Don’t blame the student, it’s in their mind: Helping engineering students to grasp complex concepts

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CONTEXT

The Thevenin Equivalent Circuit (TEC) concept has been identified as one of the first threshold concepts encountered by students in first year electrical engineering (Harlow, Scott, Peter, and Cowie, 2011). In order to assist students to learn about TEC, it is necessary to reduce the relational complexity of the concepts being taught (Halford, Wilson, and Phillips, 1998). The relational complexity framework reveals that under the traditional teaching method for TEC, nine different concepts are being combined, thus overtaxing the working memory of students. Methods for reducing relational complexity all incorporate chunking of several related cognitive units into more complex wholes, and sequential rather than parallel processing of information (Halford, Wilson, et al., 1998; Miller, 1956). These methods are essential elements of scaffolding (Wood, Bruner, and Ross, 1976).

PURPOSE

It was hypothesized that introducing a scaffolding method for teaching TEC would improve students’ ability to learn over and above a traditional teaching method.

APPROACH

First, the necessary background circuit theory was taught using simple component concepts (i.e. of relational complexity level 2 or 3). Then students were given practice along with class discussions about why things were done that way. For example, students were first given practice at finding the open circuit voltage of a network, before this concept was integrated with the other TEC concepts. Three trials were conducted, each with a control group that was taught TEC in the conventional way and a test group that was taught via the scaffolding method. After each lesson, students were given a TEC analysis problem that was scored on correctness. In the third trial, students in both conditions were asked to rate the difficulty that they would have in applying the TEC concept to a new problem.

RESULTS

The results showed that on each trial students scored slightly better when the scaffolding method was used, but these differences were not statistically significant, probably due to the large variance between the trials. In the third trial, scaffolding method students gave lower ratings than traditionally taught students on how difficult TEC would be to apply in practice. This result suggested that students’ learning experiences were better in the scaffolding method than in the traditional method.

CONCLUSIONS

The scaffolding method presented here introduces students to new concepts in manageable and consolidated chunks, building up to complex concepts when students are ready. Students’ ratings suggested that better learning experiences occurred under the scaffolding approach. Future studies will adopt improved measures for determining the learning gains provided by the scaffolding approach.

KEYWORDS

relational complexity, scaffolding, threshold concepts, cognitive load, Thevenin Equivalent Circuit.

Introduction

Conceptual learning is important to engineering practice, which utilizes theoretical concepts within problem solving (Sheppard, Colby, Macatangay, and Sullivan, 2007). Engineering modelling, design decisions, and intuitive judgements are all built on the conceptual knowledge underpinning any given engineering system (Streveler, Litzinger, Miller, and Steif, 2008). The way in which engineering students struggle with and eventually grasp difficult concepts is thus central to teaching. However, there is still little awareness and understanding of how best to teach difficult concepts. The discipline is beginning down this road by looking to cognitive psychology for an understanding of the issues involved in the acquisition of difficult concepts, which can help to inform instructional design. This exploration has been applied to teaching within several different areas of Engineering, including introductory circuit theory in electrical engineering. Streveler et al. (2008) have noted that if teachers can be helped to understand *What makes this hard?* and how to *Get beyond the symptoms to the causes* then they will be better equipped to choose better teaching methods rather than to *blame the learner* (Perkins, 2007).

There are two main reasons that students struggle with conceptual understanding of science concepts (Newcomer and Steif, 2008), which can be categorised more broadly as *misconceptions and misconstructions*. Misconceptions occur when students have deep rooted but flawed models of how physical phenomena work; e.g. *that the current in a circuit acts like water flowing through pipes,* which is sometimes true, but which can also result in the misconception that components in a circuit act in sequence (Smaill, Rowe, Godfrey, and Paton, 2012). The difficulty that students have in letting go of misconceptions can be explained by students being unable to understand how the micro-processes in physical systems work, as they are not visible. Subsequently, students are unable to conceive of how everyday experienced macro-properties can emerge from such underlying micro-processes (Chi, 2005; Slotta and Chi, 2006). For example, students cannot see electrons moving through a circuit; rather, they must just imagine what happens to a perceived ‘flow of charge’ when it reaches a battery or a resistor.

