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DC circuits: II. Identification of foothold ideas in DC circuits

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Abstract

This is the second part of a broader investigation which explores the reasons behind the contextual variations in student responses at a fine-grained level. In the previous article (John 2017 *Eur. J. Phys.* **38** 015701) it was established that the students' responses are highly context dependent at a fine-grained level. This article presents the reason for the contextual variations of student responses from their free written responses. The result indicates that students who are being triggered by the productive resources during the engagement with the task will arrive at the correct (canonical) conclusion and those triggered by the unproductive resources will arrive at an incorrect conclusion. We identified the productive foothold ideas in a simple DC circuit with a single resistive element.

Keywords: foothold ideas, DC circuits, context, resistive elements, light bulbs

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

Introduction

The first part of this broad investigation presented evidence for the variation of student responses for fine grained contextual changes in an open DC circuit (John 2017). This article looks at the reasons behind the student difficulties in the context of DC circuits. Physics education research, in the past several years, has been focused on student difficulties and their misconceptions. Many investigations into student difficulties in understanding DC circuits have performed by numerous researchers in the past 30 years. Most of them were focused on the 'misconceptions' rather than the reasons behind the 'misconceptions' (Clement 1982, Brna 1988, Tallant 1993, Hein 1999). Although identifying misconceptions helped to develop apparently effective curricula, we have not achieved the goal of helping the majority of students. The reason for this in the account of Hammer (2000) is that these findings do not give any productive resources to students or the underlying mechanism. According to the misconception perspective, student resources are an obstacle to learning and are rigid, coherent and difficult to change (Clement *et al* 1989, Tallant 1993). Furthermore, these misconceptions have to be removed and replaced by canonical conceptions, which is against the constructivist theory (Smith *et al* 1994). However, there is no confirmed evidence to suggest that we can remove and replace the 'misconceptions' and replace them with more acceptable conceptions (Dunbar *et al* 2007, Masson *et al* 2014).

Most of the investigations that identified the student difficulties used a light bulb and its brightness as a proxy for current and voltage, and the findings were used to develop instructions (Shaffer and McDermott 1992, Engelhardt *et al* 2004, Marshall 2008, Smith and van Kampen 2011) in the assumption that the findings in one context can be generalized to other contexts.

It is a common practice that physicists teach physics the way they learned and were taught. However, it has been proved over the years that this strategy is not working, simply because the language of physicists is not the same as that of students. If we want to teach students effectively we have to understand the way they learn and what they know about a particular topic rather than what we want them to learn in our way. Redish says:

> If we are to make serious progress in reaching a larger fraction of our students, we will have to shift our emphasis from the physics content we enjoy and love so well to the students themselves and their learning. We must ask not only what we want them to learn, but what do they know when they come in and how do they interact with and respond to the learning environment and content we provide (Redish 1994).

Therefore, in order to respond to students' needs we have to understand the way in which they respond in different contexts. Thus we set out to investigate the reasons behind the student responses.

The investigation into the variation of student responses using a simple (open) circuit with fine-grained contextual variations was presented in the first part of this study. The questionnaire consists of eight questions; each had a vertical and a horizontal (identical) circuit and students were asked whether the circuits will 'activate' or not. The questions were different in two aspects: (i) wordings with the same meaning—current and charge flow for example and (ii) different resistive elements—light bulb and resistor for example. The term 'activate' refers to: light up of a bulb, heat up of a heater, presence of current or charge flow in an element. Each question requested the students (i) to choose one of the given four options (forced choice responses—FCR) and (ii) to explain in detail the reason (free written responses —FWR) for choosing a particular option in the provided space. A sample question is given in appendix A.

The first part of this study presented the detailed findings from the FCR. The full instrument, *Aspects of Circuit Questionnaire* (ACQ), was given in appendix A of the previous paper. The results showed that student responses are highly context dependent and students do not consider a light bulb to be same as a resistor or a vertical light bulb to be the same as a horizontal light bulb. The second part of this study used an independent cohort (89 students) from a different university to confirm (confirmatory study, not presented in this article) whether the findings from the first cohort can in fact be applied to other cohorts. It was confirmed that the results are similar (John 2016). Thus this paper presents the reasons used by students for choosing a particular FCR from the free written responses (FWR) of the 60 students from the exploratory study.

