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DC circuits: I. Evidence for fine grained contextual dependence*

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Abstract

This is the first part of a broader study, exploring the contextual variations of the responses of 149 first year (non-physics major) university students at two South African universities in Cape Town. The data analysis was done in terms of the (i) forced choice responses (FCR), (ii) free written responses and (iii) personal interviews. This paper presents the development of the instrument (aspects of circuits questionnaire, or ACQ) used in the exploratory study and the results obtained from the FCR analysis of 60 students. The results showed that the student responses are triggered by the context framed by the questions and the results obtained from investigations using light bulbs cannot be generalised and may be reinterpreted.

Keywords: context, DC circuits, resistive elements

(Some figures may appear in colour only in the online journal)

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 with regard to light, electricity, heat and states of matter are described in *Children's Ideas in Science* (Driver *et al* 1985), while at 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

* This article was extracted from the PhD thesis submitted to Faculty of Science, University of Cape Town.

Conference on Physics Education in 2012. Stetzer *et al* (2013) reported that certain basic difficulties, including upper division courses involving analogue electronics, were found in all population groups. In addition, many of the findings that relate to the various groups mentioned also appear to be applicable to teachers (Schoon and 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).

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 RW 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 physical 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. Brooks and Etkina (2009) show that many difficulties exhibited by students, with regard to the physical understanding of force, are reminiscent of similar struggles experienced by iconic names in physics over past centuries.

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 physical 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' (Hynd and Alvermann 1986, Brown and Clement 1989, Tsai 1999, Quijas and Aguilar 2007) or 'remediating' (Murray *et al* 1990) or 'confronting' (Brna 1988, Tsai 1999) 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 'misconceptions are often symptoms of confusion at a fundamental level'.

However, in general, the 'misconceptions' model appears to lead to approaches to conceptual change (Champagne 1983, Duit and Treagust 2003) 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' (KIP) model (diSessa 1993). 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.

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 KIP 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 to 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. 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 framework for carrying out investigations, as well as their interpretation, uses a 'misconceptions' perspective rather than 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.

From the literature it is clear that light bulbs often feature in research studies. It is common practice to use the light bulb to introduce DC circuits in text books (Hewitt 1988), curriculum sequences (McDermott and Shaffer 1992), as well as for research purposes (McDermott 1996). For example, McDermott and colleagues used circuits with a battery and bulbs 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.

Thus, many of the findings that have been carried in the area of DC circuits have done so using light bulbs (Tiberghien and Delacote 1976, Evans 1978, Fredette and Lochhead 1980, Dupin and Joshua 1987). 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, which 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. Thus, the overall interpretative framework was more in keeping with the 'misconceptions' framework, rather than with the KIP perspective.

While much work has been done in mechanics, using both the 'misconceptions' and 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 for the modelling exercise as noted by Hestenes. In the case of mechanics it is easy to understand the reduction of an experienced mass into a point particle. 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. In order to understand the point charge and the flow of charge to be termed as current, we need to explain it through an observed phenomenon. 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. However, none of these approaches appear to be very successful, and students experience a range of difficulties.

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 (Leander and Brown 1999, diSessa *et al* 2002, Redish and Burciaga 2004). 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.

Thus, the present study made 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.

As stated above, 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 KIP perspective, in which context and cognitive 'grain-size' are key components. 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, this study investigated to what extent seemingly small contextual changes to a DC circuit affected students' responses. The present study focused on the following three aspects: (i) changes between equivalent resistive elements, (ii) changes to the circuit orientation, and (iii) 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 section.

Development of the instrument

The present study investigated the way in which students engage with DC circuits: (i) the role of context in students' responses and (ii) the reasoning without pre-conceptions as the outcomes. While the former could 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 and Buffler (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, FCR) and then provide a detailed written reason for the choice (free writing response, FWR). The questions used by Allie and Buffler (1998), as well as those used in later studies (Buffler *et al* 2001, Volkwyn *et al* 2008), provided detailed guidance on the design and construction of the questionnaire.

The broad thrust of the study was to look into the effect on students' responses to a number of questions in which fine-grained contextual changes were made to the simplest possible configuration that would be recognized as being part of an electrical circuit. 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. There is no evidence suggesting that the student responses will be the same when using a closed circuit and an open circuit[4]. To this end, a single battery and a single 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. 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. An expert treats any element as a resistor, and an open circuit is a non-functional circuit irrespective of the elements, words and orientations. As noted earlier, many studies assumed that this would be the case for a light bulb and a resistor, by students as well. 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'.

