Development of electric circuit understanding through fundamental concept tutorials

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CONTEXT

A significant and serious learning problem exists with students' poor understandings of fundamental electric circuit concepts. It directly contributes to issues with enrolment, retention and performance of students in electrical engineering courses and those who continue in courses often maintain these misunderstandings throughout their degrees and into the workforce.

This is an international phenomenon, one that science education researchers have been investigating for decades and is not unique to students with limited backgrounds in secondary school physics. At the University of Auckland all engineering students take seven compulsory courses after which they choose their specific discipline. Entry to this program requires the majority of students to have achieved passes in the electricity examination of the final year of secondary school physics. While students are able to gain the required grades, first-year student quiz data reveals persistent confusion about the most fundamental circuit properties and concepts.

PURPOSE

The purpose of this first stage of the research was to investigate if a set of comprehensive online tutorials focussed on fundamental circuit concepts could improve first-year students' understandings.

APPROACH

In 2015 the first author developed an online concepts quiz and, a set of intended learning outcomes for student understanding based upon physics and electrical engineering literature, and a range of fundamental circuit concepts tutorials (FCCTs). The online FCCTs were developed with a focus not on content but on a strategic blend of known educational strategies identified from engineering education, general educational literature, prior engineering practice and teaching experience. These include the use of context, circuit visualisation, variation theory and the avoidance of calculations. In 2015 first year engineering students were offered the FCCTs as optional support before their course began. After the first use the FCCTs were refined based upon student feedback. In 2016 a similar concept quiz was used with first year students and the FCCTs were again offered to students; however the first ten of these tutorials now counted as 4% of the course grade.

RESULTS

Online concept quizzes from both years revealed misunderstandings of fundamental circuit concepts held by up to 90% of students. In the first year when provided voluntary tutorials, 20% of 868 students completed five or more of the FCCTs, many leaving positive comments about them; with 60% of students not accessing them at all. In the second year, when worth 4% of the course grade, by the mid-point in the semester 55% of students had completed five or more of the required FCCTs and 31% had completed all of them. At that time students had left 583 written comments and 2250 Likert scale ratings. 75% of the ratings and 80% of the comments were positive, with many students leaving comments directly relating to clarifications of known misunderstandings.

CONCLUSIONS

The very positive response from students to work focussed on fundamental concepts justifies the resources required to develop the FCCTs and to further refine and research them in the future. This positive result indicates that there are benefits from taking a holistic view of a learning situation by critically theorizing the learning issues using an integration of literature from several fields, and then synthesizing a strategy which brings together several aspects of best practice.

KEYWORDS

Conceptual understanding, electric circuit theory, visualisation, variation theory.

Introduction

In no other time in history have our societies been so dependent upon the outcomes of STEM (science, technology, engineering and mathematics) education. However the electrical engineering programmes of learning which directly relate to societies needs have for quite some time experienced significant issues around enrolment, retention and performance of students, making it difficult to meet the growing demands upon them (Carnegie & Watterson, 2013; Meyer & Marx, 2014). One of the factors at the core of these issues are students' misunderstandings of electric circuit properties and a significant body of international academic literature exists identifying and explaining these and the learning challenges involved.

Misunderstandings held by students cover a wide range of the most fundamental circuit concepts. The characteristics of voltage, current, power and resistance are regularly confused (Duit & von Rhoneck, 1998), the terms of potential difference, electric potential and voltage are not understood, as is the terminology voltage 'drop', voltage 'loss', voltage 'across' and voltage 'at'. Current is often thought as the cause of voltage; this may relate to current generally being taught before voltage (Cohen, Eylon, & Ganiel, 1983) or to the way Ohm's law is taught and remembered formulaically as V=IxR rather than as a definition – a definition which when expressed formulaically is more correctly I=V/R. While current can be calculated correctly many students hold views that it is weakened or used up (Chang, Liu, & Chen, 1998). The single distinguishing characteristic of these concerns is that students can follow procedures to calculate answers, achieving highly whilst at the same time demonstrating so little understanding.

