

# Effect of a Diagram on Primary Students' Understanding About Electric Circuits

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**Abstract** This article reports on the effect of using a diagram to develop primary students' conceptual understanding about electric circuits. Diagrammatic representations of electric circuits are used for teaching and assessment despite the absence of research on their pedagogical effectiveness with young learners. Individual interviews were used to closely analyse Years 3 and 5 (8–11-year-old) students' explanations about electric circuits. Data was collected from 20 students in the same school providing pre-, post- and delayed post-test dialogue. Students' thinking about electric circuits and changes in their explanations provide insights into the role of diagrams in understanding science concepts. Findings indicate that diagram interaction positively enhanced understanding, challenged non-scientific views and promoted scientific models of electric circuits. Differences in students' understanding about electric circuits were influenced by prior knowledge, meta-conceptual awareness and diagram conventions including a stylistic feature of the diagram used. A significant finding that students' conceptual models of electric circuits were energy rather than current based has implications for electricity instruction at the primary level.

**Keywords** Diagrams · Electric circuits · Primary students · Science learning · Conceptions · Models · Representations

## Introduction

Much of the research into ways to help students understand scientific phenomena focuses on the perplexity that instruction fails to develop accurate understanding in particular science topics. Electricity has been extensively researched because it is a key topic in physics curricula from primary level, and the abstract concepts pose learning challenges. Whilst models,

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analogies and metaphors are common instructional resources in electricity, controversy exists over which are appropriate for learners of different ages (Mulhall et al. 2001).

Diagrams function as key tools for scientists, teachers and learners to communicate science concepts and processes (Coll et al. 2005; Mathewson 1999; Tippett 2016). They can visually represent abstract phenomena not otherwise directly observable (Cook 2006). The skills of constructing, using and interpreting science representations have become recognised as being fundamental aspects of scientific literacy (Lowe 2000; Prain and Waldrip 2008; Gillies et al. 2015; Tippett 2016). Research on labelled diagrams has shifted towards constructivist approaches and ‘both interpreting and constructing representations can lead to better understanding of science concepts’ (Tippett 2016, p. 740).

Active construction of representations during classroom teaching supports learning by helping students explain their thinking and develop conceptual understanding (Tytler et al. 2013). The Representation Construction Approach (RCA) considers students’ prior knowledge and range of possible perspectives/ideas for constructing their own and interpreting existing representations. Within the RCA framework canonical diagrams are viewed as ways of representing reality that are open to interpretation. Learning how to use the sanctioned representations of science (diSessa 2004) includes classic diagrams (and modern variations) used in instruction and assessment. As diagrammatic literacy supports conceptual development, this vital science communication tool is the focus of the current study.

Exploring how students make sense of typical diagrammatic representations might provide insights into learning about abstract electric circuits. Cheng and Gilbert (2015, p. 144) argue one way of ensuring quality teaching and learning is to scrutinise how diagrams used in teaching materials might have facilitated, or hampered, learning. The alignment of teaching practices with students’ conceptualisations about electric circuits must also be considered. To enhance the effectiveness of diagrams in science teaching, we must be aware of how primary students interpret those in common use. Factors influencing diagram interpretation include the particular type of diagram and conventions used (Tippett 2016), the resources (prior knowledge and skills) students bring to the learning situation and the purpose of using the diagram (Postigo and López-Manjón 2012).

This research aimed to investigate the effect of a diagram on primary students’ conceptual understanding about electric circuits. The study differs from previous research into learning from science diagrams by participant age (primary not secondary/university students) and absence of a teaching intervention. Students were not involved in a lesson sequence and did not receive instruction in diagram reading. To gain an in-depth understanding of how students interpret electric circuit diagrams, the process was studied in isolation. In this sense, the study approximated a clinical trial. Although directly presenting a diagram differs from normal classroom pedagogy, the strategy is common to probing conceptions research (cf Cheng and Gilbert 2015). It was used to hone-in on the impact of the diagram specifically as a learning resource devoid of influential teacher factors. Open interpretation of the diagram allowed students to use their own words in articulating thinking because they were not directed to talk about a particular concept. The interactions between students’ prior knowledge, indications of intuitive interpretive abilities, competence in using diagram characteristics (icons, labels, specific features) and explanation construction was of particular interest.

Capturing the ways young students view diagrams and apply their current knowledge may provide valuable learning insights not uncovered by previous research methods. Relatively few studies involving labelled diagrams have considered ‘the role of prior knowledge’ on learning (Tippett 2016, p. 740). The significance of the research is its

elicitation and synthesis of the nature of primary students' conceptions and the effects of untutored diagram reading on their understandings about electric circuits. The indicative example results present study findings, illustrate students' sense making from the diagram and highlight challenges encountered.

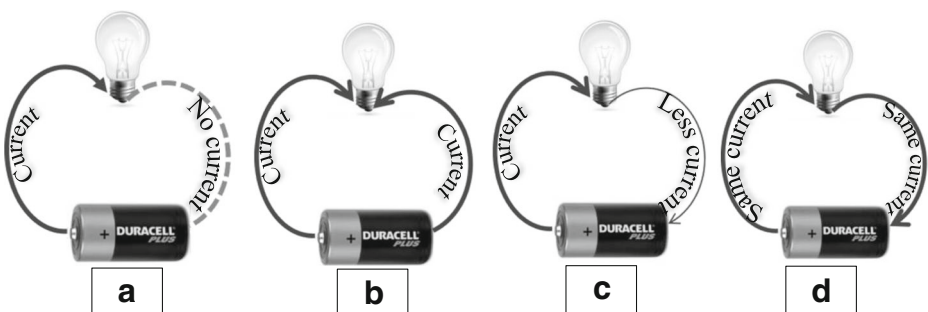
## Literature Review

This section reviews two areas of research relevant to this study: primary students' understanding of electric circuits and the role of diagrams in science learning.

### Primary Students' Understanding of Electric Circuits

Considerable research spanning 35 years has investigated students' understanding of electricity concepts, particularly electric circuits. Contemporary constructivist pedagogy signals a need to re-examine models developed from previous research that could disregard prior knowledge. A four current-flow model set is widely acknowledged as the standard for students' ideas about current in simple circuits. Following the work of Osborne and Gilbert (1979); Osbourne (1981), these models were tested and refined by Shipstone (1984, 1985, 1988).

The models (Fig. 1) identified four ways students describe current in a basic circuit. Despite varied names across publications, the models are usually outlined as follows. Model A: non-recursive/source-sink—current moves via one wire from battery to bulb, there is no current in the other wire. Model B: clashing currents—current moves in opposite directions via each wire from battery to bulb where the current collides. Model C: consumption/attenuation model—current moves in one direction from battery to bulb and back to the battery, there is more current in wire 1 and less in wire 2 after the bulb. Model D: same current/scientific—current flow is similar to the previous model but current is the same in each wire (Osborne 1983; Shipstone 1985). Research indicates that primary students (5–13 years old) favour models A and B (Osborne 1981; Solomon 1985). In these studies, students were specifically asked to talk about current which likely influenced their use of terminology and ideas expressed. These classic models have provided a useful way of categorising and comparing students' ideas about electric current flow as a specific (single) aspect of electricity. Adopting these established models makes the assumption that students have an accurate conception of electric current.