Thus, each circuit that is used as the basis of question was presented to students, and comprised 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 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.

[4] Follow up research using an instrument with a closed circuit is to be published.

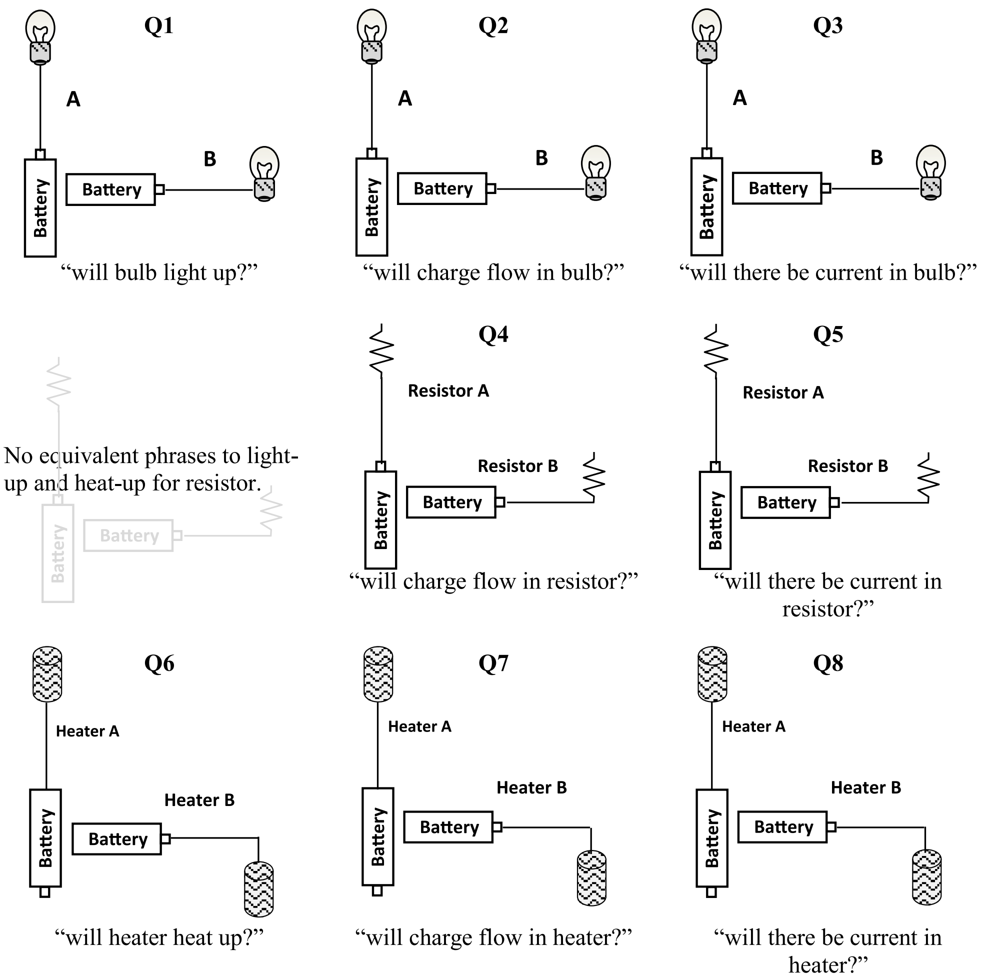


Figure 1. The combination of circuits and wording used in the eight questions.

The question consists of a ‘stem’ in which the background to the problem is sketched, followed by a debate consisting of four opinions. The respondents were asked to circle a number (1–4), and explain their reason for choosing that particular opinion.

Sample

The piloting of the instrument was conducted on a sample of 97 first year (non-major physics) university students registered in 2009. 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 their a second or third language. The main study was conducted on two independent cohorts: (i) an exploratory study on 60 students from one university in Cape

Town and (ii) a confirmatory study on another 89 students from an adjacent university. The data provided in this article are of the exploratory study on 60 students.

A number of features were changed in the final instrument. First of all, three questions were added to make a total of eight questions in the final questionnaire. 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, USA, and considered their opinions regarding randomising the numbers (1–4) of the answer choices.

The instrument: aspects of circuits questionnaire (ACQ)

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 the ACQ is shown in figure 1. (The full questionnaire is presented in the appendix.) 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. Column 1 illustrates one question each 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 all cases, 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—

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.

