “no current in any of these resistors”. Can you read the reasons?

S: “Current only flows when there is a complete circuit. Therefore, in both vertical and horizontal circuits, there will be no current flowing.”

I: Can you complete the circuit?

The student completed the circuit correctly. He was talking to himself...

S: Forget about the switch … like this, so that current can flow… but I don’t think current can flow… like ... maybe we have a circuit … so…

The student drew a circuit as shown in Figure 6.3. Pointing to the upper part of the horizontal circuit, which he drew, he said,

S: What I thought is the function of the resistor is to resist the current. Current will always flow through where there is less resistance.

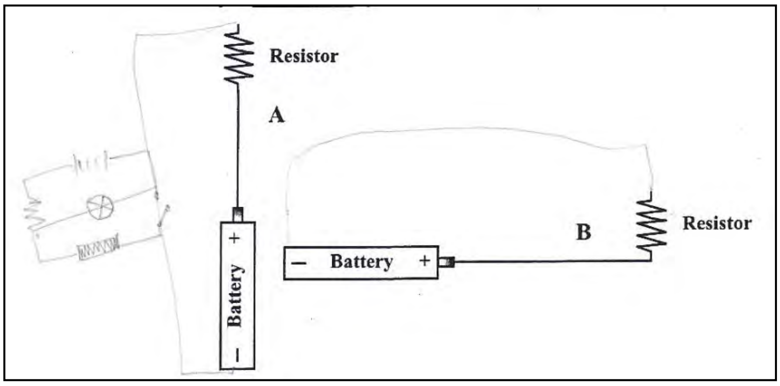


Figure 6.3: Asie's illustration: a 'complete circuit' with a switch

Asie continued:

S: The first reason the current will not flow is, the circuit is not complete, and the second reason is, the resistor resists the current. In other words, they don't stop the current, but they may slow down the current.

I: So, you say there is no current because this is not a 'complete circuit'?

He nodded his head in agreement with the statement.

I: Let us move to the next question. This is a question relating to current in a bulb. You chose the option "there will be a current in the vertical circuit, but not in the horizontal circuit". Can you read the reason?

S: "Yes there will be current, but just because it is not a complete it will not make the bulb light, because current is only from positive."

Just because the switch is open, that does not mean current will not flow … but it will not pass … because it is not complete.

I: Why did you say there will be a current in the vertical circuit, not in the horizontal circuit?

S: You don't connect the bulb like this. You see the bulb have some silver…

Pointing at the side of the cylindrical metal part of the bulb, the interviewer interjected:

I: Like a metal?

S: Yes. Then if you notice at the bottom of the bulb is black … then you have ... I think … two contacts of the bulb.

I: If you look at this figure…

The interviewer pointed to the first page of the questionnaire (Figure 6.4).

S: I think the bulb is supposed to be connected in this part of the bulb.

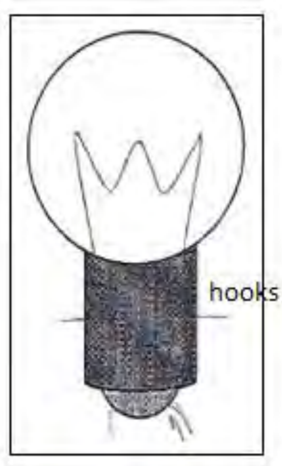


Figure 6.4: Asie's illustration: the two connections characteristic of a bayonet bulb, and two short horizontal lines, representing the "hooks" on each side

He pointed to the bottom of the bulb, drawing two lines from the convex contact point, and continued:

S: Because the bulb have two connecting parts at the bottom of the bulb, this part is just the cover of the bulb, this one only holds the bulb.

He pointed at the cylindrical metal part of the bulb, then drew a short line on each side, in an attempt to simulate the "hooks" of a bayonet bulb (Figure 6.4).

I: If you want the current in the horizontal circuit (B), what would you do?

S: I am not sure, Sir. Let us come to this.

He pointed at the vertical circuit (A), and drew a complete circuit. First, he drew the connection to the side of the bulb and then erased what he had drawn. While erasing, he said,

S: It must come to the bottom.

Then he redrew his circuit carefully, connecting it to the convex bottom part of the bulb (Figure 6.5).

I: So, if you want current in the circuit, the wire must be connected to the bottom of the bulb, not to the side of the bulb?

S: Not to the side. Side is just to hold the bulb.

I: Okay. That is clear.

I: Let us look at the next question. It is about charge flow in a resistor. You chose the option "charge will not flow in any of these resistors". Please read your reason.

S: "Charge will not flow because there is no complete circuit."

I: In this question, we are talking about charge flow and, in the previous one, we were talking about current. Is there any relationship between current and charge flow?

He did not answer the question. He appeared to be exhausted after the long conversation. Then, to break the silence, the interviewer said,

I: Okay. What would you do for the charge to flow in this circuit?

S: Complete the circuit.

I: That means your answer is consistent. You said the same in the question for the current. Okay. Can we move to the next page? This question is about charge flow in the heater and you chose the option, "charge will flow in the horizontal heater, but not in the vertical heater". Please read your answer.

S: "Charge will flow because the heater is positively charged."

I: What do you mean by positively charged?

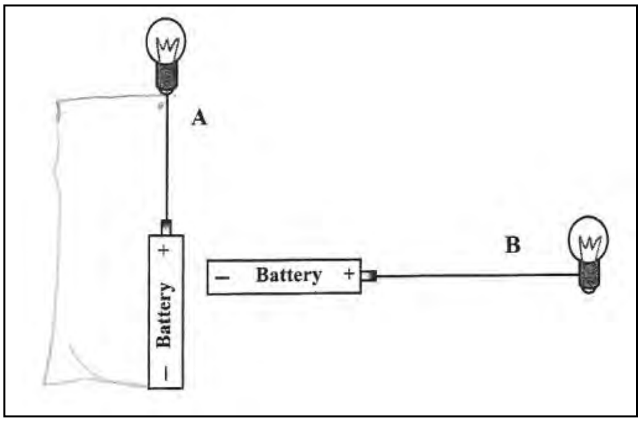


Figure 6.5: Asie's amended illustration: a 'complete circuit' in order to get current to a bulb

The student appeared puzzled by his own explanation and read his script repeatedly, trying to find reasons for his own writing. He pointed to the horizontal circuit and said,

S: Here, the battery is connected to the positive.

Then he pointed to the vertical circuit, saying,

S: In this, it is connected to the negative of the battery.

I: Charge will only flow from positive, not from negative?

S: Not from negative.

I: Okay. Let us check the next question. It is about current in a heater. And you chose the option, "there will be no current in any of these heaters". Your reason?

S: "Because the heater is connected in positive, and electrons always move from negative to positive."

Looking at his script, Asie thought for a while. Again, to break the silence, the interviewer said,

I: You chose the option “there will be no current in any”. Is it a mistake?

S: No sir. I don’t think it is a mistake. I am trying to think…

After a while, the interviewer said,

I: So your answer is correct? There will be no current in any of these resistors?

S: I think the answer is co…rre…..ct, because…

He scanned his script, read it again silently, and eventually said,

S: I think the answer is wrong … because … I said earlier … current flows only when there is a complete circuit. No, no, no…

In the questionnaire, he returned to the question relating to the bulb, saying,

S: Current flows, but it causes the bulb to light when it is a complete circuit.

Reverting to the question under discussion, regarding the heater, he continued,

S. Current flows. But I am not sure that it will heat up.

I: So, are you changing your previous answer?

S: Yes. I am changing … to “there will be current in the horizontal circuit, not in the vertical”, because horizontal is connected to the positive of the battery.

Pointing at the vertical circuit, he said,

S: Here, it is from the negative part of the battery.

I: But the reason you gave was because the electrons move from negative to positive. Is there any connection between the electron movement and current?

S: I am not sure, Sir. I don’t think electron and current the same. I don’t think I meant to say electron.

I: So what I understand here is, when connected to positive, there will be current, and when connected to negative, there will be no current.

He did not respond to this statement. He, again, went back to the illustration relating to the bulb, on which he had drawn his schematic diagram (Figure 4.14), and started discussing it.

S: Let us come back here. Here, I said current will flow from the battery, but it will not pass the switch … it will flow from both sides. That means both of the heaters will have current. But don’t think the current will make the heater to heat up.

I: Okay. Let us turn to the next question. This question relates to charge flow in a bulb. You chose the option “charge will flow in the vertical circuit, but not in the horizontal circuit”. Please read your reason.

S: “In the vertical circuit, the battery is connected to the tip of the bulb. And in the horizontal circuit, it is connected to the side of the bulb.”

I: Because the horizontal circuit is connected to the side of the bulb, there will be no charge flow, i.e. your reason is consistent. Okay. What do you think about the two terms, current and charge flow? Any relationship?

S: Charge … okay, current is the power from the battery to bulb. It is flowing through the circuit. Charge is the voltage or capacity – I am not sure.

I: What makes the bulb light up – current or charge flow?

S: Current.

I: Is there any relationship between current and charge flow?

After deep thought, the student replied,

S: I think charge is the capacity of a battery.

I: So charge is something … maybe … the property of a battery?

S: Yes. For example, if the phone [mobile] is flat, you recharge the phone. That means you take current from charger to phone, then current will flow from the battery to the phone. Phone will work only if there is enough charge in it.

I: So it is similar to … we are storing something ... the charge in the battery? That means if we have charge, we get current?

S: If there is no charge, we cannot get current.

I: How can we connect these two?

S: Charge is the something which is making the current to flow.

I: That means the charge is responsible for the current. If there is no charge, there will be no current. Has charge got anything to do with the voltage of the battery?

S: Voltage is the power of the battery. It is the capability of the battery to make charge … I mean current.

I: Thank you.

I: You were given a battery, bulb, resistor, and a connecting wire. Do they have resistance?

S: No, the wire doesn’t have. Yes, for the bulb and heater. The resistance controls the current entering the bulb or heater. Resistance allows a certain amount of current.

I: Which one has more resistance – heater or bulb?

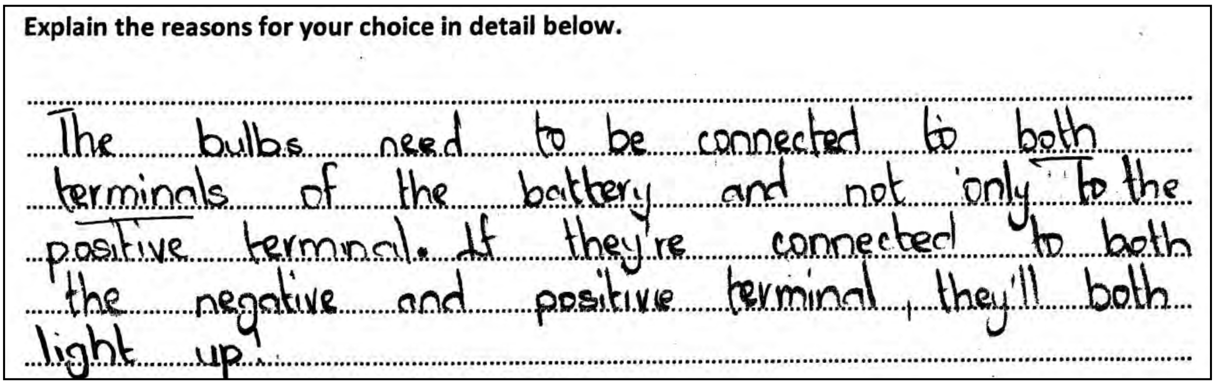
S: Bulb, Sir. More resistance is to the bulb. Because the bulb needs a small amount of current. So it has more resistance, so that it can prevent from more current entering into the bulb. Heater has less resistance because it needs more current to flow.

I: Oh … bulb has a higher resistance, so that a small current enters into the bulb because the bulb needs only small current. Heater needs more current, so it has less resistance, so that more current can come in. That makes sense. Thank you.

6.3 Swala's Interview

After some informal conversation, we proceeded with the interview as per protocol. The student was provided with the original script and we used the photocopy.

I: The first question relates to the light-up of a bulb. You chose the option "none of the bulbs will light up". Could you please read aloud the explanation you gave?


Explain the reasons for your choice in detail below.