Table 1. Number of correct responses (%) to individual questions N1 = 60.

	Light Bulb			Heater			Resistor	
	Light-up	Current	Charge flow	Heat-up	Current	Charge flow	Current	Charge flow
Correct answers (%)	43 (26/60)	48 (29/60)	45 (27/60)	50 (30/60)	57 (34/60)	43 (26/60)	42 (25/60)	38 (23/60)

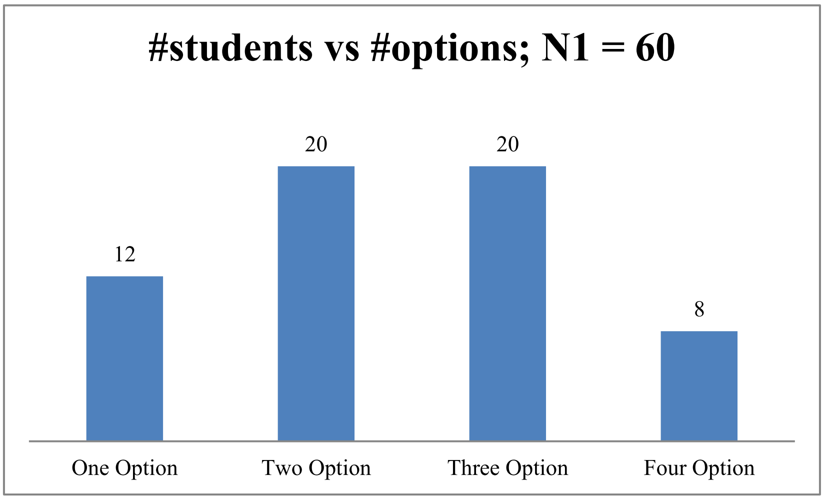

Figure 1. The number of students who used one or more options to answer all questions.

Sample

The cohort was a sample of 60 first year (non-major physics) university students. 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. (Physical science is the combination of physics and chemistry.) 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 acience as a subject, and this part of their curriculum had been included in the examination. For most students, English is a second or third language.

The study

The previous article (exploratory study) presented the contextual variation of student responses in detail. In summary, about half of the students answered each of the eight questions correctly. However, only nine students answered all eight questions correctly. Table 1 below shows the number of students out of 60 who answered each question correctly. The question with the greatest number of correct student responses (57%) related to current in a heater, and the question with the lowest number of correct answers (38%) was related to charge flow in a resistor.

Most students chose different options for the eight questions and and had different reasoning ideas; they changed from question to question with respect to the changes in the question. Even though all the questions were open circuits, and none of them would activate, many students changed their answers to the eight questions from one option to another. Figure 1 shows the number of students who opted for different numbers of options to answer all questions. Only 12 students used one option to answer all eight questions. It is interesting to note that, of these 12, nine students chose the correct option in all eight questions. Others chose a different option with respect to the context of each question, up to four options. A group of 20 students individually chose two and three options and eight students used four options to answer the full instrument.

This article presents the reasons behind the variations of student responses. The analysis of the free writing responses (FWR), elicited by the request for students to provide detailed reasoning for their answer choices, was performed using the approach suggested by grounded theory (Strauss and Corbin 1990).

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 the '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. 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 future investigations. Some examples of the original student writing (*in their own words, in italics*) and the SWRs are illustrated below.

Figures 2(a)–(f) illustrate the original student writing that was compared with the SWRs. The examples in figures 2(a)–(c) are clear, short and well-written explanations. Figure 2(d) shows a very long, but clearly explained sample with a unique idea. Figures 2(e) and (f) are examples of long writing with more than one idea, which can be difficult to comprehend. 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.

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 13–15 ideas (appendix B). Upon further grouping, six categories with subcategories emerged and are listed in table 2 with their respective codes.