Literature from physics and engineering education reports an extensive range of complex factors, including: lack of preparedness from high school education (Psillos, 1998), students understandings of electric circuit properties as 'everyday' rather than as 'scientific' (Shipstone, 1984), and only being able to indirectly interact with circuit properties making them conceptually difficult to understand (Chi, 2005). The consequent difficulty of changing understanding in these circumstances (Duit & Treagust, 2012) has led to the some of these issues being classed as threshold concepts (Scott & Harlow, 2012). Aligned with this is the belief amongst faculty in physics and engineering that the way to teach electric circuit theory is via formulae and mathematical modelling (Carnes & Streveler, 2011). There is also a belief by many students that the topic is too difficult to understand (Brown & Hammer, 2008) so students strategically work to pass examinations without developing mastery of the content (Laurillard, 2002).

What does it mean to know but not to understand?

One perspective on what it means to be so adept at calculating yet not understand what is being calculated can be gained from a common educational tool, the Blooms Taxonomy (Krathwohl, 2002) as shown in Table 1.

Table 1: Blooms taxonomy cognitive dimensions

Bloom's taxonomy of cognitive processes
Create
Evaluate
Analyse
Apply procedures
Understand (comprehend)
Remember facts

Factual recall is the base cognitive level from Bloom's taxonomy. In electric circuit theory much factual knowledge is encountered. Electric circuits have three important sets of facts that students need to know. Facts about circuit properties such as voltage, charge, current and resistance; facts about circuit components such as energy sources (e.g. batteries), resistors, capacitors and inductors; and facts about topology such as short, closed, open, series and parallel. When a student defines and recognises circuit properties, components or topology correctly they are exhibiting factual knowledge.

Conceptual understanding, or 'meaning making' is the second cognitive skill level; it is the forming of relationships between facts by sorting and testing them (Jonassen, 2006). This is no easy task for learners as it requires them to make sense of all the facts encountered in electric circuits in relation to one other. In physics and engineering, laboratory work is one tool aimed at helping students build relational understandings between the sets of circuit facts. Students however often leave laboratories with little conceptual understanding of what they have done (Coppens & De Cock, 2013). This can occur when laboratory work lacks authentic context (Amarin, Sundaram, Weeks, & Batarseh, 2011) and because students view laboratory work not as concept formation but as procedural knowledge (Zacharia & de Jong, 2014), where correct results become the focus rather than the focus being on the journey being undertaken.

Application of procedure is the third cognitive level; this involves applying formula to problems. It is a dominant activity in physics and engineering education because mathematical models so accurately capture the body of knowledge encountered in these disciplines. Repetitively carrying out calculations with mathematics is known as drill and practice. While drill and practice in itself is not poor pedagogy, as it is essential for building mastery (Hattie, 2009), without prior conceptual understanding it leads to students resorting to blind application of formulae in confusing ways (Kautz, 2007; Smaill, Rowe, Godfrey, & Paton, 2012). Drill and practice without conceptual understanding is recognisable when students make comments such as this one from the course online forum:

> *"not really sure how to do this question, since we were never showed how to do a question for a non-inverting summing amplifier".*

Bloom's Taxonomy places the building of understanding prior to the 'apply' or practice level. Much of the work undertaken by students though does not attend satisfactorily to this level. The consequences of a deficit in conceptual understanding is that students are incapable of qualitatively explaining simple circuits (Cohen et al., 1983; Maloney, O'Kuma, Hieggelke, & Van Heuvelen, 2001) even fearing having to do so. This makes it problematic moving on to work at the higher cognitive levels described in the taxonomy which include the when, where and why of using the facts, understanding and procedures that students know.

Seeing student lack of understanding in terms of the deficits in the taxonomy allows an educator to develop focus for a needed eLearning strategy. In this research the focus has become concept development. The development of concepts however is not straightforward as it requires indirect processes for probing learning and measurement; this brings to the fore an educator's skills and knowledge about teaching and learning as crucial to the process.

Pedagogy

While student's knowledge can be identified as deficient in conceptual understanding, this does not explain why the issues persist. A parallel application of Bloom's taxonomy to pedagogy – teaching and learning - can be informative here. Pedagogy begins at the factual level with educational theories of learning. The understanding level for an educator is a cognitive awareness of what these theories mean for learners. At the apply level are the practices and methods of teaching.