**Fig. 1** Current-flow models of electric circuits (arrows show current direction)

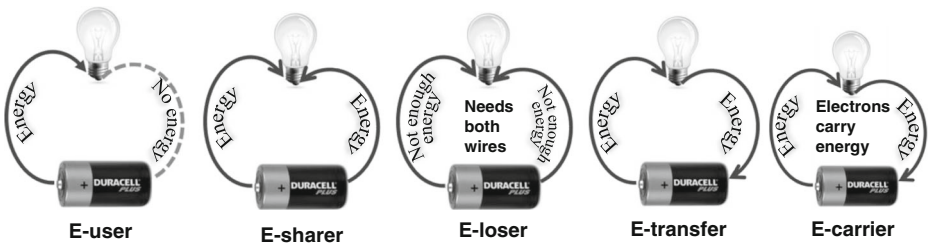
Whether primary children hold scientific conceptions of current prior to instruction remains debatable. Some argue young students know very little about electricity, specifically electric current (Etheredge and Rudnitsky 2003; Maharaj-Sharma 2011). Prior to teaching, children 9–11 years old variously drew light bulb, electrical spark, wall plug, transmission wires and fruit (currants) to represent understanding of the term current (Maharaj-Sharma 2011). Very young children (5.5 to 6.5 years old) perceive electricity as static (being inside wires, sockets or appliances) and have no conception of movement or flow of electric current (Solomonidou and Kakana 2000, p. 105).

The extant models have been so influential that researchers have applied them without questioning the substance of children's responses. For example, in a study involving eight fourth-grade students, the following pre-instructional response 'The power is going through the wire. All the power's going one way' was taken to mean the student 'held a non-recursive (model A) understanding of electric current' (Shepardson and Moje 1994, p. 500, parenthesis added) Whilst directionality is obvious, assuming that the child's use of the everyday term 'power' was indicative of current is questionable. It must be acknowledged that this study was conducted at a time when researchers were interested in identifying what scientific viewpoints were *lacking* from children's conceptual schemas with the aim of exploring ways to challenge these non-scientific views.

These outdated models require reconsideration following contemporary perspectives where scholars like diSessa (2004) and Vosniadou (2008) have led researchers to be more attentive to the substructure of students' conceptions. Productive thought, or the seeds of 'correct' conceptions, are now known to lie in intuitive ideas that would previously have been considered alternative conceptions (Brown 2010, p. 2369). Acceptance of all ideas and close examination of primary students' responses affords greater insights into children's developing conceptions about electric circuits.

Osborne argues the concept of electric current should be at the forefront of primary level electricity instruction (Osborne 1983) rather than the more familiar notion of energy. In contrast, Shipstone maintains 'the concepts of the electric circuit and energy transfer within it' are more relevant for most learners and 'are more fundamental than the concept of current' (Shipstone 1988, p. 96). Indeed, he also argued "Current" is not the term used by children at the start of their study of this subject and it would be unwise to assume that their term, commonly 'electricity' represents the concepts of current for them', (Shipstone 1988, p. 92). Further, the 'source-consumer view' (model C) is considered to be more closely aligned with 'the scientists' notion of electrical energy than that of electric current' (Shipstone 1988, p. 93). Other researchers note that primary students explain electric circuit processes using variable terms—power, electricity, energy, and (sometimes) current—that they interchange at will (Hubber 2017).

What makes electric circuits problematic to understand is that 'much of the science takes places inside the wire' (Chapman 2014, p. 5). The underlying processes in electric circuits are abstract (not directly observable), so students can only infer their effects from what happens on the surface level. This creates instructional challenges for primary teachers (Jaakkola and Veermans 2011). To overcome the problem that we cannot assume the 'something' that primary students think moves in the wires (from the battery to the bulb), in children's minds, equates to electric current, I have redefined the models (Fig. 2) removing the emphasis on current. This is more in line with recent research, and it is hypothesised to better reflect primary students' conceptions about the processes of electric circuits.



**Fig. 2** Revised models of electric circuits (*arrows show electricity/power/energy direction*)

The ‘E’ in the model names is used to flexibly represent students’ terms, electricity, power or commonly ‘energy’ to describe what moves in the wires. (For brevity, energy only is used to outline the revised models). Model 1: E-user—energy moves via wire 1 from battery to bulb, there is no energy in the other wire. Model 2: E-sharer—energy moves in opposite directions via each wire from the battery to the bulb. Model 3: E-loser—related to the previous model, each wire takes energy to the bulb, a single wire (with its half-share) cannot provide enough energy to light the bulb. Model 4: E-transfer—energy moves in one direction from battery to bulb and back to the battery, there is energy in both wires and there can be less energy in wire 2 after the bulb. Note from an energy perspective this model is scientifically accurate. Model 5: E-carrier—energy transfer is similar to the previous model but is carried by electrons inside the wires, there is a difference in energy level at the battery terminals and in wires, especially after the bulb. In this more advanced scientific model, current and energy co-exist. These literature derived models were validated in this study by testing their applicability to primary students’ conceptualisations of electric circuit processes.

The research discussed above included very simple drawings in circuit problem questions. No study has specifically investigated the nature of primary students’ explanations and understandings from interpreting a contemporary circuit diagram. The review now turns to research involving diagrams for learning science.

## Diagrams in Science Learning

Past research focused on the role of graphics in facilitating explanation of science concepts through accompanying text (Carney and Levin 2002). Lowe (1986, 1993) advocated research into diagrams themselves as communication tools. Despite their argued importance and common use, little research into the effectiveness of diagram use in science teaching had been conducted (Amettler and Pinto 2002). At that time, use of diagrams in science teaching seemed to be accepted practice rather than research-based pedagogy.

Students’ prior experience in using diagrams (Barlex and Carré 1985) and science-specific background (Lowe 1986) suggested ‘specialised knowledge and skills may be needed to interpret certain types of diagrams effectively’ (Lowe 1988, p. 112). Lowe (1993) reasoned that the use of graphic conventions, which differ depending on the diagram type and science domain, were a problematic aspect of interpreting diagrams. Arrows, for example, were especially confusing for non-science expert adults because they are used with a variety of intentions in science diagrams and their meaning is not always clear to the reader (Lowe 1993, p. 33). Other studies have reported arrows can represent measurement, force, movement, relationships, change over time, path, sequence (Schollum 1983; Heiser and Tversky 2006) and have specific meanings in different science domains. Henderson (1999, p. 19) suggested

that science diagrams, including apparently simple electric circuits, ‘could lead to several misconceptions if students were left to their own interpretations’. He cautioned that science diagrams may be obstacles rather than aids to student learning.