Misconstructions occur for several reasons. The first, described by Newcomer and Steif (2008) is due to students owning a set of disjoint phenomenological primitives called p-prims (DiSessa, 1993), that are triggered by the context. For example, an open circuit diagram that includes a battery may trigger a blind use of Ohms law, leading to the wrong conclusion that since there is no current there is no voltage (Smaill et al., 2012). While p-prims may be correct within themselves, they are frequently used separately from one another and incorrectly (Newcomer and Steif, 2008). On the surface of it, the fact that students cannot use their p-prims correctly seems puzzling, as it seems that they have the resources that they need (Hammer, 1996; Newcomer and Steif, 2008). However, cognitive psychology suggests that teachers need to factor in the mental resources that students bring, as well as the knowledge resources.

Many of the cognitive processes that occur during the learning of difficult tasks occur in working memory (Cowan, 2014). Working memory is used during the active stages of learning new concepts and during reasoning (Halford, Cowan, and Andrews, 2007). The role of working memory is to hold active some parts of the relevant information while other parts are being manipulated in some way, so as to allow all of the component concepts to be finally integrated into one whole overarching concept (Halford, Bain, Mayberry, and Andrews, 1998; Halford, Wilson, and Phillips, 2010). Simple concepts require a person to only consider one unit of information; e.g., *red square* or a single relation between two units of information; e.g., *John is quieter than Mary,* which can be written as a binary relation. However, more complex concepts require that three, four or more units of information need to be related to one another; e.g., *John is quieter than Mary at home, but louder than Frank at parties* which can be written as a ternary relation, or *the difference in height between John and Mary is* *larger than the difference in height between John and Frank,* which can be written as a quaternary relation (Halford, Phillips, et al., 2007).

In order to fully conceive of a new concept, all of its components need to be integrated at the same time into one whole relational structure within working memory (Maybery, Bain, and Halford, 1986). The process of concept integration needs deliberative processing (Goode and Beckmann, 2010), which is mentally effortful and imposes a working memory load (Halford, Wilson, et al., 1998; Maybery et al., 1986). As the relational complexity of concepts increases, understanding decreases and response time increases, with an upper limit of four variables able to be integrated into a whole concept by adults (Halford, Baker, McCredden, and Bain, 2005). This limitation described by Halford et al's (1998) relational complexity (RC) theory may be related to the capacity limits of information processing in the brain (Marois and Ivanoff, 2005). While it is still unclear how the brain imposes this limitation on working memory resources, it has recently been shown that as relational complexity increases, activity within and between two main cortical control networks also increases (Cocchi et al., 2014).

As Cowan (2014) has described, RC theory explains why a good working memory is important to learning. In order to understand concepts of different relational complexity, a person's working memory must have the capacity to cope with the integration of all of the components involved in that concept. Halford et al's theory of the relational complexity of concepts along with the discovery of the crucial role that integration plays in learning of difficult concepts (Halford, 1982; Maybery et al., 1986) have been utilised as foundational principles underpinning the *cognitive load in instructional design* framework (Sweller, 1988) and Biggs and Collis' *levels of structural complexity in assessment* framework; i.e. SOLO levels; (Biggs and Collis, 2014). The RC theory is also integral to *threshold concepts*, which are defined as troublesome, difficult and integrative (Meyer and Land, 2003).The third principle pertains to the integration of component concepts, and thus relational complexity has a fundamental role to play in explaining the difficulty of threshold concepts (McCredden et al., in preparation).

Within the framework of Newcomer and Steif (2008) described above, RC theory would describe each p-prim used by novices as a complex relation within itself (e.g., Ohms law). The integration of p-prims with one another (e.g., Ohms Law with an open circuit diagram with a battery) would require the integration of the p-prim sub-components with each other (i.e. combining the concepts of voltage and current in each case), which may tax working memory beyond its capacity. If concept integration exceeds capacity limits, then it cannot be understood, and instead students will resort to procedural learning such as plug-and-chug (Tuminaro and Redish, 2007) or rote learning. Students are therefore unlikely to integrate their p-prims together without assistance and prompting.