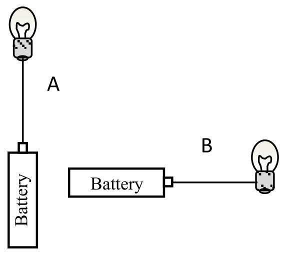
Student 1 says, "The bulb in circuit **A** will light up, but not the bulb in circuit **B**!"

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. Format of the questions after the pilot study.

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).

The final format of a question is illustrated in figure 2. (The full ACQ is given in the appendix.) Each question consists of four options. 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 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 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. Two researchers 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.

Group results

In order to discuss 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. The graphs are presented to illustrate the variation in student responses with respect to various fine-grained contextual changes in the questions. Thus the group analysis is presented by the seven graphs in figures 3–9.

Responses to light bulb circuits

Figure 3 illustrates the responses of students to the three questions relating to the light bulb. 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 number of students who selected the correct answer choice. Approximately half of the students selected the correct choice (29/60 for the 'current', 27/60 for the 'charge flow' and 26/60 for the 'light-up'). While the V(ertical) circuit was selected by a quarter of the students (19 for the 'current', 14 for the 'charge flow' and 17 for the 'light-up'), the H(orizontal) circuit was selected by a negligible number of students (one each for the 'current' and the 'charge flow', and none for the 'light-up'). Both V(ertical) and H(orizontal) circuits (VH) were selected by less than a quarter of the students (10 for the 'current', 16 for the 'charge flow' and 17 for the 'light-up').

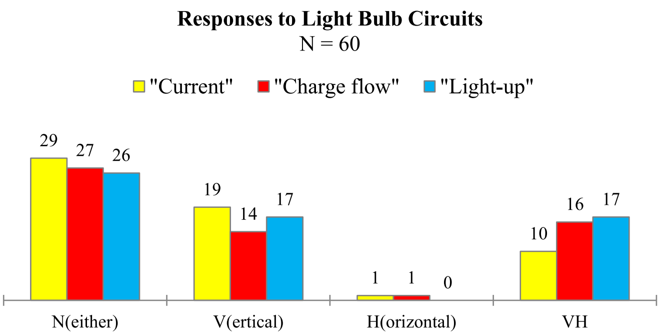


Figure 3. Students' responses to questions relating to light bulb. N = neither circuit activates, V = the vertical circuit activates, H = the horizontal circuit activates, VH = both circuits activate.

Responses to heater circuits

Figure 4 illustrates the responses of the students to the three questions relating to the heater. 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 number of students who selected the correct choice. Approximately half of the students (34 for 'current', 26 for 'charge flow' and 30 for 'heat-up') selected this choice. While the V(ertical) circuit was selected by two each for 'current' and 'charge flow', four selected the same choice for 'heat-up'. The H(orizontal) circuit was selected by ten each for 'current' and 'charge flow', and nine selected 'heat-up'. Both V(ertical) and H(orizontal) circuits (VH) were selected by a quarter of the students (13 for 'current', 17 for 'charge flow' and 15 for 'heat-up').

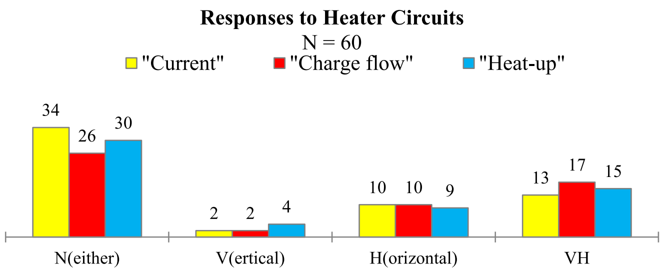


Figure 4. Students' responses to questions relating to heater. N = neither circuit activates, V = the vertical circuit activates, H = the horizontal circuit activates, VH = both circuits activate.