By 2000, visual literacy had become an essential component of science education. Lowe (2000) asserted that students’ experiences with everyday visuals (drawings, photographs and paintings) developed general skills, however, left students unprepared for the processing demands of interpreting science diagrams. This conclusion strengthened arguments by researchers (Barlex and Carré 1985; Constable et al. 1988a, b; Henderson 1999; Lowe 2000) that explicit instruction is required for students to learn how to read science diagrams.

Vekiri’s (2002) research review reported that most studies involved college students, and research was needed with younger learners. Modern primary science learning materials and assessment tests are laden with visual representations (McTigue and Slough 2010). A study reporting elementary and middle school students’ perceptions (rather than actual interpretation) and knowledge of science diagrams, led researchers to conclude that ‘diagram interpretation skills are not intuitive to students’ (McTigue and Flowers 2011, p. 588). The finding renewed calls for diagram reading instructional strategies for younger students (McTigue and Flowers 2011; Roberts et al. 2013, Slough and McTigue 2010). Such calls are not supported by research-based evidence of students’ explicit instructional needs. Without evidence of students’ actual level of interpretive competence, teachers (as more experienced interpreters of representations) do not know where to begin instruction. Primary teachers (even with low science background knowledge) will tend to approach diagrams from a superior cognitive base than their students. Gaining insights into how primary students’ interpret diagrams is necessary to develop effective, needs-based teaching methods.

A thematic review of research on labelled diagrams from 2000 to 2014 reports a shift from using to constructing diagrams (Tippett 2016). Earlier work focused on interpreting (learning from pre-constructed) rather than constructing (learning with their own) diagrams. Despite this shift, the research concluded ‘both interpreting and constructing representations can lead to better understanding of science concepts’ (Tippett 2016, p. 740). This study focuses on interpreting a type of pre-existing diagram in common use.

Electric circuit diagrams are classified as ‘depictive iconic representations’ (Tippett 2016, p. 730) or schematic diagrams. Schematic diagrams make abstract concepts more concrete by using graphic conventions to simplify communication of complex processes. As circuit diagrams convey the processes in an electrical system (circuit), they are also science models. Frequently used in teaching, ‘models are, by nature artificial, simplified, and imperfect representations that sometimes require a good bit of interpretation’ (Coskie and Davis 2008 p. 56.) The inability of a single model to completely represent reality contributes to the power of representations as purposeful abstractions of selected aspects (Hubber and Tytler 2013). Students must come to see models as ‘tools to think with’ investing their own conceptual resources to develop a broader conception of the phenomena.

Research into students’ interaction with diagrams from sociocultural perspectives sheds light on how diagrams function as thinking tools. Peircian semiotics ‘acknowledges that meanings are not embedded in diagrams but are actively created by readers’ (Cheng and Gilbert 2015, p. 144). Research with teenagers and adults led to the initial assumption that primary students would struggle to make sense from diagrams themselves. The current study

tested this notion by exploring students' attempts to construct understanding, including how the diagram affected their thinking about science concepts.

The study aimed to answer the research question:

*How does a science diagram affect primary students' conceptual understanding about electric circuits?*

This involved eliciting students' pre-conceptions, comparing their models with previous research, recording how they navigated and interpreted the diagram and determining its impact on their explanations as indicative of understanding.

## Research Method

Following an interpretive research paradigm (Cohen et al. 2011), this study employed a primarily qualitative methodology (Anderson 2007; Johnson and Christensen 2004; Maxwell 2005). The research was designed to map overall trends in the effects of diagram reading on students' explanations about electric circuits. Further in-depth analysis could reveal individual nuances relating to underlying science concepts.

This paper reports part of a larger study that investigated the effects of science diagrams on primary students' understanding of science concepts (Preston 2012, unpublished). The findings relating to students' understanding about magnets was published in a previous edition of this journal (see Preston 2016) which described the methodology including data analysis. Details of procedures specific to this part of the study only are provided here.

## Participants

A total of 20 Year 3 (8–9 years old,  $n = 11$ ) and Year 5 (10–11 years old,  $n = 9$ ) students from a government primary school in Sydney, NSW, Australia participated in the study. Students were male and female, ranged in teacher-selected ability levels (high, medium, low) and either had English as their first or second language.

## Data Collection Procedures

The six-stage method comprised two individual, task-based (Goldin 2000) clinical interviews (Clement 2000). Each interview involved three parts (see Fig. 3) where students talked aloud as they completed different tasks. Six discrete data sets were obtained from this dual interview design.





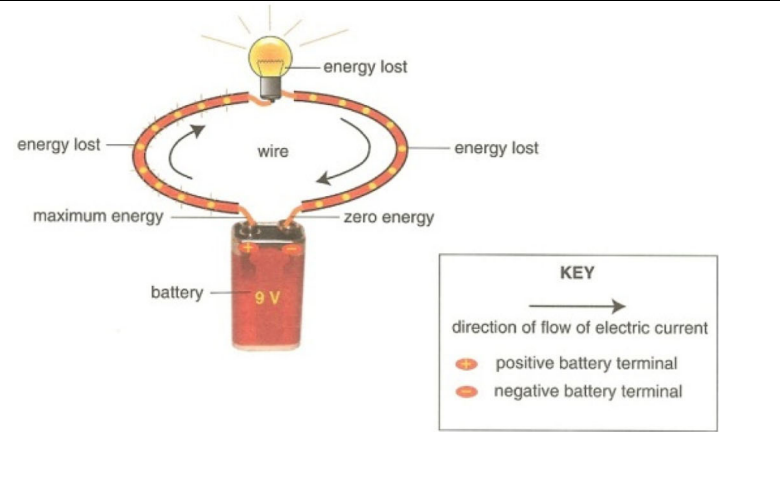
**Fig. 3** Interview segments in the six-part research design

The task and interview questions for the different interview segments are outlined next.

*Interview Resources*

The resources used for the interview tasks are pictured in Fig. 4.

The diagram was sourced from Australian Schools Science Competition, 2006, Year 5, reproduced with permission.

<i>Topic area</i>	<i>Electric circuits</i>
Task 1	
Task 2	
Task 3	

**Fig. 4** Interview resources—electric circuits



An aspect of the particular diagram used in this study, the ‘loses energy’ label is noteworthy. As captions or labels are features that can influence students’ thinking, how students might interpret this label was important. It was postulated that students’ may think of energy as being ‘lost’ rather than transformed; it could also predispose attention to energy over current. Nevertheless, exploring potential challenges students could face when interpreting existing diagrams was one of the purposes of this study. A similar approach was taken in students’ interpretation of blood flow diagrams (Cheng and Gilbert 2015).

### *Interview 1*

Students were provided with physical components to assemble a working circuit. Questions such as ‘What do you know about batteries? Can you arrange these components to make the light bulb work? Why does it work when it is connected like that? Do we need two wires? What would happen if you took one wire off? Why?’ elicited students’ prior level of scientific understanding about electric circuits. This occurred prior to the intervention phases which only involved students being asked to read circuit diagrams.