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
- A50. Charge flow mentioned
- A60. Power/energy/electricity mentioned

Examples of SWRs with [code(s)]:

1. 'must be complete circuit' [A10]
2. 'both terminals positive and negative connected to close circuit' [B30]
3. 'no complete circuit, there is no current flow' [A40]

'*charge will flow but in different directions*' SWR (RIN: 135, Q8): charge will flow in different directions.

a: Charge will flow in different directions.

'*charges will flow in both because they are both connected to a battery*' SWR (RIN: 155, Q8): charge will flow in both because they are connected to a battery.

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

'*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.

c: Both heaters are connected to circuits.

'*none of them will heat up, because in A only the negative side of battery is connected to the battery and in B only the positive side is connected. The idea/sugg .. 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 negative side of battery is connected and in B only positive side is connected.

d: Only one terminal is connected.

'*There will be a current in both A but not in B because as I said in the first page I don't think bulb is connect if a battery that means there is a current because they are directly proportional 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.

e: Directly proportional.

'*Both heaters will heat up, they are both connected in a right way 'positive and negative' like charge attract each other unlike charge repel each other, in the case they match'* SWR (RIN: 146, Q2): both heaters will heat up; they are both connected in right way. 'Positive and negative'. Like charges attract each other, unlike charges repel each other.

f: Like charges attract and unlike charges repel.

Figure 2. (a) Charge will flow in different directions. (b) Charge will flow in both circuits because they are connected. (c) Both heaters are connected to circuits. (d) Only one terminal is connected. (e) Directly proportional. (f) Like charges attract and unlike charges repel.

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

Table 2. 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		

- B50. Charge mentioned
- B60. Energy or power or electricity mentioned

Examples of SWRs with [code(s)]:

1. ‘only one side of battery connected’ [B10]
2. ‘both bulbs are connected to the positive side of battery’ [B30]
3. ‘both terminals should be connected to heater, because current flows from negative to positive’ [B40]
4. ‘battery’s end is connected to heater’s end. There are positive and negative charges’ [B50]
5. ‘no energy transfer, only one pole connected’ [B60]

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)]:

1. 'no proper connection between bulb and battery' [C10]
2. 'bulb connection is on the bottom not side, the pins of the holder are at the bottom' [C21]
3. 'connected to the side of the bulb' [C22]
4. 'connected to the battery' [C23]
5. 'connected in charge (positive and negative)' [C30]
6. 'negative of bulb not connected to positive of battery' [C31]
7. 'positive of battery is connected to negative of bulb' [C32]
8. 'connected negative charge flow' [C50]
9. 'connected to covering of copper connection' [C70]

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)]:

1. 'there is no switch' [D71]
2. 'there is no resistance' [D72]
3. 'no device like ampere and resistor to assess the flow of energy' [D73]
4. 'if battery is functioning' [D75]
5. 'no conductor' [D76]

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)]:

1. ‘no current transfer’ [E40]
2. ‘charge flow with different magnitude’ [E50]
3. ‘they receive same amount of energy’ [E60]

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)]:

1. ‘they have to be placed in connection to each other in parallel or in series form’ [F80]
2. ‘they have to be connected in parallel to each other’ [F81]
3. ‘current is more in B, because it is in series’ [F82]

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

Table 2 summarises the final coding scheme that was developed over a number of cycles of passing through portions of the data.

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

The coding scheme from table 2 was applied to the full set of responses of the cohort in table 3. 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 responses had more than one code assigned and in no cases was it found necessary to assign more than two codes.

Each entry in table 3 was colour-coded for further analysis: the choices N, V, H and VH are colour-coded as grey, yellow, blue and red respectively. The last column gives the number of correct answers. This process made it easy to see the pattern of the dataset as a whole. The first nine grey rows represent the nine students who answered all questions correctly, while the last ten rows represent the students who answered all questions incorrectly. The middle two thirds provided different answers to different questions. The responses are grouped in the order of the circuit elements (light bulb, heater and resistor). The white cells in table represent

Table 3. The FCRs and category codes rearranged in the order of circuit elements.