Responses to resistor circuits

Figure 5 illustrates the responses of the students to the two questions relating to the resistor. 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 number of students who selected the correct answer, which constituted less than half (25 for 'current', and 23 for 'charge flow'). While the V(ertical)

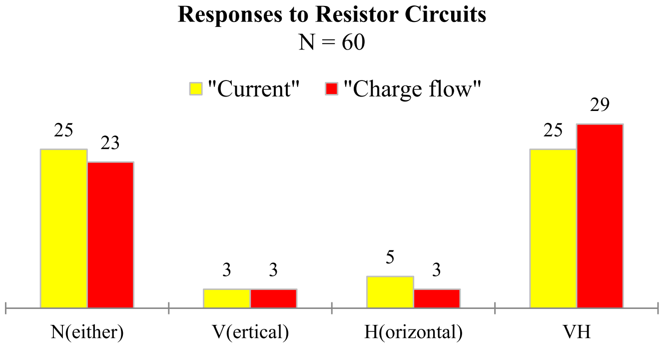


Figure 5. Students' responses to questions relating to resistor. N = neither circuit activates, V = the vertical circuit activates, H = the horizontal circuit activates, VH = both circuits activate.

circuit was chosen by three for both 'current' and 'charge flow', the H(orizontal) circuit was selected by five for 'current' and three for 'charge flow'. Both V(ertical) and H(orizontal) circuits (VH) were selected by 25 for 'current' in the resistor and 29 for 'charge flow' in the resistor.

Responses to light-up and heat-up

Figure 6 illustrates the student responses to the two questions relating to the 'light-up' of the light bulb and the 'heat-up' of the heater. 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 set of bars represents the number of students who selected the correct choice. The correct choice was chosen by less than half of the students (26 for the 'light-up' of the light bulb, and 30 for the 'heat-up' of the heater). While the V(ertical) circuit was chosen by 17 in the question relating to the light bulb, only four selected it in the question relating to the heater. While the H(orizontal) circuit was selected by nine 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 (17 for the light bulb, and 15 for the heater).

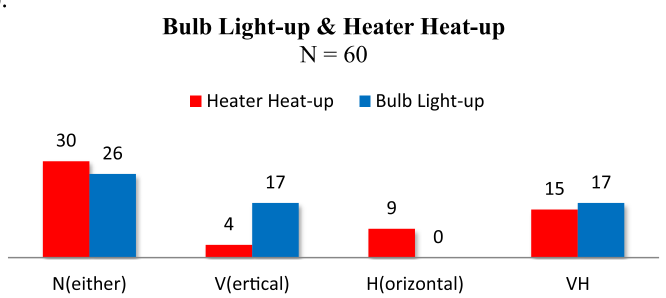


Figure 6. Students' responses to questions relating to light bulb (blue) and heater (red). N = neither circuit activates, V = the vertical circuit activates, H = the horizontal circuit activates, VH = both circuits activate.

Charge flow in circuit elements

Figure 7 illustrates the responses of the students to the three questions relating to 'charge flow'. 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 number of students who selected the correct choice. Less than half of the cohort (27 for the light bulb, 26 for the heater and 23 for the resistor) selected the correct choice. While the V(ertical) circuit was selected by 14 in the question relating to the light bulb, only two selected this choice in the question relating to the heater, and three in the question relating to the resistor. The H(orizontal) circuit was selected by one in the question relating to the light bulb, ten in the question relating to the heater, and three in the question relating to the resistor. Both V(ertical) and H(orizontal) circuits (VH) were selected by 16 in the question relating to the light bulb, 17 in the question relating to the heater, and 29 in the question relating to the resistor.

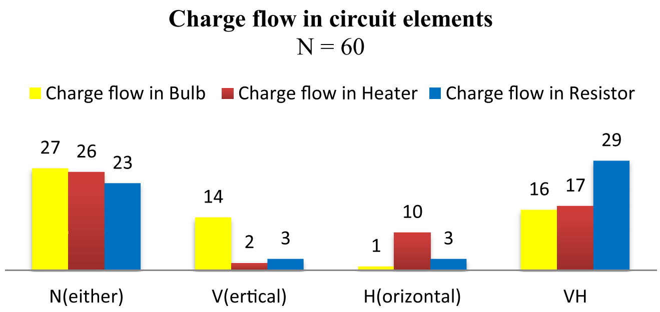


Figure 7. Students' responses to questions relating to 'charge flow' in three elements. N = neither circuit activates, V = the vertical circuit activates, H = the horizontal circuit activates, VH = both circuits activate.

Current in circuit elements

Figure 8 illustrates the responses of the students to the three questions relating to 'current' in three elements. 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 number of students who selected the correct choice. The correct choice was chosen by approximately half of the students (29 for the light bulb, 34 for the heater, and 25 for the resistor). The V(ertical) circuit was selected by 19 in the question relating to the light bulb, two in the question relating to the heater, and three in the question relating to the resistor. The H(orizontal) circuit was selected by one in the question relating to the light bulb, ten in the question relating to the heater, and five in the case of the resistor. Both the V(ertical) and H(orizontal) circuits (VH) were selected by ten in the question relating to the light bulb, 13 in the case of the heater, and 25 in the question relating to the resistor.