#### 1. Intervention

Each student was shown an A4-size pictorial-only diagram (labels and key were removed) of an electric circuit. This enabled the researcher to see whether students could recognise and make sense of the visual components and icons used in the diagram. Questions included ‘Can you tell me what is happening in this diagram? What do the arrows mean? What do you think the yellow dots are? Why are they different on each side?’

#### 2. Continued Intervention

Each student was shown a second labelled version of the same diagram. This enabled the researcher to see whether textual information (labels and key) helped or hindered students’ explanations about electric circuits. Questions included ‘What does this diagram tell you? What do these symbols mean? Can you look at the key? Why is there maximum energy here and zero energy here? What do the arrows mean again?’

### *Interview 2*

The same students were re-interviewed 1 month later to identify variations in student explanations that might indicate advances in conceptual understanding and transience or persistence of alternative conceptions. This measure was necessary to determine whether the process of interacting with the diagram made permanent or temporary changes to students’ conceptual understanding. Many researchers use such a strategy, for example, Tytler (1998) re-interviewed after a 6-month delay; this longer time period was afforded by the longitudinal nature of his study of primary students’ science learning. The same tasks for interview 1 were repeated with similar questions to determine conceptual understanding at this point in time:

3. Post-conceptions: repeat task 1—physical stimulus.
4. Re-intervention: repeat task 2—pictorial-only diagram.
5. Continued re-intervention: repeat task 3—labelled diagram.

Methodologically, the nature of the interviews and the role of the researcher in guiding students' thoughts through the types of questions asked can be considered a minimalist intervention. Interviewer-respondent interactions are complex, a non-judgemental stance respectful of students' ideas and verbatim transcription preserved the authenticity of data collected (Merriam and Tisdell 2016).

## Data Analysis

The data was processed in two ways. First, students' prior knowledge was considered through describing their conceptual models of electric circuits. Students' models were mapped against the redefined models (Fig. 2), and frequency scores were generated. The data for before and after the diagram intervention was compared across both interviews.

Second, the nature of component ideas were closely examined to reveal more about the depth and specific aspects of students' scientific thinking about electric circuits that was influenced by interaction with the diagram. Individual interview transcripts were analysed to identify key ideas, classify these as scientific or non-scientific and synthesise conceptualisations that encapsulated students' thinking for each interview segment. These were coded using a two-dimensional classification scheme for *type* (scientific, non-scientific or mixed) and *level* (low to advanced sophistication of scientific ideas) of understanding. Coded conceptualisations were represented by the use of a superscript notation. For example, Mixed<sup>H</sup> indicates non-scientific ideas are combined with high-level scientific ideas. The independence of type and level of thinking allowed instances where student understanding increased for one concept(s) but become non-scientific in relation to another (others) to be recorded. Thus, a single alternative conception would not overshadow simultaneous advances in other areas of understanding. Comparison of conceptualisations across interview segments allowed the researcher to profile qualitative changes in students' explanations about electric circuits from diagram reading. Grouped data highlighted trends representing students' diagram derived sense making of electric circuits.

## Results

Results for two ways of looking at the data are presented. First, prior knowledge of the student group is reported including the identified underlying models of electric circuits. Changes in these models across the interview period are reported in relation to the diagram. Second, changes in students' overall conceptual models according to the coding scheme developed for this study are presented. Case studies of individual students are used to provide a more detailed look at how interaction with the diagram influenced students' explanations, revealing changes in their conceptions about electric circuits.

### Students' Prior Knowledge About Electric Circuits

All students recognised and could name batteries, but their ideas about what batteries contain varied. The most common responses were power ( $n = 4$ ), electricity ( $n = 4$ ), energy ( $n = 2$ ) or a combination (electric and power, energy and electricity, energy and power ( $n = 3$ )). Individual ideas included: wires, current and wires, electrical volts and make electricity inside. Other individual responses related to what batteries do or could do: makes things work and be

recharged. The results indicate only four students correctly describe batteries as an energy source. This has implications for understanding scientifically the role of the battery in an electric circuit.

Whether students could construct a working circuit provided an indication of their practical knowledge about electric circuits. Their answers to questions about circuit structure gave insight into their conceptual understanding. Students' models about electric circuits prior to the diagram intervention are shown in Table 1.

One student conveyed the 'E-user' model explaining all the 'power/electricity' went from the battery into the bulb where it was *all* used up leaving the second wire with nothing to do except join to the battery. The most common model conveyed by eight students in response to the physical circuit was 'E-sharer'. They explicated transfer of power, electricity or specifically energy from the battery moving *up* each wire to the bulb to make it light. A further three students outlined a related 'E-loser' model. These students explained the circuit could not work if one wire was removed because there was not enough power/electricity. This implied each wire carried a share from the battery to the bulb and taking away one wire results in 'lost' power.

Four students' explanations conveyed the 'E-transfer' model where they described energy moving in a circular direction, up wire 1 from the battery to the bulb and down wire 2 to the other side of battery. Their explanations stated or implied the active presence of energy on both sides of the circuit thus indicating it was not consumed totally by the bulb. Responses from four students were too vague or brief conveying insufficient information to indicate any underlying models. In this repertoire the E-transfer model represents a scientific model because the conceptions about energy changes in the circuit are consistent with views of the scientific community about simple electric circuits. Thus, 12 out of 20 students commenced the study with non-scientific models and 4 with a scientific model about electric circuits.

## Changes in Students' Models of Electric Circuits

Changes in models of electric circuits conveyed in students' explanations across the study and within interview segments are shown in Table 2.

From the non-scientific models, the E-user model was the most persistent, with four students developing an 'energy-no energy' view at preconceptions. The related non-scientific models of E-sharer and E-loser expressed by eight and three students respectively at preconceptions disappeared in explanations about the diagram. This provides evidence that the diagram challenged the alternative conceptions underpinning these non-scientific models. Although these ideas were not extinguished altogether because the E-loser ( $n = 3$ ) and E-sharer models ( $n = 1$ ) re-appeared at post-conceptions. Thus, non-scientific models were favoured when talking about the physical circuit. The diagram had a lasting influence on seven students whose explanations about the physical circuit changed from a non-scientific to a scientific model at the commencement of

**Table 1** Students' models of electric circuits at preconceptions

Model	Frequency
E-user	$n = 1$
E-sharer	$n = 8$
E-loser	$n = 3$
E-transfer	$n = 4$
E-carrier	$n = 0$
Undetermined	$n = 4$
Total	$n = 20$

**Table 2** Students' models of electric circuits

Model	Pre-conception	Intervention	Continued intervention	Post-conception	Re-intervention	Continued re-intervention
E-user	$n = 1$	$n = 4$	$n = 3$	$n = 2$	$n = 4$	$n = 5$
E-sharer	$n = 8$	–	–	$n = 1$	–	–
E-loser	$n = 3$	–	–	$n = 3$	–	–
E-transfer	$n = 4$	$n = 12$	$n = 14$	$n = 12$	$n = 13$	$n = 12$
E-carrier	–	–	–	–	$n = 1$	–
Undetermined	$n = 4$	$n = 4$	$n = 3$	$n = 2$	$n = 2$	$n = 2$
Total	$n = 20$	$n = 20$	$n = 20$	$n = 20$	$n = 20$	$n = 19$

interview 2. It must be acknowledged that interim learning in the delay period could not be discounted but seemed unlikely from conversations with the students.