In tertiary education, lecturers have highly developed content knowledge from intensive research and/or industry experience however they often enter teaching without formal education in education. This means they may have fewer factual and conceptual pedagogical understandings about learning, curriculum and educational theory. This leads to a primary focus in course descriptions on content and preferred methods of teaching as described by Laurillard (2002). Much tertiary learning is also supported by teaching assistants. These senior students have no educational training, and significantly their own conceptual and strategic understandings of the content are at varying stages of development.

An expert educator is described in literature as someone with deep understandings from both domains - content and pedagogy; and is adept at bringing them into relationship with one other. Shulman (1986) calls this single rich blend of knowledge, Pedagogical Content Knowledge (PCK). PCK captures the ability to respond to learners' needs using the intricacies of subject content. In terms of students understanding Shulman describes the outcome of PCK as the ability to make content "comprehensible to others" (p. 9), placing PCK as one of the most significant impactors on student understanding.

Learning is not just a function of what takes place in classrooms as it takes place within educational systems. An understanding is needed as to why "schools are remarkably unsuccessful in enabling student conceptual development" (McCormick, 1997, p. 148). One reason is that conceptual understanding can only be taught and measured indirectly, whereas students must be measured for qualification purposes. Resource hungry conceptual activities are not favoured as they are neither easily quantifiable nor reproducible in examinations. In this situation rote learning of declarative knowledge, and drill and practice easily become core learning activities.

Teachers' PCK contributes at the systemic level as well. It is increasingly difficult to attract specialist physics educators into schools, consequently physics courses are often taught by non-specialists who lack conceptual understanding of fundamental concepts (Cohen et al., 1983). This leads to students maintaining and even developing further misunderstandings.

Tertiary education systems are also measured by external factors that drive summative assessment regimes and place significant constraints on resources (Laurillard, 2002), so laboratory work and concept building activities come under significant time constraints.

To work within such a complex learning situation requires synthesising an approach that includes educational theory, pedagogy, best practices and subject knowledge; while at the same time matching the constraints of existing learning systems.

Research approach

This research is part of an iterative design process aimed at improving students' conceptual understandings in electric circuit theory. It takes into account important understandings from previous research conducted within the department as well as selecting and applying best practices from a range of physics, engineering and educational literature.

Prior research with students in the first year course (Smaill, Rowe, Godfrey, & others, 2008; Smaill et al., 2012) indicated a diverse range of conceptual misunderstandings involving significant numbers of students. Using data from this along with literature from physics education the first author developed a set of intended learning outcomes, an online quiz, and 10 FCCTs. Learning outcomes are known to be powerful for students learning (Hattie, 2009), and these were defined using verbs that reflect the hierarchy of cognitive skills in the Bloom's Taxonomy:

- *identify* electric potential as the driving force in a circuit and current as a consequence of both electric potential and topology
- *express* a conceptual understanding of the terms potential difference and electric potential and therefore build a meaningful concept for the word voltage
- *identify* the topologies and consequences of closed, open, short, series, parallel in various contexts

- *explain* the terms associated with voltage (at, across, between, drop, dropped, loss, lost)
- *describe* the concept of a circuit reference (ground)
- *identify* difference in electric potential between parts of a circuit
- *explain* Ohm's law as a relationship (conceptually, not just a formula)

In 2015 the online quiz and tutorials were offered to students as optional tasks prior to the course. 506 of the 886 students voluntarily took the quiz. Results indicated widespread conceptual problems: 69% of the students did not recognise that the voltage across parallel components was the same, 88% held a concept of current weakening in a series circuit (while still being able to calculate that it did not) and 70% were not able to identify that the total resistance of resistors in series would be greater than the largest value resistor.

Tutorial themes:

The development of the tutorials was undertaken using a range of themes identified from physics, engineering and education literature. The themes selected were: non-formulaic questions, context, visualisation and variation. Avoiding formulaic questions was an important first theme as students are already proficient at procedural formulaic tasks.

Context was the second theme chosen. While academic learning involves knowledge which is abstracted and generalised (Laurillard, 2002) learning in electronics is integral with and dependent upon meaningful context (Finkelstein, 2005). Much of the work students do in electric circuit theory involves solving mathematical problems which lack authentic context. Contexts involving implications of open and short circuits on voltage and current caused by mis-wiring, poor soldering and electrical faults were used. The image of a faulty circuit board in Figure 1 was used as part of one tutorial along with implications of the short circuit that occurred: the subsequent open circuit with no voltage being present and thus no current.