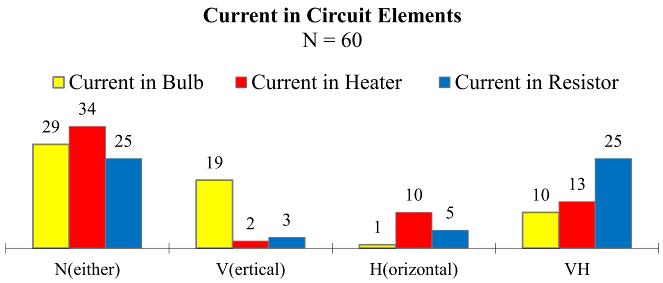


Figure 8. Students' responses to Q3, Q5 and Q8, relating to 'current' in three elements. N = Neither circuit activate, V = Vertical circuit activates, H = Horizontal circuit activates, VH = both circuits activate.

Responses to circuit orientations (vertical and horizontal)

Figure 9 illustrates the responses of the students to the eight questions relating to the orientations of the circuits. 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 number of students who selected the H(orizontal)ly orientated circuit, and the yellow bars represent the number 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. 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. 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 number of students who selected ‘charge flow in the resistor’ were the same (three) in both V(ertical)ly and H(orizontal)ly orientated circuits. The number of students who selected ‘current in the resistor’ varied between three for the V(ertical) circuit and five for the H(orizontal) circuit. However, the number of students who selected ‘heat-up of the heater’ for the V(ertical) was half that of H(orizontal) circuits; four for the V(ertical) circuit and nine for the H(orizontal).

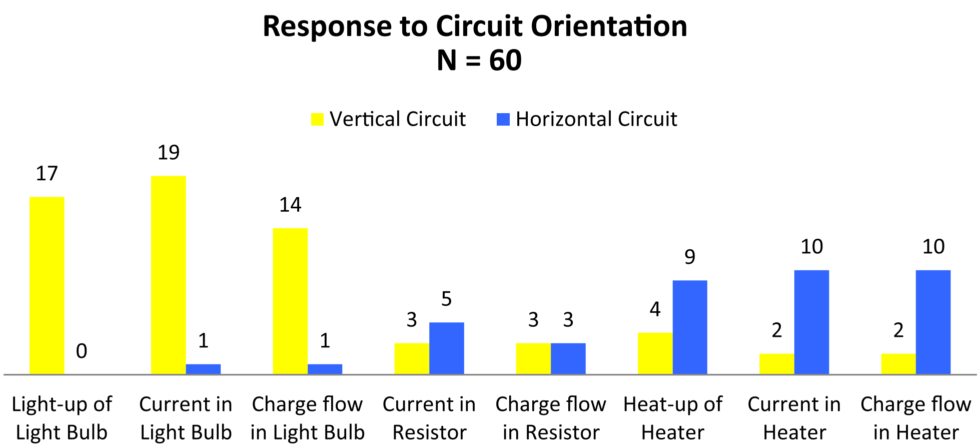


Figure 9. Students’ responses to circuit orientations.

Table 1. 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**

Student-by-student results

The second phase of analysis was done on a student-by-student basis. The data collected from the first section of the ACQ, the forced choice responses (FCR), were recorded on a spreadsheet. Each row of spread consisted of the Respondent Identity Number (RIN) followed by eight numbers. Thus, the spreadsheet comprised 60 rows representing 60 students, and nine columns (RIN and eight questions). The data were thus transformed into a more descriptive mode using an alphabetic assignment and colour coded using table 1 and presented in table 2.

Table 2 provides the translated dataset of the FCR in a thematic order of the questions presented in the ACQ. Row-by-row entries provide the eight responses of a respondent. The first column gives the RIN and the last column provides the number of correct answers of each student. The scattering of colours in the spreadsheet shows clearly that the students' responses to the eight questions were inconsistent. (The reasons behind these inconsistencies are discussed in the follow up article.) It is interesting to note that, while the first nine students answered all questions correctly, the last ten students answered all questions incorrectly; the middle two thirds 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 the following article.

Discussion and conclusion

The analysis of the dataset 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. In contrast to this, in the case of the heater circuits, 17% opted for the horizontal circuit and very 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. Furthermore, the number of students who opted for vertical circuits and horizontal circuits separately, in a resistor, was almost the same.