Fortunately, there are two strategies available for reducing complexity: *chunking* and *sequential processing*. Chunking occurs when separate units of information become integrated due to experience or practice; e.g., *velocity* is a conceptual chunk, where two variables and the relation between them (i.e., *distance / time*) have been chunked into a single concept due to experience; e.g., by seeing velocity represented as a pointer on a dial (Halford, Wilson, et al., 1998). Sequential processing occurs when one chunk at a time is dealt with rather than all at once, such as in in language, where, in order to simplify cognitive load, clauses can be dealt with in sequential order rather than embedded; e.g., *The monkey touched the duck that walked,* rather than *The duck that the monkey touched walked* (Andrews and Halford, 2002; King and Just, 1991).

Chunking and sequencing can be used together effectively in teaching. First, some of the building block concepts are learned and practiced so that they become chunked into a single complex relation or schema. The information that is presented next in the learning sequence is then able to be learned more effectively as it builds onto the chunked information, thus imposing less of a cognitive load than if all of the information had been taught concurrently.

For example, teaching students to use basic spreadsheet functions before asking them to use spreadsheets to calculate new mathematics concepts facilitates the learning of the new concepts (Clarke, Ayres, and Sweller, 2005).

The complexity of conceptual integration is fundamental to learning, yet it is difficult for teachers in higher education settings to apply this theory to teaching situations. It is not always clear how to determine the relational complexity of any new material (Cowan, 2014), or how to reduce the complexity for the students. On the other hand, primary school teachers try to find methods for reducing complexity on a regular basis. In teaching, the method of *scaffolding* has been used for several decades (Combs, 2004; Rosenshine and Meister, 1992). Wood et al. (1976) coined the term *scaffolding* after observing tutors helping 3-4 year olds to build a three dimensional block structure, a task which was beyond the abilities of the children. Although the age group is different, this type of situation is similar to teaching TEC to first years, in that there are many interacting components and the complexity of the situation is beyond the cognitive capacity of most learners.

On the basis of their observations, Wood et al. defined several strategies for scaffolding, four of which are relevant to teaching TEC:

1. Recruitment: enlisting interest in and adherence to the requirements of the task;
2. Reduction in degrees of freedom: simplifying the task by reducing the number of constituent acts required to reach a solution;
3. Demonstration: modelling “idealized” solutions for task requirements, so that they may be imitated during completion of the task;
4. Frustration control: manage and regulate negative emotional reactions to difficulties in solving the task in order to maintain commitment to finishing the task.

Relational complexity theory helps to clarify how a teacher may implement scaffolding strategy 2, *reduction in degrees of freedom* by using chunking and sequencing. In the context of introductory electrical engineering, the circuit theory concepts need to be broken down into sequential chunks containing either binary or ternary relations. While binary relations are easiest, they are not always possible. For example, one of the fundamental concepts, Ohms Law, V=IR, is a ternary relation, containing three variables: current, resistance and voltage, which are simultaneously related to another. Once this concept has been chunked through experience, it will eventually become a single conceptual chunk or schema (i.e. Ohms Law). However for beginners, Ohms Law takes up three out of the four available slots in working memory while it is being constructed. Therefore, learning activities need to be designed so as to reinforce any newly acquired circuit theory concepts so that they are properly chunked before asking students to link them to other related TEC concepts.

It is important that the sequential modules that are to be used are limited to two or three concepts in the *student’s* perception, not two concepts in the *teacher’s* perception. Teachers and students can have very different ideas about what constitutes one elementary concept (i.e. one chunk). This is due to the fact that when a person’s exposure to a given knowledge domain increases, they begin to chunk multiple elementary concepts together so as to effectively form a single advanced concept, or schema (Chase and Simon, 1973; Halford, Bain, et al., 1998). This advanced concept is then stored away in long term memory (which has an unlimited capacity), where it can be accessed when needed and used within working memory as a single chunk. Thus while complex concepts can seem to be basic concepts for experts, these same concepts involve the difficult and effortful integration of many inter-related components for novices (Larkin, McDermott, Simon, and Simon, 1980).

In the next section, the specific example threshold concept of Thevenin Equivalent Circuits (TEC) is considered. This concept has been identified as very troublesome and one of the first threshold concepts encountered by Electrical Engineering students (Harlow et al., 2011). The complexity of TEC is characteristic of the complexity found in science concepts, in that the system contains many processes containing several components, which interact with one another at multiple levels (Azevedo, Cromley, Moos, Greene, and Winters, 2011; Chi, 2005).