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	A40	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

the absence of a response. While 12 students used only one reason to answer all 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 who used only one reason (RIN 129 and 160) did not select the same answer choice in all questions.

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 for resistor circuits. A more detailed discussion about the distribution of options can be found in part I of this paper (John 2017) and in follow-up papers from the interviews.

A deeper analysis, in terms of the frequencies of codes, is shown in table 4. The highest frequency (70 responses) was for C10, which is associated with expressing the idea '…connected to/not connected to …' without any further explanation. This category could be interpreted as correct reasoning, i.e. it is not connected properly, since 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, and be provided in the third part of this investigation). The second largest set of responses was A10 in which the idea of a '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 5). Students used various written reasons to justify their answer choices; 70% of the reasons were not related to circuits, but were physical, element-related and experience based reasons. A third of the students used categories 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. It is of some methodological concern that 13% of the responses were uncodeable due to poor handwriting, incomprehensible reasoning or blank. The reasons used by students varied in each question. Among them the most popular ideas are described as follows.

In the case of light bulbs, the connectivity of the light bulb (whether connected to the side or to the bottom) and the orientation of the circuit (horizontal or vertical) influenced the responses. Regarding the battery polarity, 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. Furthermore, for a few students, the charge flowed from the positive terminal of the battery, while others perceived it as flowing from the negative terminal; in addition, for some the positive charge was stronger than the negative charge. This idea was also present in the case of current, positive stronger than negative. Another interesting idea was that a bulb has polarity, similar to a battery. The explanations for these interesting ideas were thoroughly explored in individual interviews, in a follow up paper (to be published).

Table 4. Frequencies of category codes.

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

Table 5. Parent categories and the number of responses to each question.

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

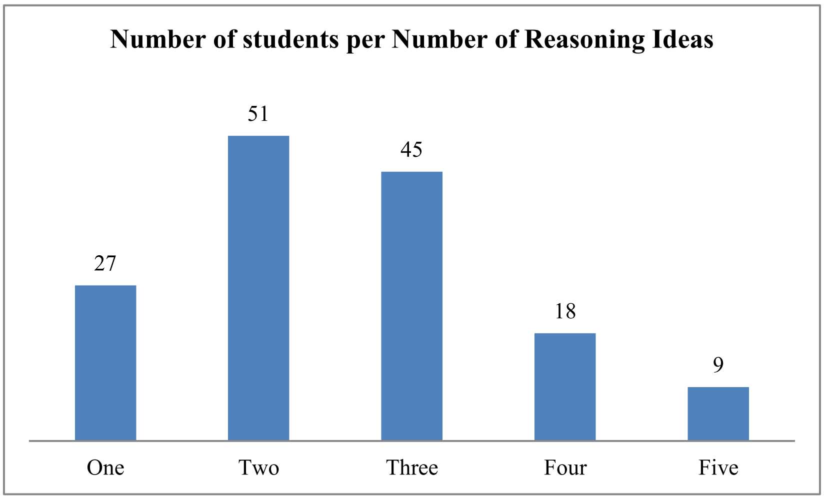

Figure 3. Distribution of students according to the number of reasoning ideas used in answering the ACQ.

Foothold/main ideas based on the written responses

One of the intriguing features at the outset of the study 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 of 149 (60 + 89) students are shown in figure 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.

Along the x-axis, each bar represents the number of reasoning ideas (RI), used by students, 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, who used only one reason, shows that the actual RI that was used was distributed across the emergent categories as follows: A = 7, B = 10, C = 8 and U = 2. Figure 4 summarizes this distribution. In addition, the number of all-correct responses is shown in red. What is most interesting is that all students in the first two categories A and B (7 + 10) answered all the questions correctly[4]. It is clear that the ideas expressed in A and B are key starting points that lead to correct outcomes in all cases.

[4] The nine incorrect students' reasons were either incomprehensible (U) or the phrase 'not connected' without any further explanation was recorded, i.e. category C (connected to an element).