The bulbs need to be connected to both terminals of the battery and not 'only' to the positive terminal. If they're connected to both the negative and positive terminal, they'll both light up.

Figure 6.6: Swala's Written Response for the light-up of a bulb

The student did what he was asked (Figure 6.6).

I: What would you do to make the bulb light up?

S: Connect another cable from here to here.

The student drew connections on the given horizontal circuit (Figure 6.7; circuit B).

I: Okay. With the vertical circuit?

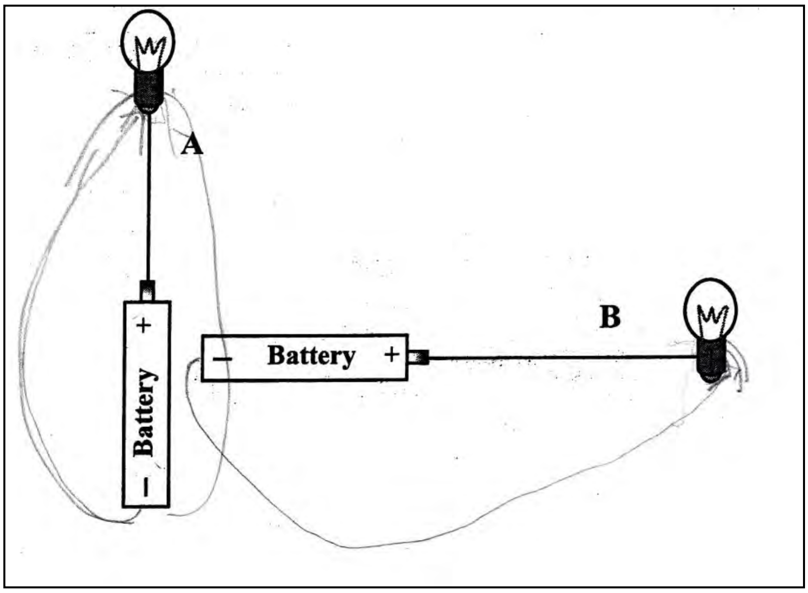


Figure 6.7: Swala's illustration: a circuit to light up a bulb

The student drew a line from the negative terminal of the battery to the convex part of the bulb (on the left of the vertical circuit A), saying,

S: One from the positive terminal to the globe and one from the negative terminal to the globe.

Pointing at the connection the student had drawn to the convex part of the bulb in the vertical circuit, the interviewer asked,

I: So, basically this wire will join here?

Pointing at the connection the student had made on the horizontal circuit, the interviewer asked,

I: Are you happy that one goes to the side and the other goes to the bottom of the bulb? You don't need this one to join the other one?

S: No, I can connect it to anywhere to the bulb.

He drew small lines on the cylindrical part of the bulb in the horizontal circuit (Figure 6.7). Pointing again at the vertical circuit, the interviewer asked,

I: What about here?

The student drew a second line (on the right side of the vertical circuit A) from the negative terminal of the battery to the cylindrical part of the bulb.

S: Yes. You can connect anywhere.

He drew a few more short lines from the cylindrical part of the bulb in the vertical circuit. Pointing at the convex part of the bulb in the vertical circuit, the interviewer said,

I: Okay. To make 100% sure, you could connect both at this point?

S: Yes.

I: Okay. Great. That was extremely useful. I want to make sure…

Pointing at the cylindrical part of the bulb in the horizontal circuit, he asked,

Would it work if both wires go to the side of the bulb?

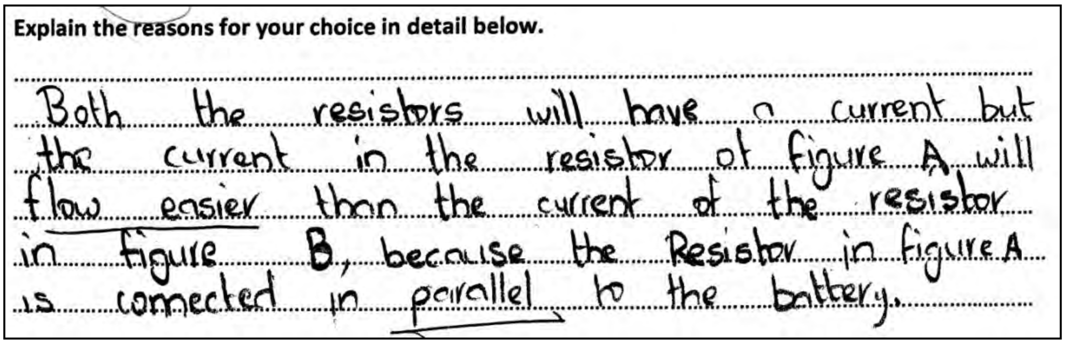
S: Yes, it would work.

I: So, it doesn't matter where the wire touches? As long as two wires touch anywhere on the bulb, it will work?

S: Yes.

I: If we turn over, it is a question related to a heater. You chose the option "the heater in figure B will heat up, but not the heater in figure A". Can you read the reason?

S: “It is connected to the positive side of the battery so it’ll heat up.”
I: Can you explain?
Pointing at the positive terminal of the horizontal battery, the student said,
S: I thought that if it is connected to the positive, it will heat up.
I: You said the vertical circuit does not work. Why?
S: It is connected to the negative side.
I: Oh… so if you wanted that heater to work, what would you do?
S: Connect from both sides.
I: And the horizontal one?
S: This one also.
I: Can you connect it?
The student drew a line starting from the negative terminal of the horizontal battery to the other end of the heater.
I: Are you changing your answer?
S: Yes.
I: How?
S: I learned more on the heaters during my physics subject.
I: Oh… when did you learn that?
S: I think last week. In the lab, when electrical energy converted to heat energy.
I: Oh okay, I see. So you now think that you would change your answer…
S: It is connected on both sides. Not on one side.
I: So, you are changing the answer to that?
The student nodded his head in agreement.
I: Let’s look at the next question. The question is related to current in a resistor. You chose the option “there will be a current in both resistors”. Please read your answer.
The student did what he was asked to do (Figure 6.8).
I: Okay, are you still happy with that answer?
S: Yah.



Explain the reasons for your choice in detail below.

Both the resistors will have a current but the current in the resistor of figure A will flow easier than the current of the resistor in figure B, because the Resistor in figure A is connected in parallel to the battery.

Figure 6.8: Swala's SWR for current in a resistor

I: Maybe you want to change the answer?

S: Yes.

I: Why do you say that one would be a smaller current and the other a bigger current? Which one is smaller?

S: Bigger A, current will flow more. Because connected parallel.

I: Is Figure A connected in parallel?

S: Yes.

I: And B?

S: No, they are not connected in parallel. Because, if they are connected parallel, the resistor is supposed to be here.

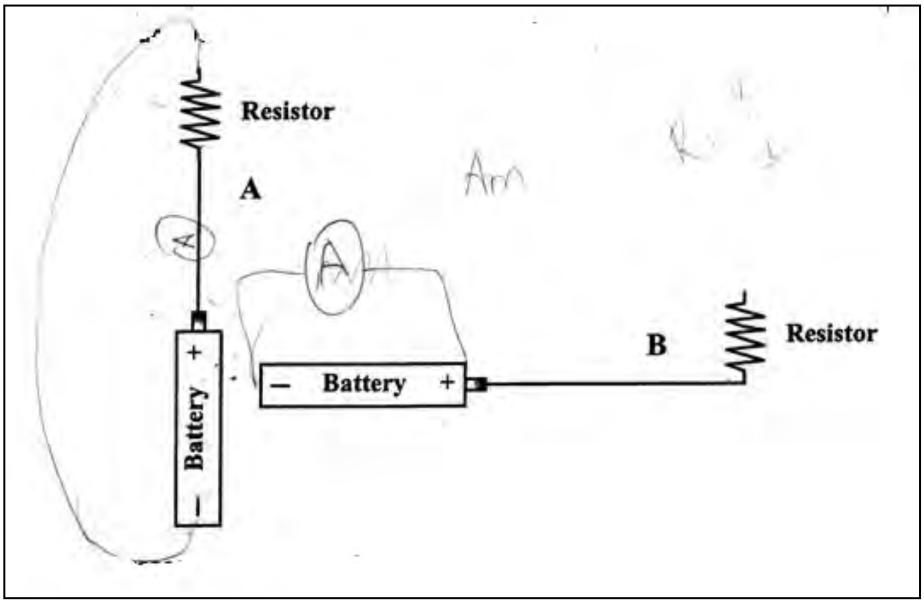


Figure 6.9: Swala's illustration: parallel circuit

He drew a resistor in parallel to the battery on the horizontal circuit (see ghost line on circuit B of Figure 6.9). The stronger line was drawn in later, when he illustrated an ammeter over the resistor.

I: So, they are not in parallel?

S: No, they are in series.

I: So, you are changing the answer for this one too?

S: Yes.

I: Okay. Which answer would you choose now?

S: "There will be no current in any of these resistors."

I: Okay.

S: They are not connected to the negative side. You see, in order … to a current, we have to connect an ampere, I mean ammeter to read the current. So, there is no ammeter, so there won't be any current. If an ampere connected this side…

He drew an ammeter in parallel with the horizontal battery (Figure 6.9; circuit B) and continued,

S: If there were an ammeter, we will see the current. So…

I: So, you are saying that if there is no ammeter, there can be no current? Can you close the circuit?

S: With an ammeter?

I: No, without.

The student drew a line from the bottom of the vertical battery to the top end of the resistor.

Now the question is, is there current in the resistor?

The student wrote an equation R = V/I (Figure 6.9; ghost writing) and, after thinking for a moment, said,

S: There will be a current in this resistor. Resistance can be calculated using voltage over current.

He pointed at the battery with his pencil and continued,

S: So in order for resistor…

He resumed his reading, silently.

I: So you are confused. Let us start again. Is there current in vertical circuit A?

After a thought, the student said,

S: No.

I: Why?

S: There is no ammeter connected, but there is current flowing. But there is no ammeter connected to show that there is current.

I: If you connect an ammeter?

S: There will be an ammeter reading.

I: Can you draw an ammeter?

The student drew an ammeter on the diagram. The interviewer interrupted,

I: No, not there. Let us start again.

The interviewer drew a circuit (Figure 6.10) and asked,

I: Is there a reading in this ammeter?

S: No. It is only connected to the positive side. If it is connected, a complete circuit…

He drew a complete circuit (Figure 6.11) and said,

Now this is a complete circuit.

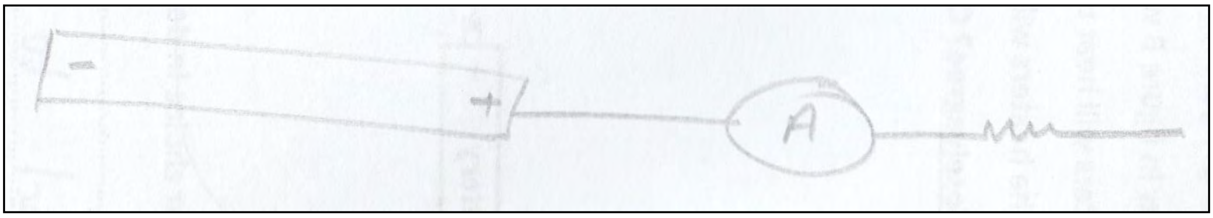


Figure 6.10: Interviewer's drawing

The interviewer drew a dark line over the ammeter and asked,

I: If we take out the ammeter, is there a current in the circuit?

S: Yes, there will be current, but no ammeter reading the current.

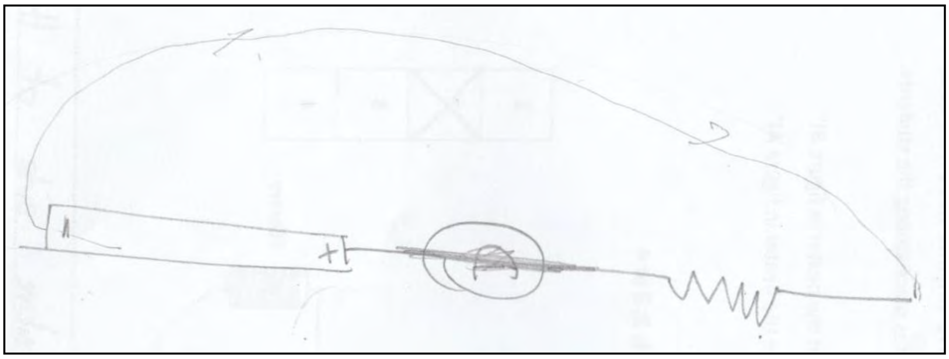


Figure 6.11: Swala's illustration: a complete circuit to obtain current

I: Okay. Let us go to the next question. The question is related to the current in a bulb. You chose the option "there will be no current in any of these bulbs". Please read your reason.