The solution to the complexity dilemma for teachers is to recognise the many constituent concepts within the advanced TEC concept (described below) and explicitly guide the students into mastering these constituent concepts one or two at a time. This strategy, which is effectively chunking and sequencing, has also been called the *isolated-interacting elements instructional method* so as to clarify the important aspects of the strategy; i.e. prelearning of the component concepts so as to reduce the cognitive load when the items are integrated (Pollock, Chandler, and Sweller, 2002). Under experimental laboratory conditions, this strategy has been shown to produce better learning outcomes for novices for a similar problem to TEC (i.e. The Insulation Resistance Test). These results suggest that the scaffolding strategy should also be effective in a teaching setting. Furthermore, the other scaffolding strategies from Wood et al, listed above can also be used; i.e. 1. *Activation*: incorporating some examples which have high practical relevance so as to foster motivation in students and 3. *Demonstration*: the use of worked examples to help reinforce elementary concepts in a relatively rapid fashion (Sweller and Cooper, 1985). Altogether, strategies 1 to 3 should facilitate strategy 4. *Frustration Control*. By giving students enough practice with each new concept before adding new concepts would allow students to feel in control of their learning rather than feeling overwhelmed by the complexity of the new information.

The complexity of the TEC concept and the use of these scaffolding strategies for teaching the TEC concept will now be described in the sections below.

Method

Thevenin equivalent circuits: many concepts embedded within a complex concept.

When students are introduced to the concept of a TEC they are typically told that a large and possibly complex linear one-port circuit can be replaced with a much simpler two element one-port circuit. This immediately raises a number of conceptual difficulties for the student. Some of the questions which arise are:

- *In what way are the two circuits equivalent if one is complex and the other is much simpler?*
- *What is a one port circuit and why do we use them?*
- *How is a Thevenin equivalent circuit useful in practice?*

Often, the teacher will then try to de-mystify Thevenin equivalent circuits by doing an example where a more complex one-port circuit is converted into a simpler one-port circuit. One of the problems with such an approach, however, is that the working through of the example actually raises a fresh new set of conceptual difficulties for the student, before resolving the confusion that already exists.

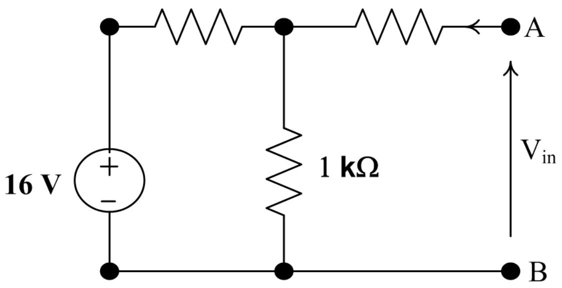


Figure 1: A typical TEC circuit used for teaching

Typically, the worked TEC example will involve the calculation of the Thevenin resistance and the Thevenin voltage for the more complex circuit. A typical example circuit for which the TEC must be found is shown in Figure 1.

To calculate the Thevenin voltage one simply has to find the open circuit voltage for the circuit. This process, however, raises a number of other embedded issues that are confusing for students within themselves:

- *Why is there no voltage drop across the 480 resistor?*
- *Which way do we calculate the open circuit voltage – mesh, nodal, superposition or some other way?*

To calculate the Thevenin resistance all the sources have to be "removed" and the resistance has to be calculated by looking back through the port of the circuit. The process of finding the Thevenin resistance raises a number of embedded questions for students:

- *Why do we remove the sources to calculate the resistance?*
- *Why do we remove voltage sources by shorting them out, whereas we remove current sources by open circuiting them?*
- *Why is it that the resistors that were in series before the shorting of the voltage source become a set of parallel resistors after the shorting of the voltage source?*
- *Why do we calculate the resistance looking backwards rather than calculating it looking from the other direction?*

Typically students can readily come to grips with all of the issues listed above if they appear in isolation. The difficulty comes because the questions often arise in such close temporal proximity that there is little time for a complete resolution of the each of the difficulties before the next one occurs.