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. Thus, the preferred orientation is likely to be triggered when primed with a situation in the task i.e. the students

Table 2. Thematic ordering and colour-coding of the FCR.

RIN	Light Bulb			Heater			Resistor		#Correct answers
	Current	Charge flow	Light-up	Current	Charge flow	Heat-up	Current	Charge flow	
1	N	N	N	N	N	N	N	N	8
2	N	N	N	N	N	N	N	N	8
3	N	N	N	N	N	N	N	N	8
4	N	N	N	N	N	N	N	N	8
5	N	N	N	N	N	N	N	N	8
6	N	N	N	N	N	N	N	N	8
7	N	N	N	N	N	N	N	N	8
8	N	N	N	N	N	N	N	N	8
9	N	N	N	N	N	N	N	N	8
10	N	N	V	N	N	N	N	N	7
11	N	N	V	N	N	N	N	N	7
12	N	VH	VH	N	N	N	N	N	6
13	N	N	N	N	N	N	H	H	6
14	N	N	N	N	N	N	H	H	6
15	N	U	N	N	H	N	N	N	6
16	N	V	N	N	N	N	N	VH	6
17	N	N	N	N	H	N	N	V	6
18	N	VH	N	N	VH	N	N	N	6
19	N	VH	VH	N	H	N	N	N	5
20	N	N	N	N	N	V	VH	VH	5
21	VH	N	N	VH	N	N	VH	N	5
22	N	VH	N	U	U	N	N	N	5
23	V	N	N	N	N	N	V	V	5
24	N	N	V	N	N	N	H	V	5
25	N	N	VH	N	N	VH	VH	N	5
26	N	N	N	VH	N	VH	N	VH	5
27	H	N	N	VH	VH	N	N	VH	4
28	N	VH	N	H	N	V	N	VH	4
29	VH	N	VH	H	N	H	VH	N	3
30	V	N	V	N	N	H	VH	VH	3
31	V	V	V	N	N	N	VH	VH	3
32	N	VH	VH	N	VH	N	VH	VH	3
33	V	V	V	N	U	H	N	N	3
34	N	VH	VH	N	VH	VH	N	VH	3
35	VH	N	N	H	N	V	VH	U	2
36	VH	VH	N	N	VH	V	V	VH	2
37	N	VH	VH	N	V	VH	U	VH	2
38	V	V	N	H	H	N	V	VH	2
39	V	H	N	H	U	VH	N	H	2
40	VH	N	VH	N	VH	VH	VH	VH	2
41	V	VH	V	N	VH	VH	N	VH	2
42	V	N	V	N	V	U	H	VH	2
43	U	V	VH	N	VH	H	N	VH	2
44	V	V	V	N	H	N	VH	VH	2
45	VH	N	VH	VH	VH	VH	VH	VH	1
46	V	V	V	VH	VH	N	VH	VH	1
47	V	U	N	H	U	VH	VH	U	1
48	V	V	V	VH	VH	VH	VH	N	1
49	VH	VH	VH	H	H	H	VH	N	1
50	V	V	V	N	VH	VH	VH	VH	1
51	V	V	VH	H	H	H	VH	VH	0
52	N	N	VH	VH	VH	VH	VH	VH	0
53	VH	VH	VH	VH	VH	VH	VH	VH	0
54	VH	VH	VH	VH	U	VH	VH	VH	0
55	V	V	V	V	VH	VH	VH	VH	0
56	VH	VH	V	H	H	H	VH	VH	0
57	V	V	V	H	H	H	H	V	0
58	V	V	V	VH	VH	VH	VH	VH	0
59	VH	VH	VH	VH	VH	U	VH	VH	0
60	V	V	V	VH	H	H	VH	VH	0
Correct Answers (%)	48 (29/60)	45 (27/60	43 (26/60)	57 (34/60)	43 (26/60)	50 (30/60)	42 (25/60)	38 (23/60)	

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.

Based on the responses to the horizontal and vertical orientations the responses were compared to see if there was any association between light bulbs and heaters, with regard to the phenomenological aspects, i.e. light-up or heat-up. 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 were significantly different. While 28% suggested that the vertical bulbs will light-up, only 7% suggested that the vertical heater will heat-up and in contrast in the horizontal orientation none of them suggested that the bulb will light-up while 15% suggested that the horizontal heater will heat-up. It is clear that there is a strong association with vertical bulbs lighting up and horizontal heaters heating up.