S: "There will be no current in both these bulbs because they're not properly connected to the batteries, in order for a current to flow in a circuit, the bulbs must be connected in both the negative and positive terminals of the battery."

I: Are you happy with the answer?

S: Yes.

I: Can you connect it properly?

The student drew a line on each circuit (Figure 6.12).

I: Okay. Let us go to the next question. This is related to charge flow in a bulb. You chose the option "charge will flow in both bulbs". Please read your answer.

S: "They are connected in the positive sides of the batteries." They are connected to the positive side of the battery. So there will be a positive charge flowing to the bulb in both figure A and figure B.

I: That means the bulbs will light up?

S: No.

I: Is there current in the circuit?

S: No. There is no current.

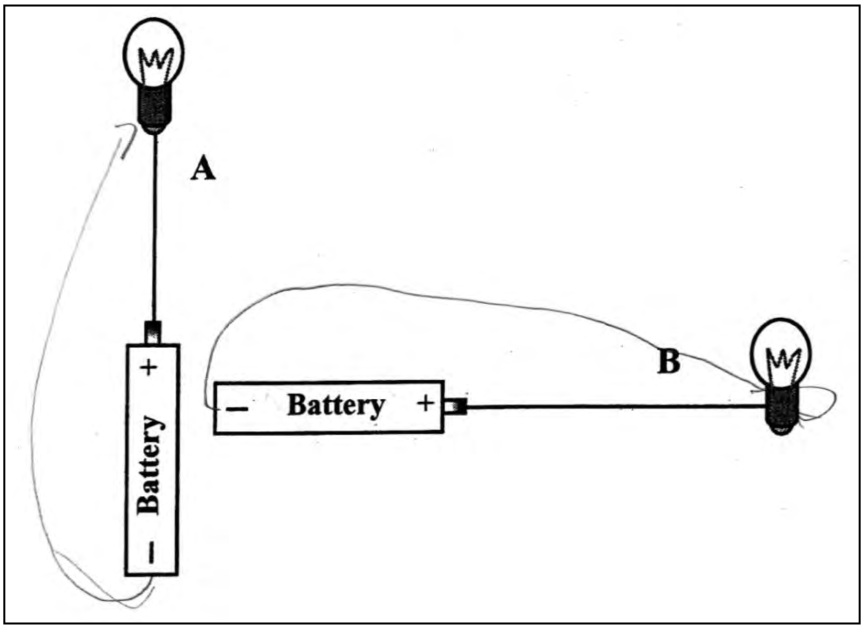


Figure 6.12: Swala's illustration of a complete circuit for current to a bulb

I: Will the charge flow all the time?

S: Charge will not flow in the whole circuit. It will flow only from the battery to the bulb. But the bulb will stay off.

I: While it is connected like this, charge will flow but it will not work until …you…

S: Complete the circuit.

I: What kind of charge?

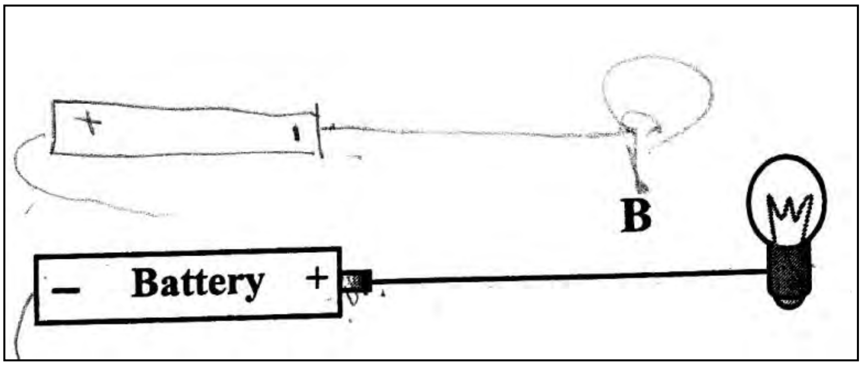


Figure 6.13: Interviewer's illustration: bulb connected to the negative terminal of a battery

S: Now it is positive charge. If it is connected to the negative side, there will be no charge.

I: So, if you have this situation.

The interviewer drew a diagram (Figure 6.13) with a negative terminal connected to a bulb.

I: When this is connected like this, what is the difference between these two – the given figure and the drawn figure?

S: In this one, it is negatively charged and, in this one, it is positively charged, since this one is connected to the negative side of the battery, and this one is connected to the positive side of the battery.

While talking, he pointed at the two circuits (Figure 6.13).

I: So, if we complete both circuits, one will be positive charge and the other will be negative charge flowing?

S: No. Still positive charge flowing.

I: You said earlier that, if connected to the negative terminal of the battery, negative charge will flow. What happens to those negative charges?

S: The positive and negative attract each other … there will be more positive charges.

I: Okay.

I: You are given a battery, wire, heater and bulb – which one has big resistance?

S: No circuit connected?

I: No, nothing connected.

S: No resistance in any of these.

I: When will it have resistance?

S: When the circuit is fully connected.

I: Okay. The bulb?

S: No resistance.

I: When you connect the bulb?

S: There will be a resistance when connected to a circuit.

I: Big or small?

S: The resistance is determined by the voltage and the current.

I: Oh, because R = V/I?

S: Yes. For battery, also no resistance.

I: When connected?

S: No resistance.

I: And the wire?

S: No resistance.

I: When connected?

S: It will have resistance passing from the bulb to the … let us say…

The student drew a circuit with a battery, voltmeter and an ammeter, and asked,

S: These are our wire right?

I: Yes.

S: So there will be a – if it is connected – there will be a resistance flowing from the battery to the voltmeter to the ammeter and the bulb.

I: How would you find that resistance?

S: These small things, last week we did a prac, so we were given some small things called resistors, those things had colours. If it was red, the colour was 2, so we can determine the resistance by using those colours. You can also calculate the resistance using the reading taken from a circuit reading of an ammeter and voltmeter.

I: If you have an ordinary wire? Will that have a resistance?

S: No.

I: Never?

S: No.

I: Okay. When the heater is not connected, it has no resistance and, when it is connected, it will depend on the voltage and…

S: And the current?

I: Okay. If you go further down, just have a look at those circuits (Appendix 7). All three circuits are the same. Just a heater, a bulb and a resistor. The question is, if you connect the current at the points 1 and 2 are the same or not? You have the options. Which one would you choose?

S: The current will be the same.

I: Is that also the same in the next question for the bulb?

S: “Current at point 1 is less than the current at point 2”.

I: But for the heater, it will be the same. And for the resistor?

S: Current will be the same.

I: Okay. Can you tell me…

S: No.

He quickly raised his hand and, with a smile, said,

S: The current all will remain the same. They all will be equal.

I: Okay. If you look at the heater, will the heater A be hotter than B, or B be hotter than A?

After reading the question carefully, the student answered,

S: I think heater B will have more heat than A.

I: Can you explain why? Why you think that is the important part?

With a smile, he answered,

S: Because heater B is closer to the battery than heater A.

I: Okay. When you look at the light bulb, which one will be brighter, or will they be the same?

S: Are there any voltmeters connected or ammeters connected?

I: No. You like voltmeters, or you prefer voltmeters? No meters connected.

S: No. We use voltmeters when we deal with the resistor.

After a thorough study of the question, he said,

S: They both will have the same brightness.

I: We can’t ask anything about the resistor. Then why do you say the same? Are they at the same distance?

S: No, they are not at the same distance from the battery. But they … let us say, the energy will be the same.

I: But, in the case of the heater, you said B will be hotter than A, and for the bulb, they are the same. Is that the kind of explanation you are giving?

S: Yes.

I: That is very useful. If an ammeter or voltmeter is connected in the circuit, do you think the situation will change?

S: No, but the reading would not be the same. If the ammeter is connected to the one with the heater…

I: Can you draw an ammeter?

He drew an ammeter.

I: When connected to an ammeter, will the hotness or brightness of the bulb change or not?

S: No. It will be the same. The only reason to connect an ammeter is to take the reading.

I: Interesting. If someone asked you what is the relationship between current and charge flow – is it the same or different or related?

S: Current is measured in amperes and charge is in coulombs. So they are different.

I: Okay. How can one connect them up?

S: Both of them?

I: Yah.

S: Charge always flows in a circuit, and current is to be you have to connect an ammeter to find your current. So, if there is no ammeter, you won’t find current.

I: Okay. With an ammeter, you can measure the current. Can you measure charge flow in an ammeter?

S: No, I don’t know.

I: Okay. So the charge flow and current, are they the same or different?

S: I think they are different.

I: Okay. That was extremely useful. Thank you.

6.4 Pam's Interview

Pam is a nervous 18-year-old female Xhosa-speaking student. This interview lasted for approximately 24 minutes.

I: While teaching the course, we leave you behind if you don't understand. Some students will understand and others will not. We are not sure why some students understand and others do not. Therefore, we would like to know why you answered these questions in the way you did. We want some clarification on your written answers.

I: Please read the answers and reasons to refresh your memory. You said, "none of the bulbs will light up" because "there has to be two wires connecting the bulb at the battery; at the positive and negative terminals". What would you do to make that work? Show with the pencil.

The student was provided with a pencil. She drew a line on the vertical circuit (Figure 6.14) from the negative terminal of the battery to the bottom of the bulb and said,

S: Connect a wire to the bulb. So that current can flow from the negative and positive terminals to the bulb.

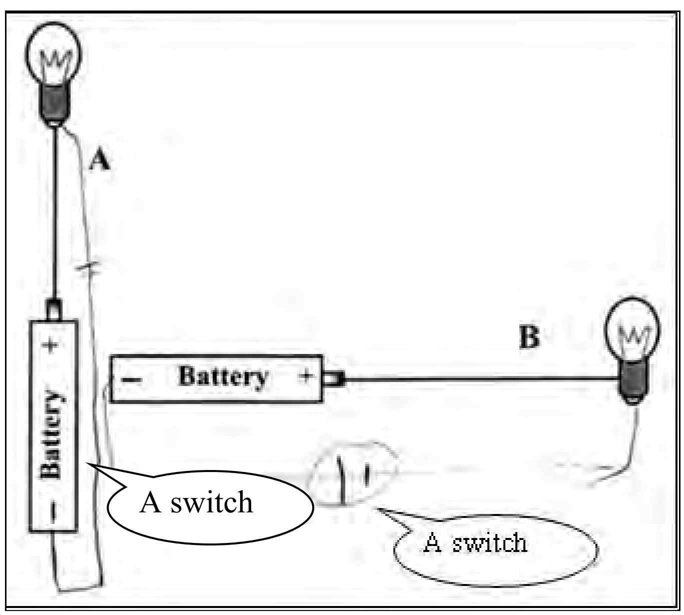


Figure 6.14: Pam's illustration: a closed circuit, including a switch

I: Do you connect the same way for the horizontal circuit (B)?

She drew a connection from the negative terminal of the battery to the bottom of the bulb, in the horizontal circuit and said,

S: Oohh ... there has to be a switch … yho…

I: Where would be the switch?

Pointing at the middle of the horizontal wire, she said (Figure 6.14),

S: Here.

I: What you mean by a switch?

S: Anything which closes or opens, if the switch is on, it will allow the current to flow.

I: Where is the idea of switch coming from?

S: From GR… 7.

I: The teacher … sort of … emphasised?

Quickly, she responded by saying,

S: She did…

I: If you did not have a switch, you would not get the full marks in your test?

She smiled and replied,

S: I would. Well … No, the switch doesn't have to be there. If I have a battery and a bulb, it will light up. Even if I don't have a switch, it will light up.