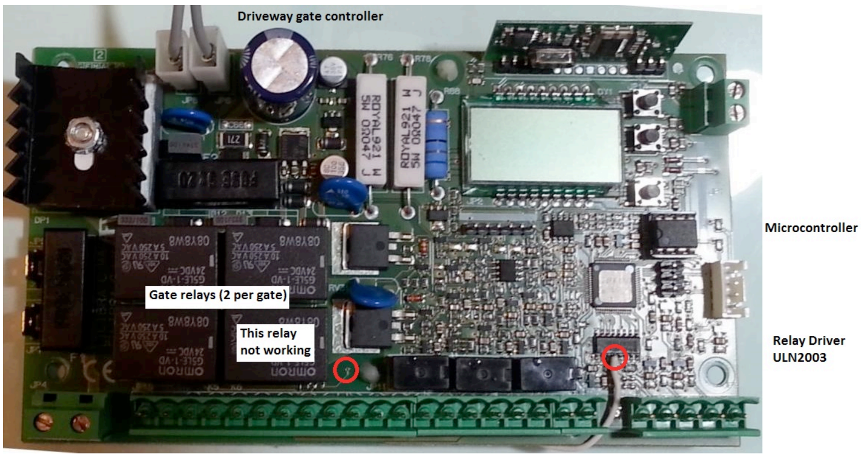

Figure 1: Image of a faulty circuit board

Visualisation of circuit properties was chosen as the next theme. Schematic diagrams are static models of circuits and give no indication to learners about what is happening in a circuit as voltage and current are only observable indirectly, e.g. by using a meter, or when a switch is closed and an LED glows. Research into circuit visualisation has shown positive benefits concerning the unobservable nature of voltage and current (Frederiksen, White, & Gutwill, 1999). Many modern simulation tools however are highly complex and present excessive cognitive load for students; they also have steep learning curves so are unsuitable for novices. An open source circuit simulator (Falstad, 2016) was identified as simple to use but rich in visual clues for development of the interrelationships of circuit properties and topology. In Figure 2 electric potential is shown in relationship to open circuits; conceptual or interrelational understanding may develop because the links between high potential (green), 0V (grey) and open circuits are made explicitly visible.

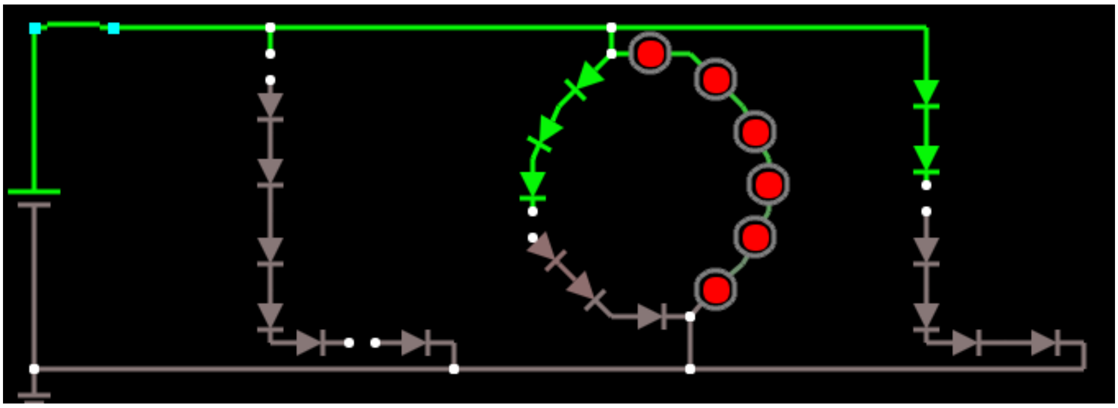

Figure 2: Open circuits in the circuit simulator

Variation theory (Marton & Pang, 2007) was seen as an important theme for the tutorials. Aspects of voltage are difficult to disentangle from current because they co-vary (as one changes so does the other) and so are seldom viewed separately and independently by students (Carstensen & Bernhard, 2009). Variation theory reveals that for co-varying ideas to become separate concepts they must first become individually discernible. In Figure 2 electric potential (voltage) is visible but current display is turned off; students are shown how the high (green) and 0V (grey) potentials can exist each side of an open circuit independent of any view of current confusing this detail.