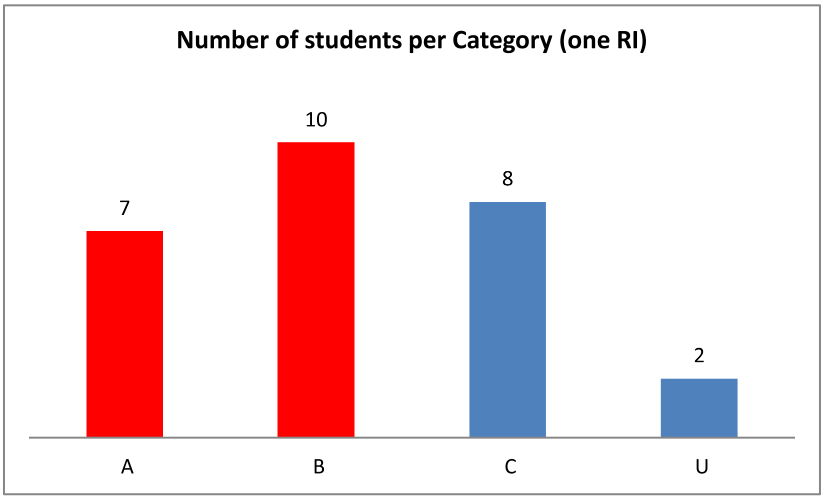

Figure 4. Detailed distribution of students (27) who used one RI to answer all ACQ questions. The *x*-axis shows the letter representing the emergent categories. All students in categories A and B answered all the ACQ questions correctly while none who used C did so.

However, while the two categories A and B emerged separately 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. This underlying construct will be referred to as *loop continuity* in future discussions. Thus, *loop continuity* is clearly critical as the starting point for productive reasoning across the contexts. In addition, *loop continuity* is a key RI that needs to be primed at the outset when confronted with a task that involves DC circuits. As a shorthand term for a RI that is primed at the outset, the term foothold reasoning idea will be used.

Discussion and conclusion

It is clear from the results of the present work that the context primes a number of other ideas that form the 'footholds' for subsequent reasoning. For some the foothold ideas are productive and for others (more than 70%) they are not productive. The results suggest that ALL students who used *loop continuity* as the foothold reasoning idea answered ALL questions correctly irrespective of the context of the questions. In contrast to this, students who used an idea other than *loop continuity* responded to the contextual triggers and answered incorrectly. Thus *loop continuity* is the key idea to be promoted with regard to the structure of the light bulb when introducing DC circuits.

This raises a question about the results we have in the literature using a light bulb both in terms of student difficulties and the misconceptions identified in DC circuits. Furthermore, our results may explain the reasons behind the degree of success over the years in improving the teaching of DC circuits.

In everyday experience it is hard to find the *completion of a loop to functionality of something* to prime a p-prim from an experience (diSessa 1988, Smith *et al* 1994, Hammer 1996). Furthermore, many teachers and instructions use a water analogy to introduce this topic. However, in everyday life experience when we close a tap the flow stops; contrary to this, in a circuit the closure of a switch makes the device work. Furthermore, the vertical flow of water is influenced by gravity, but the orientation of a circuit has no influence on current. Thus, using this analogy should be carefully considered when administered in DC circuits. Similarly, in real life experience, reversal of the battery orientation in a flash light causes the bulb not to light up. We know that this is due to the mechanical construction of the flash light, and has nothing to do with the electrical property of the circuit; but this may be interpreted, by a student, as that a light bulb has 'polarity' like a battery or LED. In fact, this phenomenon is true for any battery operated device.

The results suggests that *loop continuity* should be promoted as a primary *abstract* concept while introducing DC circuits rather than introducing the *concrete* light bulb as a phenomenological device, since the bulb primes the artefacts rather than the resistive property of an element in a *closed circuit*. Thus the functional aspects rather than the structural should be promoted in the introduction of DC circuits (Stetzer *et al* 2013). This may be against the traditional practice of teaching from concrete to abstract in mechanics. However, in the case of DC circuits almost all the concepts are abstract, namely charge flow, current, potential difference, voltage, energy etc, which explains and supports the notion of an abstract to concrete idea (Kaminski *et al* 2008). The findings will provide physics teachers and researchers with some help in the design of a new set of instructional materials to improve conceptual understanding of DC circuits.