I: In the question relating to the heat-up of a heater, you chose the option "none of the heaters will heat up" and gave the reason, "the wires have to be on both negative and positive terminals in order to heat up", i.e. there is no difference in your reasoning. Let us look at the next question, regarding the current in a resistor, in which you chose the option "there will be current in both resistors", and gave the reason, "there is current in both resistors". Why?

S: To be honest, I just wrote it because I had to write something. I don't even know what it is.

I: Okay. If you go back to the question, will you choose the same option?

S: No.

I: No? Then how come you chose that answer?

S: I don't know, because I had to write something.

I: Yes I know, but why you chose that option? There must be some reason.

S: I don't know.

I: Do you think it is wrong?

S: Probably wrong.

I: Probably wrong? If you have to answer this question now, which option would you choose?

S: I will choose “there will be no current in any of these resistors”.

I: Okay. That will be because…

S: It doesn’t have a second wire. In order for the current to flow, there has to be two wires connecting.

I: Okay. Can you connect the circuit?

She drew a correct diagram.

I: Let us move to the next question, relating to current in the bulb. You chose the option, “there will be current in both bulbs” and gave the reason, “there will be current flowing through, but the bulbs will not light up”. Do you still agree with this answer?

S: No.

She changed the answer from “both bulbs will have current” to “none of them will have current” by circling the latter option.

I: Let us look at the question relating to the charge flow in a bulb. You chose the option “charge will flow in both bulbs”. How would you explain that?

S: The positive terminals have charge will flow … so voltage … Basically, current is the flow of charge ... isn’t it? How can I explain? So … don’t know to explain.

I: Let us start from the beginning. What will happen if you connect in terms of charge?

S: Only positive charge will flow, not negative charge.

I: How do you explain the relationship between current and charge?

S: There has to be charges for current to be present. If there is no charge, there is no current. No charge, no current.

I: If you want to explain to someone, what does that actually make a bulb light up? Is it the charge or current or both?

After a long pause and deep thought, she said,

S: I have no clue.

I: With charge or current or with both?

S: With both.

I: If you want to use charge to explain how the bulb lights up, what would you say?

S: Charge flows through the wire to the bulb, and the bulb lights up.

I: If you use the current to explain?

S: Current flows through the wire to light up.

I: It sounds as if they (charge flow and current) are the same. Do you think they could be the same?

She replied with a smile,

S: Yes they could be the same.

I: Okay. That is what we want to know. At the time you wrote the test, you gave one answer. Now, you are giving another answer. How? Did you learn something now or after the test?

S: I went after the test … I went and read about electricity.

I: Oh. I see … so … that was what you thought at that time … then you went and read the book. It is quite amazing. It is the remarkable thing to do. I never heard something like this. How much reading you did, you had to do to change your mind?

S: Maybe … one page.

I: Which book? Grade 12?

S: Grade 11.

I: Is electricity interesting?

S: No. It is confusing.

I: What is most confusing?

S: The thing about resistor is confusing. I never got it from high school.

I: What you think a resistor is?

S: No, I don't have a clue.

I: You think in a heater, bulb and resistor, is there anything in common, are they the same?

S: Don't have a clue.

I: Does a bulb have a small resistance or big resistance? It has resistance or no resistance?

S: Bulb has no resistance.

I: Heater?

S: I think it does.

I: Big resistance or small resistance?

S: Big.

I: So, bulb has no resistance and heater has big resistance.
She appeared to be confused, and said,
S: No. I think bulb has resistance. Isn’t it?
I: What is a battery … what does it do?
S: It is voltage.
I: Take a guess … what is the difference between an ordinary wire and a resistor?
S: I don’t know a resistor.
I: Do you think a switch has a resistor?
S: No clue… (smiled).
I: From the English word, what is the meaning of resistance?
S: Something resists something.
I: Now the question is … what is being resisted?
S: In electricity?
I: Yes.
S: I think, here, charges.
I: It was extremely useful. Thank you.

6.5 Leo's Interview

Leo is a confident 18-year-old female Afrikaans-speaking student. The interview lasted for about 20 minutes. The first three questions, regarding the light-up of a bulb, heat-up of a heater and current in a resistor, were each answered correctly with the same reason given, "not both ends of the battery connected". The interview started according to the protocol. We commenced by reminding her of her Written Responses.

I: In the question relating to the bulb, you chose the option "none of the bulbs will light up". Please read the answer you wrote.

S: "The light bulbs are only connected to the positive side of the battery. For electricity to flow and the bulb to light up, it should be connected to the negative part of the battery."

I: What would you need to do, to light up the bulb?

S: Connect a wire from the negative of the battery to the bulb. I don't know I am right!

I: It is good to know what you think.

I: Turn to the next question. Basically, the same reason in the heater, "none of the heaters will heat up", even in the next question, "none of the resistors will have current". In all these three cases, you were using the same reason.

S: Yes.

I: Okay then, we go to the next question. Here, you are saying that, "there will be current in both bulbs". Can you just read the answer to that one?

The Written Response for the question relating to current in the bulb is given in Figure 6.15.

I: Can you please explain. I want to see that that is what you wanted to say.

S: Yes. Because electricity will flow from positive to negative through the bulb, like a round, like "stroombaan" [she was explaining in Afrikaans, with a circular motion of her hand, "stroombaan" referring to "current path"] but could not reach back to the negative. Because there is no wire to the negative. That is why … there is current, but not light-up.

I: Just explain what you mean by current.

S: Current will flow from positive to negative, but it will go through the light bulb, but it won't reach the negative side because there is no wire attached to the negative side of the bulb or the battery.

I: Can you just point out where the current will go?

She drew the arrows as shown in the horizontal figure B (Figure 6.15), talking to herself while drawing the arrows.

S: Like that.

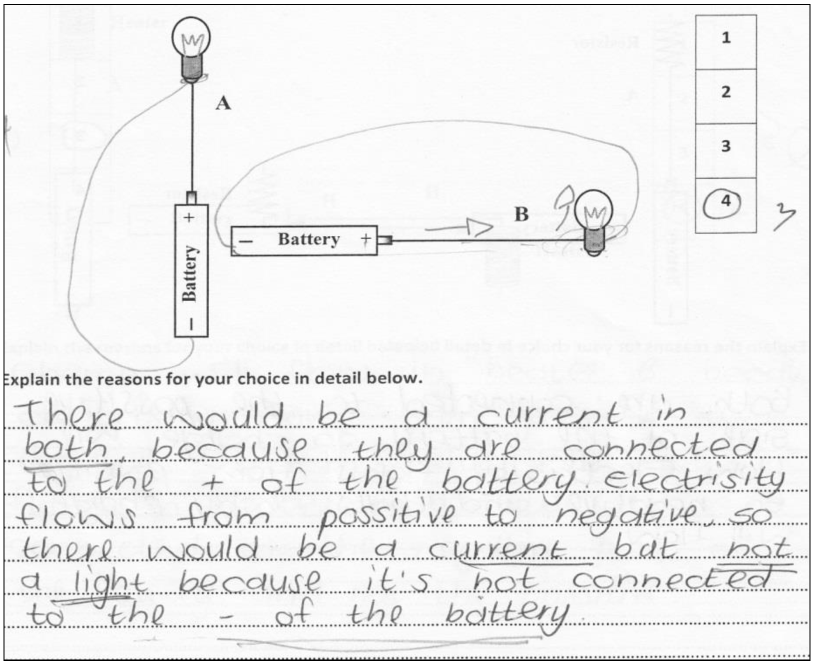


Figure 6.15: Leo's illustration: a closed circuit to get current in the bulb, and the original SWR to the question relating to the bulb

She drew a line on figure B from the side of the bulb to the negative end of the battery, saying,

S: If there was more wire, it would have light up.

I: Okay.

The instructor pointed at the vertical figure A, and asked,

I: What would you do to light up the bulb in this vertical circuit?

S: Connect it to the other side with a wire.

She drew a connection (Figure 6.15, figure A) from the negative terminal of the battery to the bottom of the bulb.

I: How would you explain this to a child?

S: Electricity flows from positive to negative, so it will flow through the wire through the bulb. If there is a wire in the negative side, the bulb will light up, if there is no wire, the bulb will have current, but not light up.

The instructor pointed at the vertical figure A,

I: Can you do it for the other one?

S: It is basically the same.

Pointing at both vertical (A) and horizontal (B) figures, the student said,

S: I don’t see any difference between … like that, like that…

Pointing at the connections of both bulbs, the instructor said,

I: The difference I noticed is that the horizontal circuit is connected to the side of the bulb and the vertical to the bottom of the bulb.

In her drawing, in the vertical circuit, two wires are connected to the bottom of the bulb while, in the horizontal circuit, both wires are connected to the side of the bulb.

Pointing at the bottom of the bulb in the vertical figure:

I: Are you happy about the two connections? Are you happy that the two wires are connected to the bottom of the bulb?

S: I don’t know what that really means! It’s just touching, connected … they are connected, so the current will flow.

I: Okay. The next question is related to charge flow in a resistor. You chose the option “charge will flow in both resistors”, and you gave the reason as “both are connected to the positive side of the battery”. Will charge flow if the battery is connected to the negative?

S: No, because the charge will flow from positive to negative.

I: Okay. It is clear. Let us go to the next question. This question relates to the “charge flow” in a heater. You chose the option “charge will flow in heater B, but not in heater A”. Please read what you wrote.

S: Charge will flow in heater B because electricity flows from positive to negative. Charge will not flow in heater A because it’s connected to the negative part of the battery and not the positive.

I: Good. The next one is current. Your reasoning was the same (as for the charge flow), but in this case, you said current.

S: What is the difference between current and charge? That is the problem actually.

She laughed.

I: Do you think charge will flow as current?

S: Yes. I think so.

I: If you have a heater, resistor and bulb, does the bulb have resistance?

S: Should have one.

I: For heater?

S: Probably also.

I: Not sure?

Her response was a laugh.

I: Battery?

S: Internal maybe.

I: What does that mean?

S: I don’t know.

I: Will you understand after the course?

S: Maybe I will.

The student was given three circuits, each with two heaters, two bulbs, and two resistors in series and each connected to a battery.

I: Do you think the current flowing in these heaters is the same or different?

S: Same.

I: In the bulb?

S: No difference.

I: Will the heaters have the same degree of heat?

S: Yes.

I: Will the bulbs have the same brightness?

S: Yes.

I: Thank you very much.

6.6 Tishik's Interview

Tishik is a 33-year-old male French-speaking student from Congo. This interview lasted for 27 minutes. After some informal conversation, we proceeded with the interview as per protocol. The student was provided with the original script and we used the photocopy.

I: In the first question, you chose the option "none of the bulbs will light up". Please read out the question and the answer you wrote.

S: "It's four because the bulb is only on positive side. For it to light, it should be connected on both sides which is negative and positive."

I: So if you want to connect it up, how would you do it? Just show what you would do.

The student drew a figure (Figure 6.16, L.H.S.), with the positive terminal of the battery touching the convex part of the bulb, and a wire from the negative terminal of the battery to the cylindrical part of the bulb. While drawing, he said,

S: I would put the bottom of the bulb to the positive side, and then take something to connect the negative to this side, for it to light. Because you have to … both two sides, both negative and positive.

I: If you turn the battery around…

The student drew a battery with the terminals swapped (Figure 6.16, R.H.S.).

… would that work?

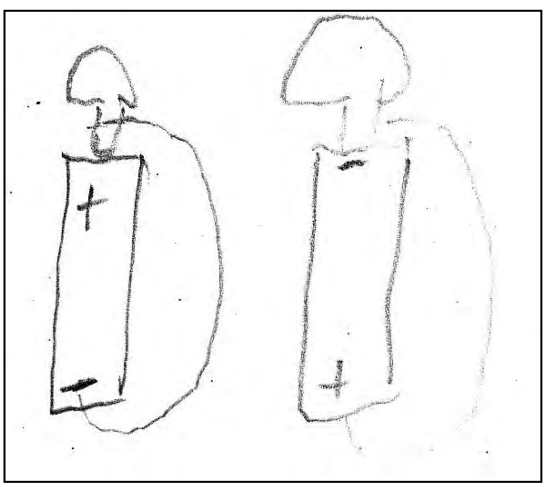


Figure 6.16: Tishik's illustration: connection to light up a bulb

S: I don't think so. Because I have never tried.