The most obvious result is that the scientific E-transfer model was promoted by the diagram, increasing to 12 and 14 with the labelled and unlabelled diagrams respectively, a change that was sustained across the interview period. This comprised the notion that 'power/electricity/energy' was present on both sides of the circuit. Some students described the amount, for example, energy as being less after the bulb. Others spoke of 'energy' and 'used energy' as a way of communicating that some energy was still present in the second wire and moved towards the battery. Except for a distinction between energy transfer and transformation, this model represents most closely the scientific (energy-based) view of electric circuits.

The number of students for whom models could not be determined reduced slightly because the diagram stimulated them to include more details which enabled their underlying conceptions to be detected. This was not the case for two students whose explanations remained vague suggesting lack of ideas.

### Changes in Students' Explanations of Electric Circuits

Group data analysis identified three overall trends concerning changes to students' conceptions about electric circuits from their diagram derived explanations (see Table 3). Comparing the coding of conceptualisations from the first to last interview segments indicated students' understanding was enhanced ( $n = 15$ ); reduced ( $n = 3$ ) or both reduced and enhanced ( $n = 2$ ). Clearly, the diagram had an overall positive effect on students' understanding about electric circuits for the majority of students in this study.

This data portrays the end result of the intervention but does not capture the qualitative *nature* of changes in students' explanations nor the range of ideas expressed in response to the diagram. For this closer examination of individual student explanations about electric circuits is required. Five students Bill, Barry, Norma, Josh and Sharon (pseudonyms) were selected to illustrate specific outcome trends shown in Table 3. In the following section students' explanations are indented, their actual words are italicised and gestured components are in brackets. Post-conception interview segments are excluded for brevity.

### Enhanced Understanding

Evidence of enhanced of understanding about electric circuits was manifest in students' explanations revealing the different ways the diagram aided sense making. Bill a high-

**Table 3** Outcomes of interaction with the electric circuit diagram

Change in students' conceptual models	Coding categories		Number of students	Exemplars	
	Initial	Final			
Enhanced	Scientific <sup>L</sup>	Scientific <sup>M</sup>	2	15 Bill Barry	
	Scientific <sup>M</sup>	Scientific <sup>A</sup>	1		
	Mixed <sup>L</sup>	Mixed <sup>M</sup>	7		
	Mixed <sup>M</sup>	Mixed <sup>H</sup>	1		
	Mixed <sup>M</sup>	Scientific <sup>M</sup>	1		
	Mixed <sup>L</sup>	Scientific <sup>H</sup>	2		
	Mixed <sup>L</sup>	Scientific <sup>M</sup>	1		
Reduced	Scientific <sup>H</sup>	Scientific <sup>M</sup>	1	3	
	Scientific <sup>M</sup>	Mixed <sup>M</sup>	2		
Enhanced and reduced	Scientific <sup>L</sup>	Mixed <sup>M</sup>	2	2	Sharon
Total	<i>n</i> = 20				

ability Year 5 student was already knowledgeable about electric circuits. He easily constructed a working circuit and explained:

*Batteries provide energy and are used to power things that need energy. Two wires are needed so that energy can go from the source back to battery. It would go out with one wire but I am not sure why.*

He commenced with a scientific model that described energy transfer from the battery in one direction involving both wires to complete the loop. Bill knew this process would stop with one wire but could not explain why. His explanation comprised medium-level scientific understanding (Scientific<sup>M</sup>).

Viewing the diagram Bill explained:

*The power's going through from the positive to the light bulb and then back to the negative. The arrows mean energy's flowing through; the electricity. Electricity is made up of electrons in the wires. I think those are the electrons (yellow dots). In the LHS wire they have energy but on the RHS they have no energy.*

He precisely described that the direction of power movement around the circuit before elaborating the arrows indicate 'energy flow' which he explained *is* electricity from electrons in the wires. Applying this advanced knowledge, Bill deduced electrons were symbolised inside the wires. He explained electrons have energy, suggesting this only applies in the wire leaving the battery. His explanation comprised advanced scientific understanding (Scientific<sup>A</sup>).

Reading the labelled diagram Bill explained:

*I just don't get it, because that says energy lost and that also says energy lost! Oh I get it, it's using a little bit of energy while going thru the turn, more energy lost (bulb), its losing more until it's zero. Maximum energy where the power goes through (positive) goes to losing energy goes to zero energy (negative). The arrows show direction of current, the flow of energy, electricity.*

After initial cognitive conflict created by the labels, Bill revised his previous explanation to convey an elaborated view of energy reduction around the circuit. He also described an energy difference (potential) between the positive and negative sides of the battery. Although Bill stated the arrows show current direction (from the key), he equated it to this understanding of electricity

as energy flow. The concept of energy dominated his thinking. By the end of the first interview, Bill had developed an explanation that conveyed advanced scientific understanding (Scientific<sup>A</sup>).

The lasting effect of the diagram was evident in the second interview where Bill only needed to be shown the unlabelled diagram to express a coherent explanation:

*Positive has maximum energy then uses energy, light goes on, then uses more energy before it is zero energy at negative. The electrons make current, those (LHS dots) have more energy. The arrows show the flow of current, the way the electricity goes, like water current. That's a 9 volt battery, the more volts you have the more energy.*

Bill articulated a succinct explanation including progressive energy reduction, electric current (using an analogy) involving electrons with appropriate amounts of energy and additional information about volts. His final explanation comprises a two-dimensional view of electricity encompassing both current and energy conveying advanced scientific understanding about electric circuits (Scientific<sup>A</sup>).

The overall pattern of changes in Bill's conceptualisations about electric circuits was:

$$\text{Scientific}^{\text{M}} \rightarrow \text{Scientific}^{\text{A}} \rightarrow \text{Scientific}^{\text{A}} \rightarrow \text{Scientific}^{\text{A}} \rightarrow \text{Scientific}^{\text{A}}.$$

Bill's understanding of electric circuits was enhanced by building on his existing scientific conceptions to develop a sophisticated explanation. The diagram stimulated recall of additional knowledge which he ably applied to the diagram. Bill's reflective thinking enabled him to revise initial erroneous ideas. He successfully assimilated new information introduced by diagram labels demonstrating an understanding of scientific terminology.