Students response to the tutorials

Student voice collected as part of qualitative research on teaching practice emerged in education in the 1990s as important in providing a unique and important perspective on learning (Cook-Sather, 2006). To capture student voice, students were encouraged to leave feedback on the tutorials using two seven point Likert scales and two comment fields to rate the effectiveness of the content and the circuit visualisations.

In 2015 the online tutorials were offered as optional learning prior to the course beginning, and 20% of the 868 students completed (answered the questions in) five or more of the tutorials. Some of these students left positive ratings and comments about the tutorials indicating benefit from developing the FCCTs. A further 20% of the students looked at five or more tutorials but did not answer any questions in them. Interviews with 13 students at the completion of the course revealed that several students selectively chose which FCCTs to engage with based upon a perception of their understanding of the content and not upon actual data of their understandings as gained from the results of the concepts quiz. Others chose not to do the FCCTs because they did not count as marks for the course, or because the student was not going to choose electrical as their specialisation.

The tutorials were refined for 2016 and students were given the incentive to engage with and complete the tutorials by allocating 4% of the course grade to them, with the due date being the final exam for the course. An appeal to students was made for them to complete the FCCTs prior to the first test at the mid semester point. Students were encouraged to leave feedback about what they had learned, the benefits of the tutorials and simulations on their understanding and to make comments about potential improvements. By the first test, 55% of the 867 students had completed five or more of the ten tutorials, with 31% completing all ten (while 30% had not accessed them). Students left 583 written comments and 2250 Likert scale ratings. Figure 3 is a graph of the Likert responses; 227 or 10.7% of these were 1, indicating that, according to a student, a tutorial or a visualisation provided no benefit to existing understanding, 73% of the responses indicated that the tutorial provided useful (4) through to transformative (7) benefits, of which 12.8% of the tutorials were seen as transformative in nature by the students.

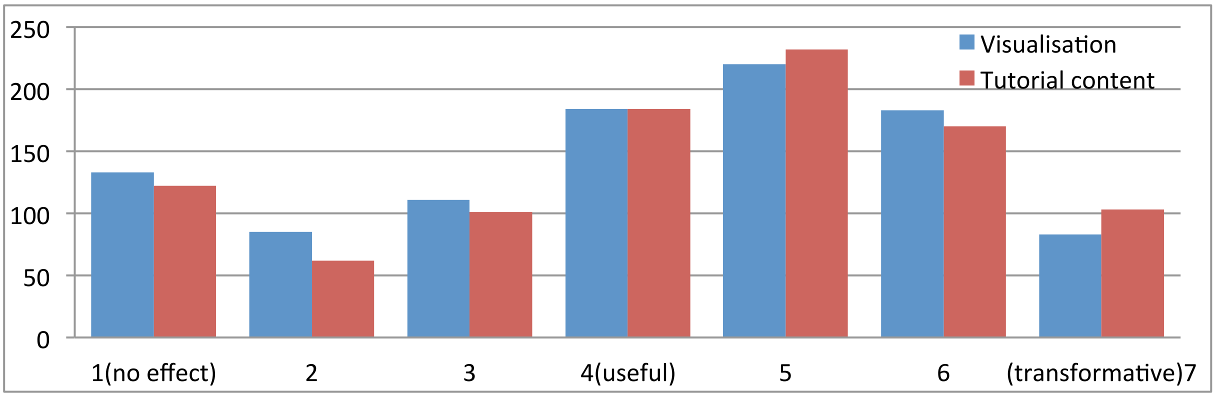

Figure 3: Likert scale responses on tutorial and visualisation effectiveness

The written responses ranged from single word to paragraph length. Students left 159 positive comments about their learning; these were categorised according to known misunderstandings. The highest number of positive comments in one category (47) related to clarification about the separation of the co-varying properties of voltage and current.