Pointing at the L.H.S. of the figure, he said,

S: I have tried this. I have seen this working.

Pointing at the R.H.S., he said,

S: I think, in this case … I think … it will work. Because it still has a negative and positive for it to light.

I: So you say it will work?

S: It might work, but I am not sure.

I: In your experience?

S: Yah, for the bulb and battery, because I have tried when we were young, I have tried putting, we used to do electricity stuff, light might… you might experience electricity problem at home … to try to fix it, the way get these kind of little stuff…

I: But you are not sure this would work?

S: I am sure, in the first case, it will work, but in the second case, I am not sure … it might work. Because the light needs a positive and a negative side. So if we have both, it might work, but I am not sure. I am sure, in the first case, it will work.

I: It is interesting. Thank you. If we turn to the next three questions, about the heater, the resistor, and current in the bulb, you gave the same reason for each.

S: Yah.

I: Okay. The next question relates to charge flow in a resistor. You chose the option "charge will flow in both resistors". Please read what you wrote there.

S: "There will be flow of electricity because of the side positive. That flow will be there waiting to connect with the other one to create a reaction which is electricity."

I: Can you try to explain?

S: When I said there will be flow of electricity [it is] because of the positive side. If you see both resistors A and B, both are connected on positive. There is no one connected to negative.

He read his writing again and said,

S: What I mean is, for me, my understanding is that flow is that or presence of … not electricity, but presence of something, waiting for the negative to create electricity. I don't know I am making sense.

I: I think I can see what you are saying. Are you saying that charge will flow at the time it connects, or are you thinking that charge will flow at the present time or in future? I am trying to get your language clear.

S: Okay. At present – when you connect the battery?

I: Yes.

S: I think it will flow at present. Because as soon as you put there will be flow.

I: If you keep the battery for a long time, does it keep flowing? Or does it stop?

S: Now it depend with the battery. If the battery is not flat, it will stay flowing. As long as the battery is charged, the flow will be there. If the battery is flat…

I: What you're saying is that, once you put the battery to the end of this resistor, you will have a flow of charge? That will remain the same way until the battery runs out?

S: Yah.

I: If we go to the next question, you chose the answer "there is no current in any of these heaters". Why do you say that there is no current? Can you please read out what you wrote?

S: " … because of the one side only connection."

Pointing at the vertical figure A, he said,

S: I am not sure, in this case, there will be a flow because it is connected to the negative side.

Pointing at the positive and negative terminals of the battery, he continued,

S: But I am sure that there will be a presence of current as soon as you connect the two.

I: Let me summarise. For the bulb or the heater or the resistor to work, you need a complete loop. When there is a loop, there is a current…

S: I don't get you. What is the meaning of the loop?

I: A loop is when both positive and negative are connected all the way.

S: Okay.

I: In those cases, there is a current. Because of the current, these things work. When you have only one connected, you only have flow of charge – there is no current.

The student nodded continuously in agreement with the statement.

I: Okay. Thank you very much.

I: Is the current the same or bigger or smaller at points 1 and 2?

S: I think the current will be equal.

I: I noticed that you used the word electricity. If you want to explain electricity to your younger brother, what would you say?

The student went into deep thought. The interviewer broke the silence and said,

I: Okay, you can use the words voltage, charge, current, etc.

S: That is very very interesting question. I think I have to think… I don't know.

He smiled and did not answer.

I: Or … I see these words, electricity, charge, current, voltage; how are they connected? You used the word electricity. Are you talking about charge, current, voltage, or about the lighting up … what does the word mean to you?

S: Electricity takes all of them. In electricity, you find current, voltage; electricity is complex.

I: How do you see the relationship between the current and the charge?

S: The current gives charge. For you to get charge, you have to rely on current. That is my understanding.

I: Thank you very much. A last one: what you think about charge?

S: Enough electricity. If I say enough electricity…

After deep thought, he continued,

S: … if I say in this battery charged, I think it is enough electricity in the battery.

I: Okay. That sentence of yours was worth it. Give this man a chocolate!

We all laughed together.

I: Thank you.

6.7 Siya's Interview

Siya is an 18-year-old male Xhosa-speaking student. After some informal conversation, we proceeded with the interview as per protocol. The student was provided with the original script and we used the photocopy. The interview lasted for 23 minutes.

I: The questions were all about batteries, light bulbs, resistors and heaters. If you look at the very first question, it was related to a battery and bulb, and you chose the option "none of the bulbs will light up". Can you read what you wrote?

S: "It's because both bulbs are being connected only in one terminal of the battery which is positive charge."

I: Okay. In order to make it work, what would you do?

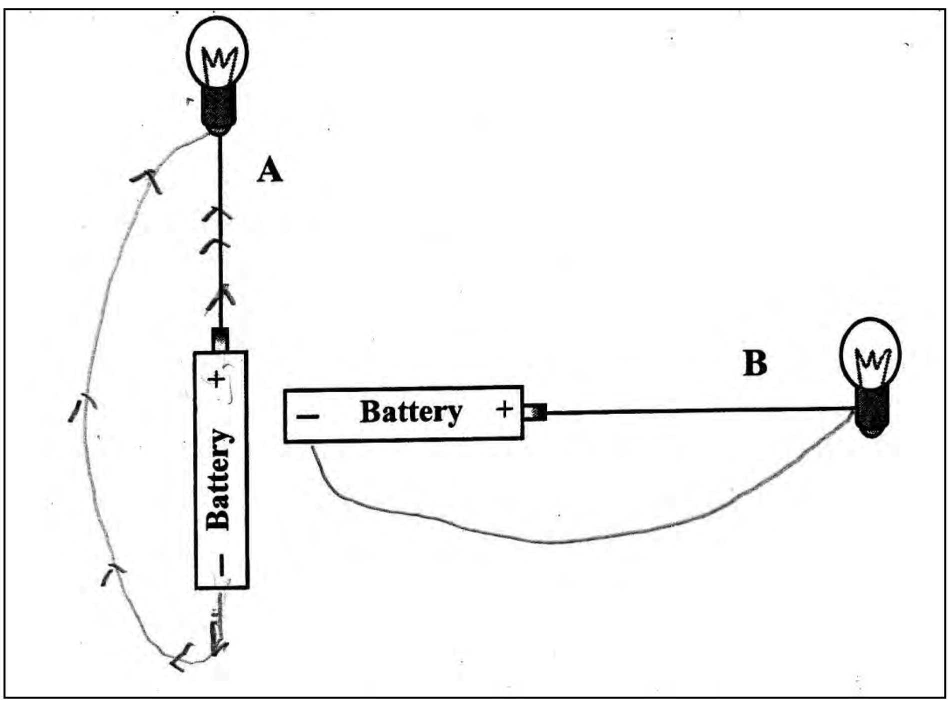


Figure 6.17: Siya's illustration: a circuit to light up a bulb

S: It is to be connected to both positive and negative side, so that the electricity can flow in both sides. Connect the bulb from the other side.

I: Please show by drawing it.

He drew a connection from the negative terminal of the battery (on the vertical circuit) to the given connection on the bulb, on the convex part of the light bulb (Figure 6.17, figure A). In the horizontal circuit, he connected the body of the battery to the metal cylinder of the light bulb (Figure 6.17, figure B). He drew these lines carefully so that they joined the given connection of the light bulb in each circuit.

I: If you want to explain to someone, say for example, to your brother…

S: Current is flowing from both sides of the battery to the terminals of the bulb.

I: I did not understand. Can you draw some arrows to show the direction of flow?

He drew arrows to indicate the direction of current (Figure 6.17).

I: Is it the same things flowing in both wires?

S: No. One is positive and the other is negative charge.

I: Okay. So from the positive terminal, you are getting the positive charge, and from the negative terminal, the negative charge?

He nodded his head in agreement.

I: Let us turn to the next question. It is about the heat-up of a heater. You chose the option "none of the heaters will heat up", and gave the reason "because only one terminal". Is it the same [answer] as the previous one?

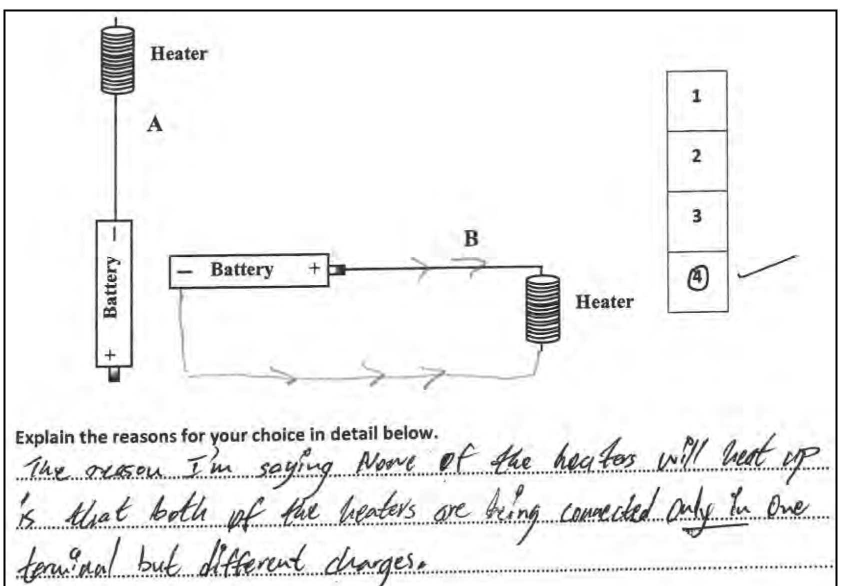


Figure 6.18: Siya's illustration: to heat up a heater

S: Yes. When I was answering this question, I was visualising this as if I am carrying a bulb here and one connected to the positive terminal like this. I imagined a bulb, it won't light up. That is how I answered this question.

I: Oh, I see. So you took the idea of the bulb and moved it to the heater!

S: Yes.

I: To work the heater, what would you do?

He drew a line and arrows on the horizontal circuit (Figure 6.18).

I: That is a good consistent picture. Okay. Let us move to the next question: it is about the current in a resistor. You chose the option "there will be no current in any of these resistors". Please read.

S: "Because in order for current to flow on the battery, it must be connected to both charges." That is what I said in the previous question.

I: Okay. Let us go to the next question. It is about current in a bulb. You chose the option "there will be a current in both bulbs". Can you please read your answer?

S: "There will be a current in both, but it won't be that much."

I: Can you explain?

S: There was a charge that was going into the bulb, but was not enough to light up the bulb. There was a small charge, but they didn't make the bulb light. There need the negative terminal in order for the bulb to light up.

I: So can I summarise what you are saying? There is current going from the battery to the bulb, but it is small.

S: Yah. I was confused, because the first question was the same. But this one, there is a current going, but it is very small.

I: So it won't light?

S: No, it won't light. But there is a current.

I: Just tell me why it won't light?

S: There is not enough charge. Because it is connected to only one terminal.

I: Oh … Okay. So can I ask you to point out where the current is?

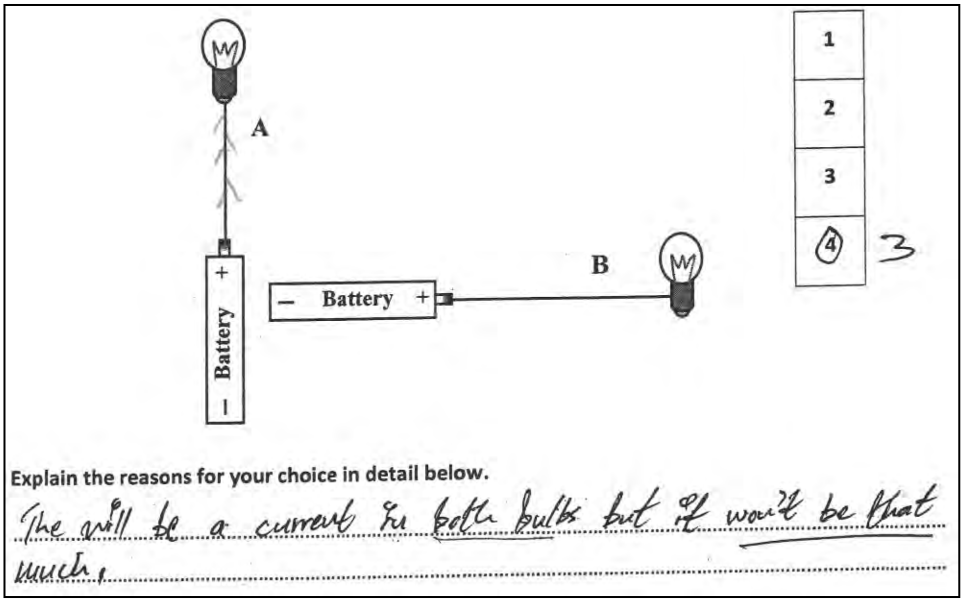


Figure 6.19: Siya's illustration: charge flow from one terminal will not make the bulb light up

He drew arrows (Figure 6.19) to illustrate the current, and said,

S: Because the other side, there is no wire connected.