A strategy for mastering the Thevenin threshold concept

As alluded to above, mastering the Thevenin threshold concept actually requires mastering the many sub-concepts which make up the overall advanced concept. The following scaffolding strategy (chunking and sequencing) is thus proposed. This strategy teaches (and gives practice and feedback with) each of the embedded concepts one at a time (steps 1 to 3), before working through the entire TEC problem solving process (step 4), and also including feedback (step 5), as follows:

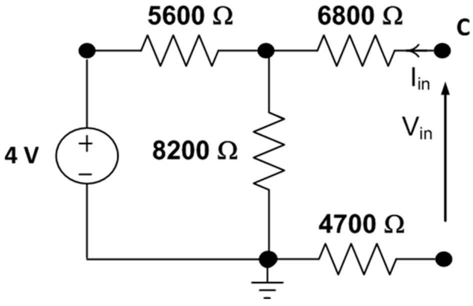
1. Begin by giving students practice at de-activating sources and re-drawing circuits with the sources removed.
2. Give students practice at finding the open circuit voltage of a network like that in Figure 1.
3. Discuss why it is that we need to replace complicated circuits with simpler equivalent ones in practice. Give a practical example of connecting an output to a circuit and calculating the resulting current flow, explaining that (if the circuit is linear) we do not necessarily need to know the internal workings of the circuit – just its open circuit voltage and its internal resistance.
4. Give students practice at integrating the concepts they have mastered in Steps 1-3 above; i.e., give them practice at doing TEC problems such as the one in Figure 1.
5. Ask students to raise any further questions they have with TEC and give feedback before giving them further practice.

The above strategy differs from the conventional teaching approach in a couple of ways. Firstly, practice with finding the open circuit voltage and deactivating sources are given before engaging with the notion of a TEC. Secondly, the usefulness of the TEC (along with the presentation of a relevant practical example) is discussed before the first practical example of Thevenin analysis is performed, allowing motivational reinforcement to occur.

This paper hypothesises that the non-conventional scaffolding approach will enable students to improve their learning of TEC when compared with the traditional approach. To test the hypothesis, three different experimental trials were conducted among students in the first year Electrical Engineering unit (Introduction to Electrical Systems - ENGG1300) at the University of Queensland. In each trial a control group and a test group were selected. The control group was chosen to be one tutorial group, while the test group was chosen to be another tutorial group. The students in the control groups were taught with the traditional approach and the students in the test groups were taught with the scaffolding approach. The control group was taught by mimicking the contents of a YouTube presentation of TEC which has more than a hundred thousand downloads, and would therefore appear to be a good implementation of the conventional teaching approach (see https://www.youtube.com/watch?v=4qEaI4FpYpw). The test group was taught according to the scaffolding methodology outlined in Steps 1-5 above.

After the teaching had been conducted, the students in both groups were given a TEC analysis problem and allocated 10 minutes to complete it individually. Both groups were then asked to perform a TEC calculation, with marks allocated between 0 and 2. The questions are given in Figure 2 below. In Trial 3, the test and control cohorts were asked to rate the following statement on a 5-point Likert scale: “On a scale of 1-5, indicate whether you feel you understand how you could use Thevenin equivalent circuits in practice (where 5 =Very difficult, 4 = Difficult, 3 = Medium level of difficulty, 2 = Easy, 1 = Very easy)”

A. Find the Thevenin voltage for the circuit in the Figure. Show your working.



B. Find the Thevenin resistance for the circuit in the Figure. Show your working.

Figure 2: The TEC analysis and calculation problems given after the lesson

Results

Marks: To test the hypothesis that the scaffolded approach would lead to higher achievement, the test group and control group data for all three trials was subject to a 2-way between-groups ANOVA. The results showed that in each trial, the students in the scaffolding method gave better results that those in the traditional teaching method (Figure 3). However, these differences were not statistically different (F_1,290 = 2.2 NS). This lack of significance is probably due to the marks available only ranging at intervals between 0 and 2, so that very little variance was available for any differences to be discovered. The results also showed differences between the three different trials, which was close to being statistically significant (F_2,290 = 2.9; p = .06). This variation was due to the trials being run on different days of the week with different instructors. It was greater than the between trial variation, thus reducing the detectability of any differences between scaffolding and traditional methods. There was no significant interaction between trial and method of instruction used.