In comparison, Barry a medium-ability Year 3 student commenced with little knowledge of electric circuits. Helped to construct a working circuit he explained:

*Batteries give things power, they've got a lot of electricity inside them. It has to be attached that way so electricity can run through this bit (LHS wire) and the electricity can run through this bit (RHS wire) and it (bulb) uses a lot of power, gets more electricity. If you remove 1 wire the light turns off automatically because it doesn't have enough power. You need two wires connected so the electricity can run through both wires and meet and give it power.*

Barry conveyed a non-scientific explanation of electricity exiting the battery, moving up both wires and used by the bulb. Linked to this, he also explained one wire provides insufficient power and electricity has to meet in the bulb to give it power. Barry's initial explanation conveys a view of electricity movement to power the bulb comprises non-scientific and low-level scientific ideas (Mixed<sup>L</sup>).

Viewing the diagram Barry explained:

*The wires have little things (inside) to make them have different amounts of electricity. Those (RHS wire) don't have those sparks things in them because they are not using that much electricity. The minus side doesn't use as much power as the plus side which uses more power. RHS has more power because it's plus, LHS has less power because it's minus.*

Barry conveyed a different view of a circuit with a power-rich (LHS) and power-poor (RHS) side. He related the amount of electricity/power present and that used to the plus and minus symbols. Barry's power-based (energy *not* current) explanation now conveyed medium-level scientific ideas (Scientific<sup>M</sup>).

Barry explained the labelled diagram:

*Says this has zero energy and this has maximum energy, it has lost some energy. That energy it's gone in with the sparks (to the bulb). The arrows mean where the wires are going. It's using the power to go to this one (bulb) and then it travels back down on this one (RHS wire) so it never runs out.*

Influenced by the 'energy lost' labels and the different appearance of the intra-wire symbols ('sparks') Barry's explanation reverted to the E-user model where all energy is consumed by the bulb. His view of RHS wire direction changed but returned to the battery for more power and 'never runs out', indicating continuous activity but implied infinite power supply. Barry's revised explanation now comprised low-level scientific and non-scientific ideas (Mixed<sup>L</sup>).

His explanation remained consistent for interview 2:

*The arrows mean this (LHS wire) is taking all the energy into the bulb and the RHS wire is taking the energy back to the battery and you're reusing it. The yellow dots are where it's losing energy but on the RHS they are not losing energy because I think they are having a rest. The plus means going this way (up), minus means it's going back into here (battery) minusing from the light.*

Barry now referred to energy in favour of power and associated the 'yellow dots' (inside wires) with 'losing energy' evidence of influence of diagram labels. He resorted to an anthropomorphic view to justify reduced energy use on the RHS. Barry continued with unidirectional energy movement and the erroneous concept of reuse. His conceptualisation increased in level of scientific ideas though non-scientific ideas remained (Mixed<sup>M</sup>).

From the labelled diagram, Barry stated:

*That means it has zero and that means it has maximum energy, this means it has energy lost there and there. I was wrong there, I didn't say anything. The plus means the battery terminal (positive) and the minus means the negative battery terminal. I am not sure what the arrows mean.*

Barry read the labels noting which parts he had remembered and was unable to comprehend the meaning of electric current relating to the arrows. His conceptualisation remained unchanged (Mixed<sup>M</sup>).

The overall pattern of changes in Barry's conceptualisations about electric circuits was:

$$\text{Mixed}^L \rightarrow \text{Scientific}^M \rightarrow \text{Mixed}^L \rightarrow \text{Mixed}^L \rightarrow \text{Mixed}^M \rightarrow \text{Mixed}^M.$$

His understanding about electric circuits was enhanced by overcoming an alternative conception changing from a two-way to a unidirectional circuit model. He adopted the term energy but erroneously implied its supply was endless.

Like Barry, Norma a Year 3 low-ability student also commenced with little knowledge about electric circuits. Shown how to construct a circuit, she explained:

*Batteries help things move and can sometimes run out because they use all their energy. The light wouldn't work as well if you remove one wire because two wires can make it powerful. The battery has lots of energy inside and it makes power.*

Norma conveyed an ‘E’ loser model where one wire does not provide as much energy as two, along with the notion that energy produces power. Her explanation comprised a mix of non-scientific and low-level scientific ideas (Mixed<sup>L</sup>).

Using the diagram Norma explained:

*A battery with two wires going into the light. The ‘yellow dots’ are the energy that comes around. They are different because they are different wires, red and white. The arrows mean the energy that’s going (up) and the energy that’s going down so it keeps going like that.*

Her explanation showed enhanced understanding by describing a scientific model involving a cyclical, continuous flow of energy around the circuit. Norma’s conceptualisation now comprised medium-level scientific ideas (Scientific<sup>M</sup>).

Norma explained the labelled diagram:

*Tells you the same thing but with the energy lost and everything connected. Battery, energy lost, energy lost, energy lost, and zero energy and maximum energy. There is maximum energy on this side (LHS wire) because it’s the new energy that’s going around and on the way back it’s a bit slower because it’s used the energy on the light and it’s not that much anymore. The arrows mean going up and going down doing a big circle.*

Norma described an E-transfer model with more ‘new’ energy and ‘slower’, ‘less’ energy. Maintaining an energy (*not* current) based model (ignoring the key) she conveyed higher level scientific understanding (Scientific<sup>H</sup>).

Norma’s explanation remained consistent for interview 2:

*The energy is going up and then the energy is coming down again when it’s been used (in the light). The arrows mean electricity is going around. The ‘yellow dots’ are the energy that comes in through the light. They are different because energy’s going up, it’s all powerful (LHS) and coming down it’s a bit less (RHS) because it’s been used in the light.*

Her almost word-for-word repeated explanation suggests stable conceptions underlined Norma’s thinking. The only difference was an association of energy movement with electricity influenced by the arrows. Norma’s conceptual understanding remained scientific (Scientific<sup>H</sup>) and was unaltered by re-exposure to the labelled diagram (Scientific<sup>H</sup>).

Thus the pattern of changes in Norma’s conceptualisations about electric circuits was:

$$\text{Mixed}^{\text{L}} \rightarrow \text{Scientific}^{\text{M}} \rightarrow \text{Scientific}^{\text{H}} \rightarrow \text{Scientific}^{\text{H}} \rightarrow \text{Scientific}^{\text{H}} \rightarrow \text{Scientific}^{\text{H}}$$

Norma’s understanding about electric circuits was enhanced because the diagram challenged an alternative conception and aided her to develop scientifically accurate ideas about the role of energy in electric circuit functioning.

### Reduced Understanding

Understanding about electric circuits was reduced when less detail was provided by students or the diagram promoted alternative conceptions. The second reason that diagram reading



generated non-scientific ideas is of interest. Josh a high-ability Year 5 student commenced with moderate scientific knowledge about electric circuits.