I: Having only one connection, you are saying that is not enough?

S: Yes.

I: So you need…

S: Both.

I: Great. Okay.

I: Now we turn to the next one. It is about charge flow in a resistor. You chose the option "charge will not flow in any of these resistors". Can you please read what you wrote?

The student read the reasons (Figure 6.20).

I: What would you need for the charge to flow?

S: You need another wire.

He drew a wire in the vertical circuit (Figure 6.20).

I: Are they negative charges or posi …?

The student pointed to the negative and positive terminals, respectively, and replied,

S: This is negative charge and the other is positive charge.

I: Okay. I understand. The next question is related to the charge flow in a heater. You chose the option "charge will flow in both heaters". Can you read what you wrote there?

S: "Charge will flow in both heaters but different charges which they have been connected in to them." I was trying to say that different charges are flowing in those heaters A and B. In A, there will be negative charges flowing, and in B, positive charges (Figure 6.18).

I: So basically the same as the bulb?

S: Yah.

I: You used the bulb to work this out?

S: Yah.

I: Let us look at the next question. It is related to the current in a heater. You chose the option "there will be no current in any of these heaters". Can you read what you have written there?

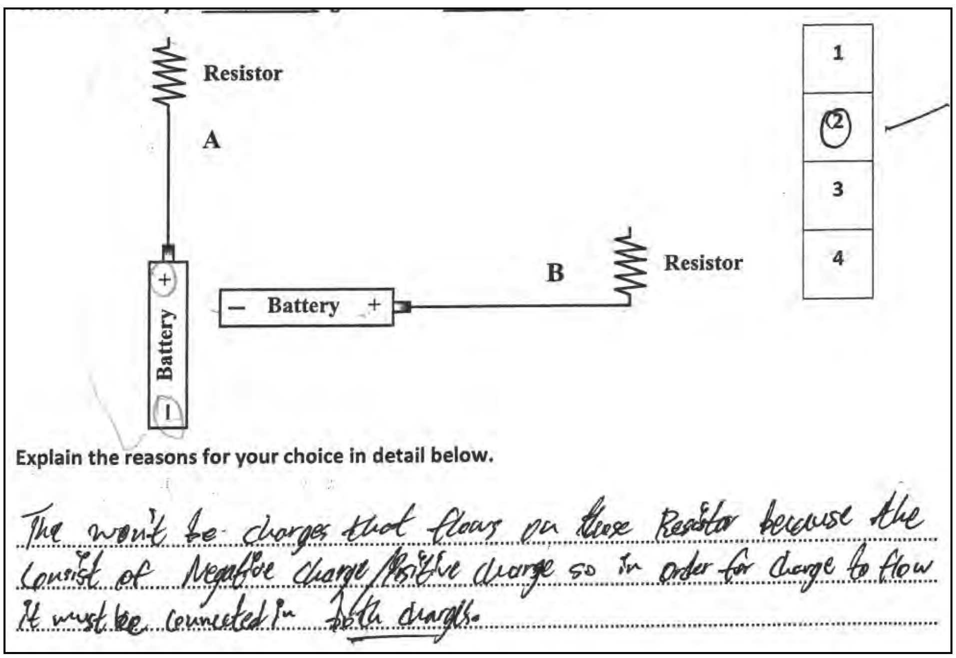


Figure 6.20: Siya's original Written Response to the charge flow in a resistor

S: "It's because both heaters are being connected only to one terminal of the battery but in different charges."

I: What I want to understand is, in one case, you said there would be charge flow in both heaters, and in the other, you said there would be no current. Can you explain?

S: It was asking the heaters are going to be light or not … That is why I mentioned charges here.

I: But I am trying to look at the previous question and this one together. In one case, it is about charge flow, and in the other, it is about current. In the first case, you wrote there would be charge flow, but in the second, you wrote there would be no current. I am trying to understand the difference between these two answers.

S: When I am saying there won't be any current, I mean there has to be both charges flowing to the heater.

I: Oh, so current is when the circuit is complete and when the charges flow from both sides?

S: Yah.

I: So there is no current, for the simple reason that one arm is missing. But there is charge flow in each arm. So if I get clearly what you are saying, you have two arms, each arm can have charge flowing to the heater or bulb or resistor. When charge is flowing from both arms, you have current. Then the thing will work?

During this confirmation, he nodded his head in agreement, and finally said,

S: Have current – yes.

I: Great. That is very clear.

I: In the next question, you chose the option "charge will not flow in any of these bulbs". I am confused. Is it still the correct answer, or am I misunderstanding it?

After reading his script, the student replied,

S: According to the way I was answering these questions, this answer was incorrect.

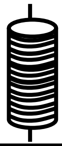
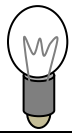
I: So, is this the answer you are giving or not?

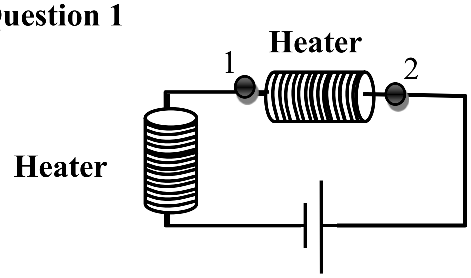
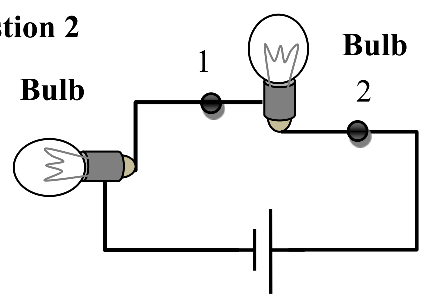
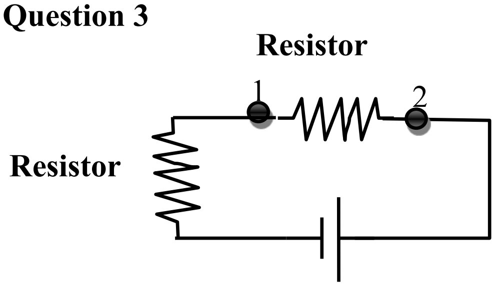
Reading his script again, he said,

S: No. The answer would be "charge will flow in both bulbs".

I: Okay. Thank you.

Appendix 7: Additional Questions

The circuit elements used in the previous questionnaire are shown below. Tick (√) N, S or L below each element. N = No resistance; S = Small resistance; L = Large resistance.											
 **Heate**											
N	**S**	**L**	**N**	**S**	**L**	**N**	**S**	**L**	**N**	**S**	**L**
Study the three circuit diagrams below carefully and Tick (√) the correct statements.											

Question 1 	Current at point 1 is less than the current at point 2.
	Current at point 2 is less than the current at point 1.
	Current at point 1 is equal to the current at point 2.
	Heater A will be hotter than heater B.
	Heater B will be hotter than heater A.
	Both heaters A and B will have the same hotness.
	None of the heaters will heat up.
Question 2 	Current at point 1 is less than the current at point 2.
	Current at point 2 is less than the current at point 1.
	Current at point 1 is equal to the current at point 2.
	Bulb A will be brighter than bulb B.
	Bulb B will be brighter than bulb A.
	Both bulbs A and B will have the same brightness.
	None of the bulbs will light up.
Question 3 	Current at point 1 is less than the current at point 2.
	Current at point 2 is less than the current at point 1.
	Current at point 1 is equal to the current at point 2.
	There will be no current in the circuit.

Appendix 8: FCR and Summarised Written Responses (SWR) of UN1

RIN	Bulb Light-up		Heater Heat-up		Resistor Current		Bulb Current		Resistor Charge flow		Heater Charge flow		Heater Current		Bulb Charge flow	
	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR
101	4	no **complete circuit**, there is no complete current flow; there must be a connection from +ve & -ve side of the battery	4	must be **complete circuit**; only one side	2	**incomplete circuit**	3	**incomplete circuit**	2	Charge is there when there is a +ve & -ve connection. But this is **incomplete circuit**	2	**incomplete circuit**	4	**incomplete circuit**	3	**incomplete circuit**
102	4	**power** is coming out **only on the** +ve **side of battery;** power from the positive should be connected to the **+ve part of bulb** and -ve should be connected to the **-ve side of the bulb**	4	**power** or **cable** only connected to **one side of battery,** should be connected to both **+ve and -ve**	2	must be connected to both **+ve & -ve**	3	bulb is taking current from **only the +ve cell of the battery,** it should be taken from both	2	to show that the resistor has **power,** it should be connected on both **+ve & -ve sides** of battery	2	should be connected to both **+ve & -ve** sides of battery	4	should be connected to both **+ve & -ve** sides of battery	3	should be connected to both **+ve & -ve** sides of battery
103	4	both terminals, **+ve & -ve** connected to **close circuit**	4	**both terminals** should be connected to heater	2	both **+ve & -ve** needed to **complete/close** circuit	3	both +ve & -ve needed to **close circuit**	2	**both terminals** of battery should be connected	2	**both terminals** of battery should be connected	4	**both terminals** of battery should be connected	3	**both terminals** of battery should be connected
104	4	both bulbs are connected in the **+ve side which is protons** and is not in the negative side	4	same reason as , not connected to **both ends**	2	**only one end**	3	it's connected to **one end of battery**	2	**only one end of battery**	2	**only one end of battery**	4	**only one end of battery**	3	**only one end of battery**
105	4	both **+ve & -ve** contact needed	4	**both terminals** should be connected to heater, because current flows from -ve to +ve	2	closed circuit **diagram** was drawn	3	closed circuit **diagram** was drawn	2	closed circuit **diagram** was drawn	2	need complete circuit	4	same	3	same
106	4	both sides of the battery must be in contact with bulb	4	only one side of battery working	2	both sides of battery are not in contact, this is an open switch	3	this is as if the switch is open	2	this is open switch, only one side of the battery is connected	2	same as in page 6	4	only if close switch	3	only one end of battery, open switch
107	4	should be connected to both sides of the battery, creating closed circuit	4	should be connected to both sides of the battery, creating closed circuit	2	should be connected to both sides of the battery, creating closed circuit	3	closed circuit required	2	closed circuit required	2	closed circuit required	4	closed circuit required	3	closed circuit required
108	4	both bulbs are connected in the +ve side of battery, but needs to be connected to both sides	4	only connected to one side of battery	2	only connected to one side of battery	3	only connected to one side of battery	2	only connected to one side of battery	2	only connected to one side of battery	4	only connected to one side of battery	3	only connected to one side of battery
109	1	bulb A - battery connected directly to **bulb connector** to the electricity; in bulb B - battery only touching the **side of the bulb** which does not receive electricity charge	4	battery and heaters are **not forming a circuit,** so charges attracted in to the heater won't be **exerted** out again	2	there is **no circuit** connecting the two on **both ends,** both sides need to be connected so that the **+ve & -ve** charges flow	3	**no circuit** connecting **both +ve & -ve sides** to let the charge flow	2	**no circuit** for the system to work	2	**no circuit**	4	**no circuit**	3	**no circuit between the batteries and bulb**
RIN	Bulb Light-up		Heater Heat-up		Resistor Current		Bulb Current		Resistor Charge flow		Heater Charge flow		Heater Current		Bulb Charge flow	