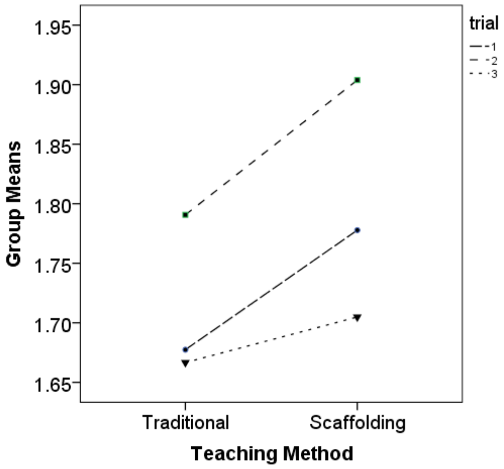


Figure 3: The group means for the traditional vs the scaffolding method for trials 1 to 3.

Level of difficulty in applying the TEC in practice: Students' average rating of difficulty was 2.26 for those who experienced the scaffolding method and 2.83 for those who experienced the traditional method. This difference (shown in Figure 4) was significant when subject to a between groups t-test; i.e. (t _46 = 2.5; p = .015) revealing that the students in trial 3 who experienced the scaffolding method believed that they would have less difficulty in applying the TEC concept in practice that those taught by the traditional method.

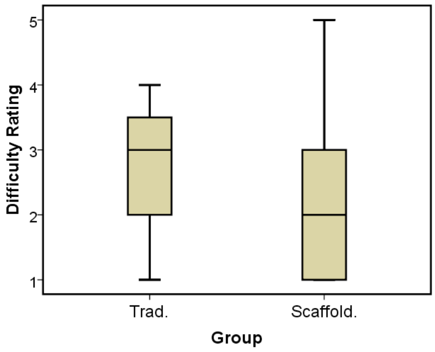


Figure 4: Levels of perceived difficulty in applying TEC.

These preliminary results give some indications that the scaffolding method has some benefits for students' learning of the difficult TEC concept. This conclusion is only tentatively supported by the current study, even though the chunking and sequencing strategy has been shown to be successful in a laboratory setting (Pollock et al., 2002). The scaffolding strategy may be better supported in future studies using more rigorous methodologies. Possible improvements focus on timing and questions used, as follows:

Timing: It has been shown that learning takes time and practice for consolidation (Squire, 1986), suggesting the following strategies:

- For teaching: allow a longer time for practice and consolidation of the component concepts before introducing the more complex concepts.
- For testing: give students repeat tests a week or two later after the TEC concepts have been taught and practiced. Delayed testing may reveal greater benefits for scaffolding than immediate testing.

Questions used: Using correctness of problem solving as a measure of knowledge acquisition has the drawback that students can resort to procedural strategies which do not require understanding (Tuminaro and Redish, 2007). Therefore, problem solving may not uncover any difficulties that students may be having with the crucial reasoning tasks. Instead, concept questions (e.g., Smaill et al., 2012) could be adapted to TEC as a preferable method for testing understanding. Such concept questions may still use procedural steps embedded within them; e.g., they may require students to choose an appropriate procedure from a set of possibilities, where the choice would be based on the student's conceptual understanding of the type of circuit provided.

Future test problems could be constructed so as to allow for a marking scheme with greater variance, such as a 5 point scale, thus allowing for differences between groups to reach statistical significance, The RC theory provides the *representational rank* method for defining the relational complexity of any given assertion (Halford, Phillips, et al., 2007). This measure could be applied to the test concepts as well as to typical answers. This would allow the marker to select which particular level of complexity each student is displaying within their answers.

Conclusions

The relational complexity framework reveals that traditional teaching of the difficult concept of Thevenin Equivalent Circuits is likely to overload students' working memory capacities. To overcome this problem, scaffolding strategies of chunking and sequencing, along with enlisting interest and using worked examples was trialled. The TEC concept was broken down into its constituent sub-concepts which were taught one or two at a time. The scaffolding strategies used have shown some promise for improving students' learning, even though not statistically significant. Future studies will attempt to overcome the null result found here by addressing issues of timing and test problem design. This will require deeper understanding of the component concepts in terms of their relational complexity and of the ways in which they need to be successfully chunked and combined, as well as a refinement of the procedures used.

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