After constructing a circuit, Josh explained:

*There's an electric (sic) in the battery and you can use the power inside. If you remove one wire the bulb goes off because there's only one entry and no exit. Unscrewing the bulb also turns it off because the light is off the things.*

He described a scientific model where power entered through one wire and exited through the other describing unidirectional motion in a closed circuit. Josh also explained the bulb must be in direct contact for it to work conveying medium-level scientific understanding despite English language challenges (Scientific<sup>M</sup>).

Viewing the diagram, Josh explained:

*The yellow dots are electric, power. They are different because there's some power inside here (LHS wire) and when the light used it there's no power, not enough power left (RHS wire). The arrows mean change, the way the electric goes.*

His explanation conveyed a non-scientific model of 'electric' [sic]/power (words he uses interchangeably) being present in the LHS wire only. The intra-wire symbols mislead Josh in a similar way to Bill on his first diagram reading. His understanding changed to reflect a mix of scientific and non-scientific ideas (Mixed<sup>M</sup>).

Viewing the labelled diagram, Josh explained:

*Maximum energy, zero energy, energy lost, energy lost, another energy lost, zero energy, battery & maximum energy. First energy is out of the battery so its full energy, when energy has been used its zero energy. Plus & minus, maximum energy & zero energy, battery terminal, negative battery terminal. Positive is strong, negative is weak. The Arrows mean change in direction of flow of electric current. Current is elemental.*

Josh synthesised the labels to 'deduce' the energy changes from 'full' energy to 'zero' after being used and attempted to explain current lacking either background knowledge or English words. His conceptual understanding remained unchanged (Mixed<sup>M</sup>).

Josh's one-sided power view was repeated in interview 2:

*Plus is the new electricity, the globe uses it and there is no electric left, then goes in the battery. It goes, plus, minus, plus, minus. The yellow dots are electric, there (LHS) it has power, the bulb uses it and there (RHS) none left.*

Although 'new electricity' and 'no electric' were substituted for power, Josh maintained an E-user model where 'the globe uses' all the electricity. Although he described a cyclical direction, the RHS wire is devoid of electricity influenced by the intra-wire symbols. His conceptualisation remained the same as previously (Mixed<sup>M</sup>) and was unaffected by re-exposure to the labelled diagram (Mixed<sup>M</sup>).

The pattern of changes in Josh's conceptualisations about electric circuits was:

$$\text{Scientific}^M \rightarrow \text{Mixed}^M \rightarrow \text{Mixed}^M \rightarrow \text{Mixed}^M \rightarrow \text{Mixed}^M \rightarrow \text{Mixed}^M.$$

Josh's understanding about electric circuits was reduced because a specific feature of the diagram promoted an alternative conception resulting in a non-scientific model that was reinforced by further exposure to the diagram.

## Enhanced and Reduced Understanding

In some cases, conceptual understanding about electric circuits was both enhanced and reduced: one aspect became better understood whilst confusion was generated about another. The first part of Sharon's interview (medium-ability Year 5 student) is sufficient to illustrate this.

Helped to assemble a circuit Sharon explained:

*You always need two wires to join to the light. Battery gives energy and it joins to the light and sends up something and then it makes it light. Remove one wire it doesn't go, you need two to join onto the plugs.*

Her explanation conveys some understanding of a complete circuit along with a vague notion that 'something' travels in the wires for the bulb to work. Her conceptualisation comprises low-level scientific understanding (Scientific<sup>L</sup>).

Using the diagram, Sharon explained:

*There is a battery and this is sending light to that and the bulb is sending it to the battery. The arrows mean going this way and that way. It is the battery going into the light and the lights going into the battery. The yellow dots are the energy that gets into the light.*

Initial confusion is evident concerning what moves unidirectional around the circuit. The intra-wire symbols make Sharon think 'light' moves inside the wires. When called yellow dots, she decides the symbols represent energy. Sharon conveys medium-level scientific and non-scientific ideas (Mixed<sup>M</sup>) which is maintained.

The pattern of changes in Sharon's conceptualisations about electric circuits was:

$$\text{Scientific}^L \rightarrow \text{Mixed}^M.$$

Sharon's understanding about electric circuits was enhanced by outlining a partial scientific electric circuit model with unidirectional transfer around the circuit and reduced because she initially misconstrued light as moving inside the wires.

## Discussion

This study aimed to investigate the effects of diagram reading on primary students' understanding about electric circuits. Overall, students' understanding was enhanced with scientific, unidirectional, energy-based models of electric circuits being promoted. The interplay of students' prior knowledge, meta-conceptual awareness, intuitions and negotiation of diagram conventions impacted on students' meaning making.

Bill developed the most sophisticated, coherent explanation. His advanced verbal-symbolic knowledge (of electrons, volts and current) was a clear advantage. Whilst prior knowledge was not a precursor for diagram effectiveness (students with low-level prior knowledge also benefitted), the ability to apply existing knowledge to information from the diagram enhanced his understanding. This supports Cheng and Brown's (2010) finding that how students' use their existing verbal-symbolic knowledge determines what sense they can make from diagrams and the sophistication of explanations formed.

Bill's strong meta-conceptual awareness signalled the information provided in the labels contradicted his previous thoughts about relative energy levels around the circuit. This enabled him to make conscious decisions about which resources to retain, drop or further consider. Cheng and Brown (2010) found such critique and revision was necessary for students to construct sophisticated, consistent, and coherent explanatory models.

Norma and Barry were both influenced by the diagram to revise their initial E-loser and E-sharer models to the scientific E-transfer model. The arrows were a catalyst, guiding their thinking about the direction of energy movement in the circuit. For Norma, this was sufficient to challenge the non-scientific model of power/energy/electricity going up both wires and her revised model was maintained. Barry eventually capitulated to the E-transfer model after vacillating between the two, suggesting his intuitive ideas were more resistant to change. These examples demonstrate the characteristic feature of arrows being a key element in promoting the scientific E-transfer model for primary students. Although arrows have been reported as problematic (Amettler and Pinto 2002; Henderson 1999; Lowe 1988; Schollum 1983), in this study they helped students to revise non-scientific models.

Josh demonstrated how the non-scientific model of 'E-user' was directly influenced by a specific feature of the diagram. Differences in intra-wire symbols led Josh to an incorrect conception about energy levels and energy usage by the bulb. For some students, this reinforced a non-scientific model held from the start. Josh developed this idea during initial interaction with the diagram. These symbols are an example of a stylistic convention used to exaggerate part of a process but can negatively impact students' conceptual understanding (Wheeler and Hill 1990). As these symbols were not labelled, students were left to guess exactly what they represented. Such stylistic features of diagrams can be problematic for primary students because they are 'too open to different interpretations that are deviant from the scientific meaning intended by authors' (Cheng and Gilbert 2015, p. 144).

In addition to answering the research question, the study sought to validate the revised electric circuit models. These new models successfully encompassed primary students' ideas about electric circuits. They enabled nuances such as vagueness or certainty in students' thinking to be determined. General or specific language and interchangeable or consistent use of terms were indicators of students' understanding. The terms power, electricity or specifically energy were used predominantly by students in this study to convey the general idea that 'something' (not current) was moving around the circuit, thus revealing a critical difference in students' conceptual models to previous research (e.g. Osborne 1983; Shipstone 1985).