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, questions 3, 5 and 8, in which the presence of current was asked for, all three elements were compared. Figure 8 shows comparative responses to the questions relating to current in three elements. The four sets of three bars represent the number of students who responded to current-related questions for the three elements. While 32% students suggested that the vertical light bulb would have current, only 2% suggested the same for the horizontal light bulb. Conversely, while 17% students suggested that the horizontal heaters would have current, only 3% had the same opinion in the case of the vertical heaters. However, the resistor shows two differing features. Firstly, the number of students who suggested that there would be a current in either resistor was significantly lower than for either 'current in the bulb' or 'current in the heater'. Secondly, there is no significant difference between the numbers in the results for the vertical and horizontal resistors.

A light bulb is a familiar context but a resistor is not. However, the resistor, for most of them, is known as a concept with two terminals in the electric circuits that was used only in the class room. In the presented circuit diagrams, that the resistor circuits were not connected to both ends may have prompted them not to choose the vertical and horizontal options. Furthermore, the familiarity of bulbs hanging from a ceiling in a single wire might have influenced many to choose the vertical option. In the case of heaters, the fact that bar-heaters are one of the familiar room heaters in South Africa might have contributed to the higher number of students opted for horizontal circuits compared to vertical circuits. In a resistor circuit, the option 'both vertical and horizontal circuits' will activate, was chosen by more students than that of the correct answer. This may be because they recognise that the two orientations are equivalent, which is an unfamiliar (conceptual) element without artefacts similar to a bulb and heater. Furthermore, the lowest cumulative percentage of the vertical and horizontal options may be because the resistor being a passive element made it 'easier' for them to recognise the equivalence of the orientations.

In summary, the data analysis of the FCRs showed that most students support the activation of the vertical bulb; in contrast 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.

There are two main implications that follow from the present work. Firstly, starting with light bulbs may be problematic in the sense that these findings cannot be generalised to other contexts; and secondly, research findings based entirely on instruments or observations made from circuits involving light bulbs may, in some cases, require re-interpretation. The first implication is discussed in more detail in the second part of this article.

Acknowledgments

I would like to thank the students who participated in the study. I am indebted to S Allie, Department of Physics, UCT, who supported me throughout this project and all other colleagues who gave creative advice.

Appendix. 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 stapled together before being presented.

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.

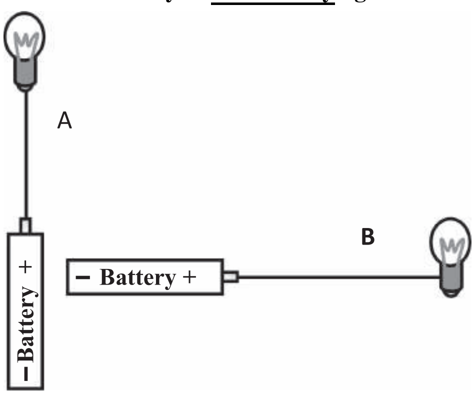
Student 1 says, ‘The bulb in figure A will light up, but not the bulb in figure B!’

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 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 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.

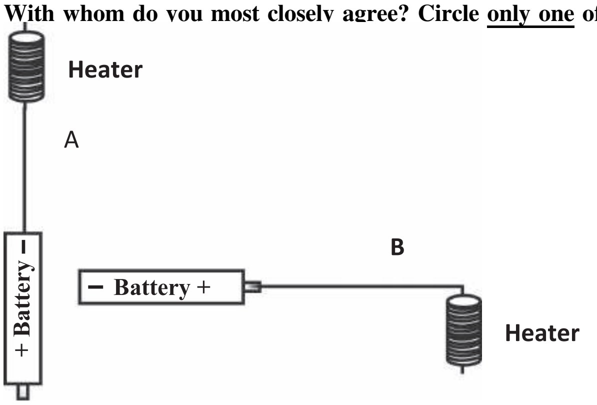
Student 1 says, ‘The heater in figure A will heat up, but not the heater in figure B!’

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.



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Explain the reasons for your choice in detail below.

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(Continued.)

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.