	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR
110	1	A was connected from battery to right connection part of bulb. In B, battery is connected to the wrong place of bulb.	4	incorrect way, not from +ve to -ve of battery	2	circular flow from +ve to -ve side of battery not completed	3	circular flow from +ve to -ve side of battery not completed	2	incorrectly connected	2	incorrectly connected	4	incorrectly connected	3	incorrectly connected
111	3	connected to the battery	4	no flow of current	2	resistors are separate, no circuit board	3	bulbs are separate to each other, no circuit board, switch and batteries	2	not connected to circuit board	2	no flow of current	4	no connection between A & B, because A is separate from B	4	connected to battery
112	4	battery has not shown +ve & -ve	4	one is connected to +ve side and other one connected -ve	1	A connected at the same line, B is connected parallel	3	not connected to +ve & -ve	1	A connected in parallel	2	only connected to one side of battery	4	connection	3	connection is not correct
113	4	no energy transfer, **only one pole** connected	4	no energy transfer, **only one pole** connected	2	**only one pole** of battery connected	3	no energy transfer, no current, circuit is not turned on	4		2	only **one end** of battery	4	no energy transfer from one device to another	3	no power because battery is off
114	4	no **proper connection** between bulb and battery	4	**improper connection**	2	**Resistor stops current flow** and putting in a circuit prevents current flow	3	circuit is not properly set up	2	**Resistor stores current** and thus it **will not just have free flow current**, but it will be stored in the resistor	2	not a proper connection	4	improper connection		
115	4	battery has +ve & -ve charges to light it up, **needs both charges**	4	connection **not compete**, need to be connected to **both terminals**	2	both +ve & -ve of battery needs	3	only one end of battery, no electricity	2	**How about we connect the resistor in B to the -ve terminal in A and connect both resistors together at the other end. Whether connected in series or parallel there will be a charge.**	2	connection is not complete, -ve & +ve needs	4	**Battery doesn't have enough charge to heat up a heater. This has a supply of 1.5 volts, that is too little.**	1	**positive end** of battery will supply charge to bulb
116	4	should be connected to **both sides** of the battery, the **+ve & -ve** sides	4	needs **both sides** of battery	2	only **one end of battery**	3	**needs both +ve & -ve of battery**	3		3	charge will flow in **different directions**	4	**needs both +ve & -ve** of battery	4	same charge
117	4	only connected to +ve of battery, does not form complete circuit	4	not connected +ve to -ve	2	not connected +ve to -ve	3	no current flowing	2	not connected	2	not connected +ve & -ve	4	not connected +ve to -ve	3	not connected
118	3	doesn't matter the position of the battery and bulb, energy is transfered	4	both not connected to -ve terminals	2	circuit not complete	4		2	I have answered this question before	2	I have answered this question before	4	I have answered this question before	4	I have answered this question before
119	4	Wire from bulb is connected to -ve terminal of cell. Must be both +ve & -ve.	1	Heater release +ve Q, which will be attracted by -ve charges of battery.	3	Current will differ due to voltages of battery and circuit.	3	Connection is **not complete**; needs connection of +ve & -ve.	3	when there is current, there will be charge flowing	2	no I flowing	4	one terminal only	3	circuit **not complete**
120	4	only +ve of battery	4	Needs both sides of battery.	3	Doesn't matter the position of the resistors connected.	4	correctly connected	2	only one end of battery	2	both +ve & -ve need to be connected	3	Doesn't matter the side of the battery.	3	previously answered
RIN	Bulb Light-up		Heater Heat-up		Resistor Current		Bulb Current		Resistor Charge flow		Heater Charge flow		Heater Current		Bulb Charge flow	

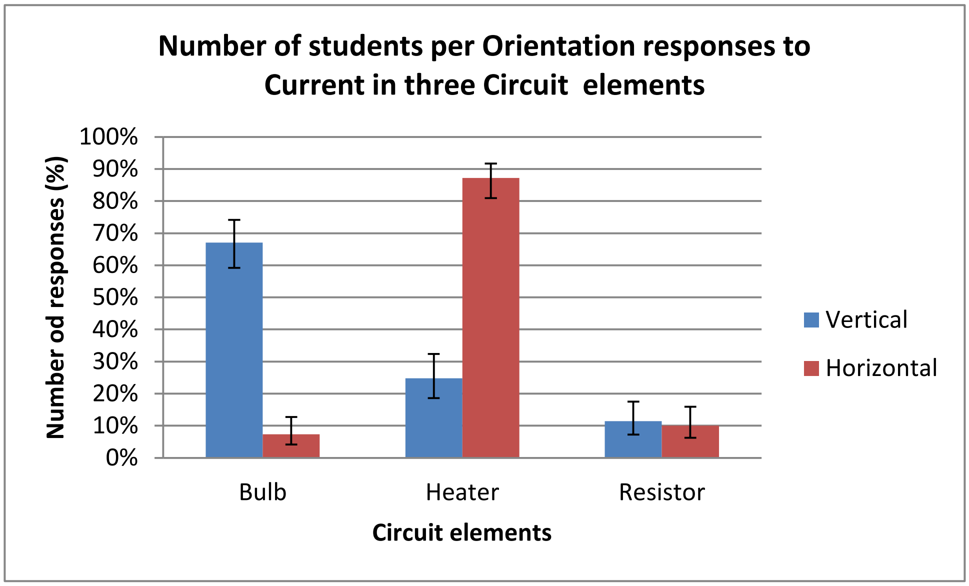
	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR
121	4	**only +ve** of battery connected	4	no **circuit**, needs +ve & -ve	2	If **circuit** was formed	3	no **circuit**, current cannot just flow from +ve end	2	no full **circuit**	1		1		4	**There will be a running charge, bulb will not light up; no circuit**
122	1	connected in a charge (+ve & -ve)	4	**Heater to be heated, needs battery with high voltage, the one used looks to be having small voltage.**	2	Resistor is supposed to be **connected in parallel** to a battery to produce current.	3	bulb and battery must be connected in **parallel** to produce current	1	a flow of charge begins from a +ve charge to a -ve charge in a resistor	2	**charge will not flow in heater, because there is no resistance**	4	**Heater can overpower the batteries. So no current in heater.**	3	battery must be connected parallel and **there must be a resistor**
123	4	if connected to battery and the switch is on	3	connected to battery	3	connected to battery	3	no current transfer	2	**because charge is for charging a battery and resistor doesn't flow charge**	2	**Heater does not charge, it uses electricity**	4	**Heater is not a current, it's an appliance, uses electricity.**	3	**Bulb does not charge, it only uses electricity just like an appliance.**
124	3	Bulbs are connected no matter **how the battery is placed.**	4	**Nothing pushing** the electric charge from battery to heater.	2	**resistor is a device that resists electric flow of energy, but it carries electricity**	1	A connected to black zinc Iron, B connected to middle part	1	R connected to battery	2	**There is nothing that helps the heater to draw energy; not enough device to help electric flow.**	4	**no devices like ampere and resistor** to assess the flow of energy	1	A connected correctly. There will be energy from battery to bulb.
125	4	no wire connected to -ve part of battery, only +ve current, **need +ve & -ve current**	4	no +ve part of battery connected, you need a +ve & -ve current	3	**both is +ve current**	2	B connected to +ve part of bulb	3	I flowing through +ve part of battery	3	there is a current in both, B +ve & A -ve	3	current is different; one is +ve & other is -ve	3	no -ve current in figure A & B
126	4	No other cable to connect to other opposite charge. Should be connected from the -ve charge of the battery or other side of bulb.	1	**-ve charge weaker than +ve charge, B may need -ve charge**	2	not connected to circuit	3	not connected to circuit	3	**Positive charge is stronger than -ve charge**	2	charge will flow in B, **but it won't release heat**	2	**Heater is being charged** is **+ve charge which is stronger than -ve charge.**	4	**they won't light up,** not connected to circuit
127	3	Connected to battery which has power	2	B connected to right side of the **battery, the part with the stick**	2	**Resistor stops the flow of current**	4	there will be a current or power	2	**Resistor stops the current**	4	**B connected to right side of the battery, the part with the stick.**	2	**B connected to right side of the battery, the part with the stick.**	4	Connected battery which has power.
128	1	B not set to proper place where receive energy	2	Battery connected incorrectly, energy must flow from +ve to -ve.	3	current flows, even if one end connected	1	properly connected	3	current flows	4	A incorrectly connected	4	both incorrectly connected	3	both incorrectly connected, must connect on both +ve & -ve
129	1		4	none of the wires are touching the correct side of battery. Not bulb	3	Connected properly.	1	Connected properly.	3	Connected properly.	2	Not connected properly.	4	Not connected properly.	1	Connected properly.
130	4	incomplete circuit, -ve not connected	4	incomplete circuit, not closed -ve & +ve not connected	2	incomplete circuit	3	incomplete circuit	3	terminal connected will supply charge	3	terminal connected will supply electric charge	4	incomplete circuit	4	connected terminal will supply Q, not light up
131	1	R is not connected	2				1		2			cannot explain	4	not connected right way	1	2 bulbs are connected in opposite direction
132	3	If the battery is functioning.	3	Heater is connected, if the battery is functioning.		Needs explanation.	3	**There is no resistor connected, resistor must be connected.**	3	There is a **Resistor** in each battery.	3	Heater is connected, if the battery is functioning	3	there must be a **Resistor** in each battery	4	Both bulb and batteries are connected, if the battery is functioning.
RIN	Bulb Light-up		Heater Heat-up		Resistor Current		Bulb Current		Resistor Charge flow		Heater Charge flow		Heater Current		Bulb Charge flow	

	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR
133	4	only connected to +ve	1	A is connected straight path, B placed like.. Enough electricity will not flow to heater.	3	doesn't matter if series/parallel	4	There are 2 types of bulbs, one has two small pins at the bottom of the bulb on either side, and the other one can be connected to current under the bulb.	2	Charge is something you calculate, **charge does not flow like current.**	2	**Charge needs to be calculated. Charge does not flow like current.**	2	A is **connected to -ve side.**	3	**Charge needs to be calculated. Charge doesn't flow like current.**
134	4	Battery connected to one side	1	Battery A connected straight and there are no disturbances.	1	current will move up	4	there will be **different flow of current**.	3	there will be **difference in current direction.**	3	battery is connected to H	4	battery not connected to both sides	4	
135	3	they receive same amount of energy	3	position does not matter	3	**the magnitude of current in both resistors** will be different, **lengths of conductors** are not same	3	not all poles are connected	3	Q flows in both with different magnitude.	1	direction is not the same	4	not all poles are connected	4	Q will flow in different directions
136	4	**Only 1 connection. In A,** negative wire is not connected to -ve of battery with the -ve of bulb. In **B, will never light because, if you connect +ve of battery to -ve of bulb**	4	In A, only -ve side of battery is connected to battery. In B, only +ve side is connected. Can **combine the two sketches to heat up.**	1	In A, current is in series and moving from +ve to -ve.	1	In A, +ve connected to +ve, but only half connected; in B, +ve connected to -ve, which is wrong connection.	3	both connected right way, but A in series & B in parallel	4	Q will flow only from +ve to -ve	2	where there is Q, there is current	1	correct connection
137	4	There is no switch or resistor, it will not light up. Only +ve side is connected.	4	Each of them connected to 1 side of battery. A is connected to -ve and B is connected to +ve.	1	**A - There is no break up of current, because it is in parallel. B - Current will break along the series connection.**	1	A - connected correctly, to the end where there are electric cables. B - no electric flow.	1	connected only to one connection	2	as in Q2	4	as in Q2	3	as in Q1
138	3	They are connected correctly.	3	you connect a battery to a heater	2	They have to be connected in **parallel** to each other.	1	They have to be placed in connection to each other in **parallel or in series** form.	4	Connecting the resistor to battery, gives an impression that the battery is giving electricity to resistor.			2	**Heater has more mass, battery has more voltage.**	2	The one connected to **north will work,** because it doesn't have **force acting on it, e.g. force of gravity.**
139	3	Each has their own source. **It does not matter if they are not connected in a circuit.**	3	Depending on the power of battery. **From experience.**	3	Resistance prevents electricity to pass in much volts. If volts are same, current same too.	4	flow of electricity	3	**they are not in a circuit**	3	current will flow	3	**they are equal in charge in Physics I know**	4	would be charge flow, except the **battery is low**
140	1	**A - battery is connected to correct position of bulb,** B - not connected properly, power can't light up bulb.	1	Wire connection in B is sealed with a cover in heater, so B will not heat.	4	A - there is a slight mistake, the wires not connected straight.	1	A - correct connection; B - not connected to the **position where bulb cannot be able** to accept the flow.	3	correct, no gap	1	battery is not connected directly to heater	4	Battery wire not straight in A. B has some fault.	3	the connection is not accepted by any bulb
RIN	Bulb Light-up		Heater Heat-up		Resistor Current		Bulb Current		Resistor Charge flow		Heater Charge flow		Heater Current		Bulb Charge flow	