> *"I learnt that voltage does not flow through circuits, how only charge flows and voltage is just the difference of potential between two points and is not something that flows"*

Students left 31 specific comments relating visualisation to this clarification process

> *"Visualisation of the charge and voltages made things a lot clearer in a short amount of time"*

Ten of the comments related to clarification of terminology around voltage

> *"This tutorial was actually incredibly helpful! It solidified the idea of where electrical potential shall reside! Whoever designed this tutorial needs a raise!"*

Eight comments indicated change in understanding about current.

> *"It helped me understand the movement of current. That charge only flows where there is a potential difference / voltage, not just when there is a path for it to take"*

Students left six positive comments about the role of context in the tutorials.

> *"I like the way things are explained in relation to how things are done in practice"*

Students left 16 comments about increased conceptual understanding of topology.

> *"The explanations and diagram/circuit simulation supported each other well so I was able to understand the potential differences across different areas of the circuits and how it relates to electric current in the open and closed circuits".*

In the 13 interviews conducted with students in 2015, no student expressed a clear understanding of what 'ground' meant. In 2016 students left 8 positive comments about this.

> *"This helped me understand how we can have negative voltage with respect to the ground"*

Localised and sequential thinking about circuits are common themes in physics literature; students left two responses directly relating to this.

> *"It was really good seeing how changing your input voltage would affect how the current flowed in other parts of the circuits"*

Transfer of learning is a significant goal of education, one student commented:

> *"I liked the representation of the single line circuits; it helped my understanding of some of the questions that I've seen in the course book"*

One student commented positively on the non-formulaic nature of the questions:

> *"I have always felt very weak in electrical concepts. I 'know' what they are in terms of how they are taught at high school, but it still took me a long time to work through the possible answers and eliminate the incorrect. I think the options that are provided did help me to correctly apply the superficial understanding I had of the concepts by making you engage in them, rather than there being one very clearly correct answer as there often is."*

Three comments indicated that some students retained their existing misunderstandings. In this case the student held to the misunderstanding of voltage being caused by current, this was in direct contrast to information in the tutorial.

> *"I learnt that voltage is the electrical energy difference between two points - there is no potential difference across a closed circuit because current is flowing without resistance. There is potential difference across a resistor because of resistance to flow of charge."*

Students left a range of general positive comments ranging from single word to sentences.

> *"I think I could have answered test questions without knowing this but, knowing it is just better"*

One student left a negative comment applying his/her own level of understanding to the majority of the class.

> *"Isn't NCEA L3 Physics (or equivalent) a requirement for engineering? It seems like this should be a separate foundation course. For 90% of students, it's a waste of time"*

Conclusion

The significant number of positive comments and ratings from students directly relating to clarifications of known misunderstandings indicates the value in providing fundamental tutorials focussed on basic concepts. The effectiveness of such an educational resource is however shaped by many factors. A number of these factors are student related. In the first trial most students chose not to do the optional FCCTs even though they knew that they had not done well in the quiz. Some students stated that they chose FCCTs based upon their perceptions of what they did not know and not what the quiz indicated they did not know.

The factor with the largest impact in education relates to educators (Hattie, 2009) and involves the careful theorizing of an educational strategy. The strategy behind this research involved a synthesis of: research from secondary and tertiary learning on electric circuits, theories of knowledge from cognitive psychology and education, literature on pedagogy, the development of learning outcomes and the selection of thematic content selected from a range of best practices from several education areas. Whilst it is common in research to isolate one variable and control for others, the complex nature of the problem and pedagogical experience indicated a blend of themes might be of benefit. Two of the themes, context and non-calculation type questions, received a number of positive comments from students. Clarification of voltage and current, and the use of visualisation however received the majority of the specific comments. Variation theory coupled with visualisation appeared to create a significant impact on student understanding. Variation theory indicated the need to isolate the co-varying properties of voltage and current, and visualisation made this possible. Together they created the opportunity for students to distinguish between characteristics of each circuit property.

Implications for the next stages of research

This research is an iterative design process, one where student voice is as integral to the research process as the theories that underpin it. Refinement of the FCCTs will take place to incorporate the feedback provided by the students. Data collection via interviews with students is being undertaken to investigate impacts of the FCCTs on students' future learning in electrical engineering and to identify from students what other conceptual tutorials that they might benefit from.

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