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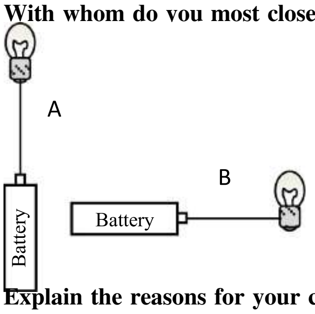
Appendix A. Format of the questions

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.

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

Appendix B. Key ideas used in three elements

Appendix B.1. Key ideas (KI) from the 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 B.2. Key ideas from the summarised written responses (SWR) to the three questions relating to the heater. The grey shaded area indicates the KIs for the correct answer choices (see the 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 B.3. Key ideas from the summarised written responses (SWR) to the two questions relating to the resistor. The grey shaded area indicates the KIs for the correct answer choices (see the 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	

References

Brna P 1988 Confronting misconceptions in the domain of simple electrical circuits *Instruct. Sci.* **17** 29–55

Clement J 1982 Students' preconceptions in introductory mechanics *Am. J. Phys.* **50** 66

Clement J, Brown D E and Zietsman A 1989 Not all preconceptions are misconceptions: finding 'anchoring conceptions' for grounding instruction on students' intuitions *Int. J. Sci. Educ.* **11** 554–65

diSessa A A 1988 *Knowledge in Pieces* (Mahwah, NJ: Lawrence Erlbaum) pp 49–70 , ch 4

Dunbar K N, Fugelsang J A and Stein C 2007 Do naïve theories ever go away? Using brain and behavior to understand changes in concepts *Thinking with Data* ed M Lovett and P Shah (New York: Lawrence Erlbaum) pp 193–206

Engelhardt P V, Gray K E and Rebello N S 2004 How many students does it take before we see the light? *Phys. Teach.* **42** 216

Hammer D 1996 Misconceptions or P-prims: how may alternative perspectives of cognitive structure influence instructional perceptions and intentions *J. Learn. Sci.* **5** 97–127

Hammer D 2000 Student resources for learning introductory physics *Am. J. Phys.* **68** S52

Hein T L 1999 Using writing to confront student misconceptions in physics *Eur. J. Phys.* **20** 137–41

John I 2016 DC circuits: contextual variation of student response *PhD Thesis* University of Cape Town (unpublished)

John I 2017 DC circuits: I. Evidence for fine grained contextual dependence *Eur. J. Phys.* **38** 015701

Kaminski J A, Sloutsky V M and Heckler A F 2008 Learning theory. The advantage of abstract examples in learning math *Science* **320** 454–5

Marshall J 2008 Students' creation and interpretation of circuit diagrams *Electron. J. Sci. Educ.* **12** 2

Masson S, Potvin P and Riopel M 2014 Differences in brain activation between novices and experts in science during a task involving a common misconception in electricity *Mind, Brain Educ.* **8** 44–55

Shaffer P and McDermott L 1992 Research as a guide for curriculum development: an example from introductory electricity: II. design of instructional strategies *Am. J. Phys.* **60** 1003–13

Smith D and van Kampen P 2011 Teaching electric circuits with multiple batteries: a qualitative approach *Phys. Rev. Spec. Top.—Phys. Educ. Res.* **7** 1–10

Smith J P III, diSessa A A and Roschelle J 1994 Misconceptions reconceived: a constructivist analysis of knowledge in transition *J. Learn. Sci.* **3** 115–63

Stetzer M R *et al* 2013 New insights into student understanding of complete circuits and the conservation of current *Am. J. Phys.* **81** 134–43

Strauss A and Corbin J 1990 *Basics of Qualitative Research: Grounded Theory Procedures and Techniques* (Newbury Park, CA: Sage)

Tallant D P 1993 A review of misconceptions of electricity and electrical circuits *Proc. Third Misconceptions Seminar* pp 111–5