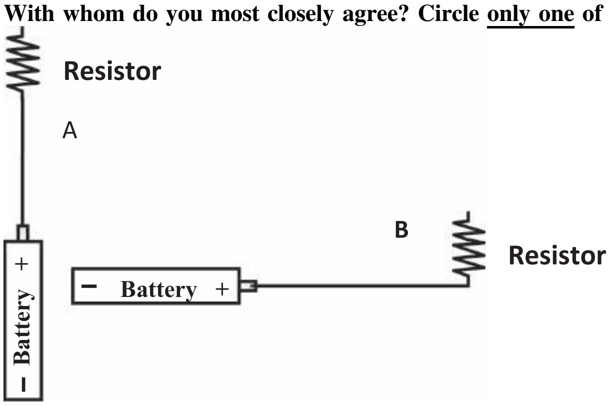
Student 1 says, ‘There will be a current in figure A, but not in figure B!’

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.

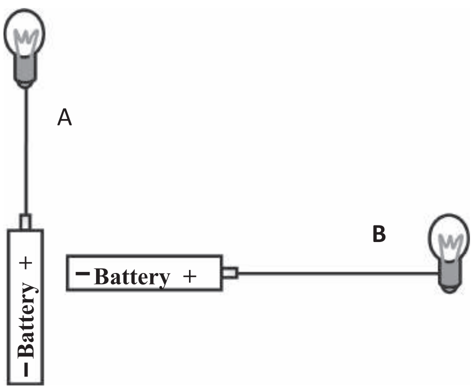
Student 1 says, ‘There will be a current in figure A, but not in figure B!’

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 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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(Continued.)

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.

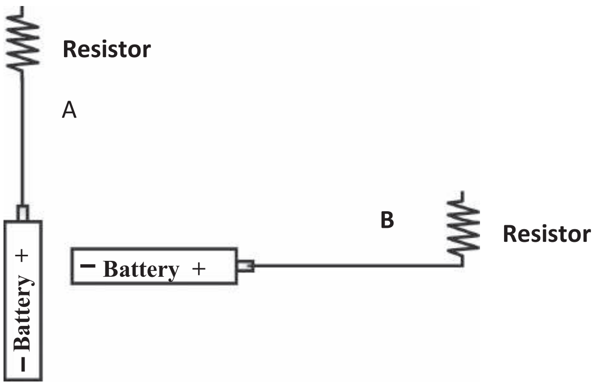
Student 1 says, ‘Charge will flow in figure A, but not in figure B!’

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.

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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.

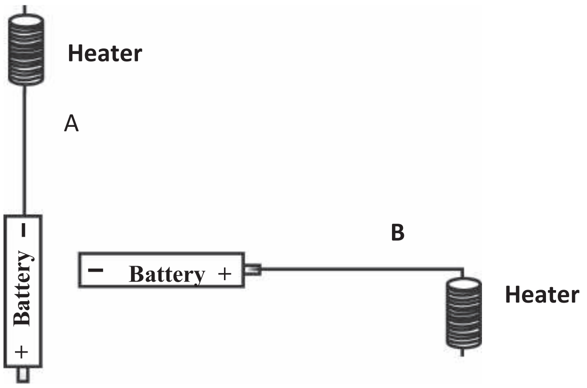
Student 1 says, ‘Charge will flow in figure A, but not in figure B!’

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 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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(Continued.)

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.

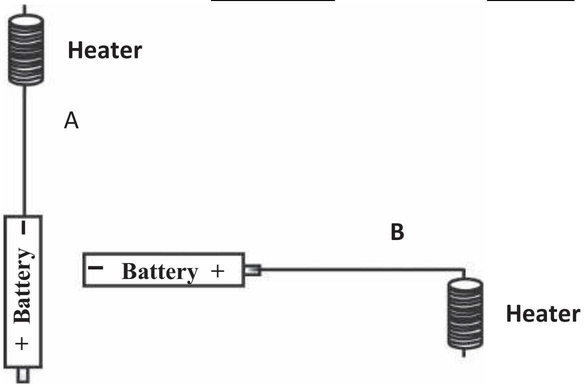
Student 1 says, ‘There will be a current in figure A, but not in figure B!’

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.

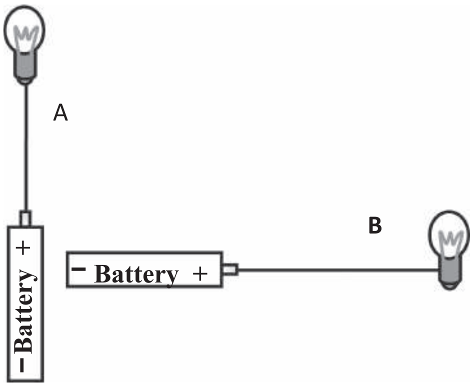
Student 1 says, ‘Charge will flow in figure A, but not in figure B!’

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 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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