In accordance with Shipstone (1988), it would be wrong to assume this language equated with the concept of current and would fail to convey the students' intuitive and developing understanding about electric circuits. Current was hardly mentioned, with energy being the dominant concept underlying students' thinking. It must be conceded that the labels 'energy lost, maximum energy and zero energy' likely influenced students' language. The uptake of the term energy could also be explained because it strongly aligned with students' existing ideas. Re-application of the revised models at different phases in the study enabled identification of change or stability in students' conceptualisations. This was particularly useful for collecting evidence of advancements in understanding which indicated a consolidated view of the role of energy in electric circuits.

## Implications for Teachers

A practical finding of this study is that diagrams assist teachers to determine students' specific instructional needs concerning conceptual understanding. A clear factor influencing students'

ability to explain electric circuits was their use of scientific language. Instruction involving active discussion of terminology, for example, what students mean by electricity in different contexts (Hubber 2015), is recommended for deeper diagram processing. Evidence from this study showed students lacked specific terminology (and associated understanding) to explain firstly what batteries provide (i.e. an energy source) and secondly what happens to that energy in a connected electric circuit. Targeted instruction should commence with the battery as an energy provider progressing to transfer and transformation of energy within the circuit. These concepts require more than knowing how to make a working circuit to be developed.

This paper raises questions about the order in which electricity concepts should be taught in primary school. Contrary to the argument ‘it is essential they first understand about electric current’ (Osborne 1983, p. 80), this study indicates energy is a more appropriate foundational concept. Starting with children’s existing knowledge and building on those ideas (Chapman 2014, p. 6) aligns with constructivist research-based practices. Very few students had prior knowledge of electric current and the results indicate the everyday terms power and electricity were more congruent with energy.

Contemporary scholars argue the need for both energy and current to be introduced to primary students (Hubber 2015, Kallunki 2009). Focusing on children’s understandings of electric current only down-plays the complex interactions at work within an electric circuit. Separating current flow from the associated action of electrons as energy carriers diminishes the prime function of electric circuits as energy transfer devices (the purpose for which we use them). Further an emphasis on current remaining constant throughout a circuit rather than being used up (alternative conception) overshadows the development of an understanding of what is ‘given up’ (transferred and transformed), that is, energy. To address the tenacity of the idea that something is ‘used up’, energy, not current can account for what is expended (Summers et al. 1997) with an emphasis on conversion rather than consumption.

Consolidating and deepening students’ understanding about the role of energy before teachers introduce electric current provides an anchor for connecting this concept to existing knowledge. Hubber (2017, p. 213) concurs ‘the introduction of the concept of electric current with the movement of electrons needs to be accompanied by ideas associated with energy transfer and transformation’. The approach of beginning instruction about electric circuits with energy is suggested to help counter the finding that in high school ‘current is the primary concept used by students’ (Cohen et al. 1983, p. 407). Consequently, students misconceive that potential difference results from (not causes) current flow and think the battery is a current source. As a solution, I advocate a teaching approach that emphasises the ‘big ideas’ of science in which energy takes precedence. Ideas associated with one of the ten big ideas of science (see Harlen 2015) that are appropriate for 5–14-year-old students are encompassed in the proposed explanatory sequence for teaching about electric circuits summarised in Table 4.

The sequence in Table 4 commences with an energy focus, providing a reason why electrons move and how this makes electrical devices work (i.e. by giving them energy). That electrons move (and current remains constant) I argue has been over-emphasised to the detriment of energy transfer, almost ignoring the significance of this universally important process. Just as one cannot happen without the other, the significance of both energy and current in this process must be emphasised. If the fact that electrons can be made to move is important scientifically, surely more so, is the cause of motion (energy difference/potential). Highlighting that moving electrons carry energy provides the missing link needed to explain its transferability. I am not arguing that energy should be taught in favour of current, ‘potential difference and current are the key concepts necessary to understand electric circuits’ (Cohen

**Table 4** Explanatory sequence for ideas involved in electric circuits

Aspect	Explanation of process	Simple interpretation
Battery	‘The chemicals in the cells of a battery store energy’	The battery is an energy source
	Chemical reactions produce a difference in charge with potential to do work.	Chemical energy makes battery terminals have positive and negative charge
	Energy ‘released when the battery is connected so that an electric current flows’	Chemical energy changes (transforms) to electrical energy
Electric current	‘Objects can be made to change their movement by pushing or pulling’	Electrons (in wires) are forced to move, pushed away (negative terminal) and pulled towards (positive terminal)
	‘Energy is transferred from 1 object, which is an energy source or resource, to another’	Moving electrons carry energy (energy transfer)
Bulbs, wire etc.	Current transfers ‘energy to other components in the circuit and on to the environment’ (Harlen 2015, p. 23)	Energy changes (transforms) to light (and heat) in bulbs, sound in buzzers, movement in motors and some heat in wires

et al. 1983, p. 407). The order in which these concepts are introduced though, needs a re-think. The cause (i.e. the potential difference) should come before the effect (electron-flow). The notion that moving charges carry energy that *can* be given up (transformed) to produce light and heat in a bulb is then a logical instructional step.

Following constructivist principles, commencing instruction about electric circuits from primary students’ existing conceptions requires building on energy-based electric circuit models. Combining energy-based electric circuit models with representation construction pedagogies (Tytler et al. 2013) to test this approach in primary classroom settings is a recommended direction for future research.

## Limitations

Like all exploratory studies, this research is affected by some limitations. The small sample size and data collection in a single school limits the ability to generalise these results. Also, the inability to control for the possibility of interim learning by students between the two interview phases must be acknowledged.

## Conclusion

Allowing open, untutored, interpretation of a diagram and examining the explanations constructed provided insight into how primary students think about electric circuits. The approach highlighted aspects of a particular visual representation that helped or hindered students’ understanding. The results demonstrate that diagram reading enhanced conceptual understanding by framing students’ explanations about electric circuits. Irrespective of prior knowledge, mid-upper primary students could make at least some sense of electric circuits by interpreting the diagram. The conceptualisations conveyed by primary students’ explanations indicated a range of underlying energy-based conceptual models about electric circuits. The important

finding that energy not current was the prevalent concept underlying students' thinking contrasts with previous research.

Students' understanding about electric circuits did not comprise a complete scientific model. Their explanations focused on energy transfer, with incomplete understanding of energy transformations and the concept of electric current was absent. Thus students' explanations left room for further learning about electric circuits. The study shows the power of labelled diagrams for framing and shaping primary students' thinking. It further supports the value of using visual representations in teaching and learning science. Diagrams can be used by teachers to elicit students' understanding. Instruction can then target specific learning needs about abstract scientific phenomena like electric circuits.

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