	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR
141	1	wire in B is not connected properly to **-ve or +ve charge of bulb**	3	battery is connected to the charge of heater; energy or power is flowing from battery to heater.	3	connected	1	the wire is not connected to the bulb B	3	both connected	3	heater is connected to battery, therefore energy is flowing from battery to H	4	no current	4	charge will flow
142	1	A is more closely connected to the **bottom of the bulb** where bulb gets electricity	4	Battery should have 2 wires to connect to the heater for it to react. One on each side.	3	**Resistor makes current flow to the next object.** Connects more than one thing at a time.	1	A - battery is more closely connected to the **bottom of the bulb** where it gets its energy supply from.	3	**Resistors** are there to make electricity travel to more than one place.	4	Charge will flow in B; battery's end is connected to heater's end. Therefore +ve & -ve charges.	4	Heater has two points + & -, which need a charge on each side. In both fig it only has one charge connected to one side.	1	Battery is connected to **side of bulb and not bottom.**
143	3	doesn't matter the position of the battery and bulb	3	doesn't matter the direction of the batteries, as long as current flows	3	doesn't matter the direction of the battery	4	doesn't matter the direction of the batteries, as long as current flows	3	doesn't matter the direction of the battery	3	doesn't matter the direction of the batteries, as long as current flows	3	doesn't matter the direction of the battery	4	doesn't matter the direction of the batteries, as long as current flows
144	1	B connected **to covering** of copper connection.	3	doesn't matter the connection, parallel or series	3	doesn't matter the connection, parallel or series	1	no **conductor** in B	3	Q stimulated by battery	3	both have batteries which will release Q	3	doesn't matter the connection	1	B connected to **insulator not a conductor**
145	4	**incomplete circuit,** only +ve connected	4	A is connected only negative and B only +ve	3	I flows from +ve to -ve	1	A is connected to the correct point	2	Q cannot flow, only I.	2	Q cannot flow, only I.	2	I flows from +ve to -ve	3	Q cannot flow, only I.
146	1	B not connected, Q will **reflect** to battery.	3	both connected right way "+ve and -ve"; like Q attract, unlike Q repel each other	3		1	In A, charges enter. In B, charge does not enter.	2	there is no switch	3	like Q attract	3	unlike Q attract each other	1	
147	3	I will flow from -ve terminal to +ve of battery.	2	A - **Not connected to the output side of battery**. Current flows away from the wire, not into it.	3	Connected from the **side of battery** that puts out current.	4	**There are no resistors** connected in the system, bulbs will experience a current.	3	properly connected to battery, release charge	4	system is not properly connected in the battery	2	A is not properly connected	4	connected to the right side of the battery, where charge flows out
148	3	A will be brighter, connected to the **steel side of bulb;** B will be dim.	2	heater B is connected to the **front side of the battery, while A** uses the back of battery.	3	shape doesn't matter	4	A will be brighter, B will light dim. Bulb B is connected to side of bulb.	3	connected to the **front side of battery**	3	B connected to the **front side of the battery**. A at back side.	4	both connected to the wrong side; A **front of battery,** B wrong side of H.	1	Bulb A connected at **front of battery and back of bulb. B is connected to the other side of bulb.**
149	1	Battery is connected in the wire of bulb A; B not connected to the proper side.	3	both are connected with battery	3	I = V/R	1	If there is battery, there is current. They are directly proportional to each other.	3	Connected to battery	3	both connected to battery	3	in battery, there is voltage	1	Bulb B is not connected the right way to battery.
150	3	they are series & parallel connections	2	Heater B connected to the side where electricity can flow. A is connected in opposite side where electricity does not flow.	3	doesn't matter, series or parallel	1	In A, battery is connected to the bulb at the end of bulb, where current flows. B connected to the middle.	3	doesn't matter, series or parallel	4	A is connected to the opposite end to where it should be	2	A is connected wrong way to battery	1	B is connected to the middle of bulb
151	3	switch the bottom on	3	there is electricity in the battery	3	there is electricity in the battery	4	there is electricity in the battery	3	there is electricity in the battery	3	positive & -ve together	3	positive & -ve together	3	only if +ve & -ve close together
152	3	no matter direction, there is electricity in the battery	3	there is power in the battery; direction doesn't affect	3	there is equal energy in the battery	4	battery supplies equal current in each bulb	3		3	Q will flow from each battery to heater	3		4	Q will flow in both
RIN	Bulb Light-up		Heater Heat-up		Resistor Current		Bulb Current		Resistor Charge flow		Heater Charge flow		Heater Current		Bulb Charge flow	

	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR	FCR	WR
153	3	A connected parallel, B series	3	irrespective of parallel or series connection	3	A connected parallel, current has to be shared.	4	A will light brightly because it is connected to battery parallel. B will light dim, because it is connected series.	3	current is more in B, because it is in series			3	A bright; B dim, because of the way they are connected.	4	more charge in A, because it is connected parallel
154	1	A connected to the wire of the battery through the end of bulb. B not properly.	3	both connected properly; doesn't matter series or parallel, they will light up	2	**R block up current**	1	battery is connected properly in A. In B, battery is not connected properly.	3	R is an electric blocker	3	Battery gives the heater a current. Where there is I, there is Q.	1	A connected properly	1	A is connected to a battery directly. B is not connected.
155	1	bulb connection is on the bottom not side, **the pins of the holder are at the bottom.**	2	only B connected	3	series or parallel, doesn't matter	4	Both are connected to battery. Battery has current and it is transferred to bulb.	3	battery lets the charge flow	4	only B is connected. A not connected.	2	A not connected, but B	4	both connected
156	1	A connected at the canter into the bulb	2	B will heat up, because heat is coming from the +ve side of battery. In A, heat is coming in wrong side.	4	A connected to the head of the bulb	1	in A, battery is connected to the head of the bulb as a centre of light bulb.	1	in B, charge will resist	4	in B, heat is coming from battery to heater	2		1	it is so strong and connected
157	1	A connected to the bottom end, where bulb receives electricity. B is not connected to the bottom end and will receive power.	3	both are correctly connected to a circuit	3	no reason	1	A properly connected at bottom end. B not properly connected to the bottom end.	3	there are no visible obstacles to the flow of Q	3	both are properly connected	3	properly connected	1	A is properly connected at the bottom end to the battery. B is not properly connected (not at the bottom end)
158	3	there will be a flow of current, no resistor like an open switch or resistor	3	they will not light up the same, because B in parallel & A series, Q will be different, two heaters not lighting up the same.	3	I will be different	4	there will be flow of current from batteries to light up.	2		3	it will move straight up from battery with no resistance to the heaters	3	no resistance	4	there is neither a resistor nor open switch
159	1	A connected to the **terminal point so power can flow from the battery** through. B is not connected to the **terminal point on the bulb.**	2	battery can only submit power when cable connected to the front part with the little lead or **the +ve side of battery**	3	connected to the right side of the battery	1	there has to be a current	3	there is current, so there is charge	4	charge will flow in B because it is connected properly	2	B connected properly	1	A is connected properly to **the terminal point of the battery and the bulb respectively**
160	3	Bulb A & B connected to the batteries which supply energy to bulb to light up.	2	In A, the battery & heater connected the other way. Heater in B is connected to one side of battery which **doesn't supply energy.**	3	both resistors connected to the **end of the battery, which supplies energy**	4	Both are connected accurately. So they will light up.	3	connected correctly	4	Heater is not connected properly.	2	Connected to the **end that doesn't supply energy.**	4	connected correctly

Appendix 9: Graph from Figure 5.6 plotted with 95% Confidence Intervals and Error Bars



Appendix 10: The procedure to calculate 95% Confidence Intervals of proportions

The Confidence Interval of a Proportion:

The web calculator was used from the site: http://vassarstats.net/prop1.html

This unit will calculate the lower and upper limits of the 95% confidence interval for a proportion, according to two methods described by Robert Newcombe, both derived from a procedure outlined by E. B. Wilson in 1927 (references below). The method uses the Wilson procedure without a correction for continuity.

For the notation used here, n = the total number of observations and k = the number of those n observations that are of particular interest. Thus, if one observes 23 recoveries among 60 patients, n = 60, k = 23, and the proportion is 23/60 = 0.3833.

To calculate the lower and upper limits of the confidence interval for a proportion of this sort, enter the values of k and n in the designated places, then click the «Calculate» button.

References:
Newcombe, Robert G. "Two-Sided Confidence Intervals for the Single Proportion: Comparison of Seven Methods," *Statistics in Medicine,* **17**, 857-872 (1998).

Wilson, E. B. "Probable Inference, the Law of Succession, and Statistical Inference," *Journal of the American Statistical Association,* **22**, 209-212 (1927).

Appendix 11: Key ideas used in three elements

Appendix 11 A

Key Ideas (KI) from Summarised Written Responses (SWR) to three questions relating to the light bulb. The grey shaded area gives the KIs for the correct answer choices.

Group No.	Students' Key Ideas of a light bulb	Number of students			
		light up	Current	Charge flow	
1	incomplete circuit/circuit is open/ no complete circuit	8	8	7	Reasons used to arrive at the correct answer choices
2	positive and negative should be connected	11	10	5	
3	only one connection, no energy/ power transfer	6	2	2	
4	Improperly/incorrectly connected	1	3	4	
5	properly connected	1	3	5	Reasons used to arrive at the incorrect answer choices
6	energy is transferred	1	0	2	
7	connected to battery	8	5	6	
8	positive end will supply charge	1	1	2	
9	not connected in parallel/series	2	3	1	
10	charge/current/energy/electricity	3	2	3	
11	there must be a resistor	1	3	1	
12	horizontal bulb is not connected	3	2	3	
13	positive of bulb connected to negative of battery	1	1	0	
14	bulb connector	12	8	5	
15	Miscellaneous	1	2	1	

Appendix 11 B

Key Ideas from Summarised Written Responses (SWR) to three questions relating to the heater. The grey shaded area indicates the KIs for the correct answer choices (see text for details).

Group No.	Students' Key Ideas of a heater	Number of students			
		heat-up	current	charge flow	
1	no complete circuit/incomplete circuit/circuit is open	4	6	5	Reasons used to arrive at the correct answer choice
2	positive and negative should be connected	15	7	8	
3	only one connection, no energy/power transferred	6	6	6	
4	incorrectly connected	1	5	5	
5	properly connected	1	3	3	Reasons used to arrive at the incorrect answer choices
6	energy is transferred	0	2	1	
7	connected to battery	19	11	8	
8	positive connected to battery	3	7	10	
9	positive end will supply charge	1	2	1	
10	vertical circuit is not connected	2	2	1	
11	charge/current/electricity	1	2	2	
12	there must be a resistor	4	2	2	
13	Miscellaneous	2	3	3	

Appendix 11 C

Key Ideas from Summarised Written Responses (SWR) to two questions relating to the resistor. The grey shaded area indicates the KIs for the correct answer choices. (see text for details)

Group No.	Students' Key Ideas of a resistor	Number of students		
		Current	Charge flow	
1	complete circuit/closed circuit	8	9	Reasons used to arrive at the correct answer
2	positive and negative should be connected	7	3	
3	only one connection	4	5	
4	incorrectly connected	0	1	
5	properly connected	1	3	Reasons used to arrive at the incorrect answer choices
6	connected in parallel/series	9	4	
7	resistor stops current	5	4	
8	connected to battery	7	8	
9	positive end will supply current/energy/ charge	2	5	
10	current/charge flow	3	3	
11	charge doesn't flow	0	1	
12	positive of battery connected/positive current	1	0	
13	current/charge will differ in vertical and horizontal circuit	1	2	
14	miscellaneous	8	7	