Improving Understanding of Electrical Concepts Using Visualisation, Collaboration and Experiential Learning

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Introduction

Diagnostic testing of first year Engineering students has identified a common lack of understanding of conceptually rich parts of the curriculum, despite meeting grade entry requirements at the secondary-tertiary border (Smaill et al., 2012), (Hawkes & Savage, 2000), (Rylands & Coady, 2009), (Thomas & Klymchuk, 2012). This is particularly common in Electrical Engineering, with abstract concepts like those in electromagnetism often difficult to teach through traditional two-dimensional mediums. Students relying on rote memorisation can recall base concepts and achieve passing grades in secondary examinations, though this does not establish long-lasting conceptual understanding of the material (Biggs, 1987), (Ramsden et al., 1989) or retention of information (Felder & Brent, 2005). Weaknesses in student knowledge are subsequently exposed if content is presented in a new context, or after a long period of time, as is common in transition to a tertiary education environment. These conceptual misunderstandings establish a motivation for this research — identifying an innovative approach for improving secondary students' conceptual understanding to better prepare them for STEM education at the tertiary level. A preliminary form of this work has already been presented at the Electronics New Zealand Conference 2016 (Varoy et al., 2016). This is extended with the proposal of a new conceptual framework for the development of educational digital technologies, a broader evaluation of electromagnetism misunderstandings in secondary school with associated learning activities, and a thematic analysis of student responses to an educational smartphone application.

Established Educational Theory

Passive lecture-based learning has been shown to be ineffective for establishing deeper understanding in students (Berrett, 2012), (Williams et al., 2001) as this style incites boredom, frustration or confusion for many students (Linn, 1996). *Collaborative Learning* has been recognised as a powerful strategy to improve student interest, participation, critical thinking, conceptual understanding and result in better information retention as described by Webb (1982), Baker et al. (1999), van Boxtel et al. (2000) and Gokhale (1995). *Visualisation*, defined by Gilbert (2005) as: Concrete, Verbal, Symbolic, Visual and Gestural, can be utilised individually or combined to develop educational resources. Innovation is required in this aspect, revolutionising traditional methods of visualisation — like static, two-dimensional diagrams — with modern digital technologies. *Experiential Learning* proposed by Kolb (1984) focuses on the philosophy that learning is a "process where knowledge is created through the transformation of experience". This consists of the four phases: Concrete Experience, Reflective Observation, Abstract Conceptualisation and Active Experimentation. Typically implemented through experiments or practical demonstration, this is plagued with administrative complications with Abrahams & Millar (2008) indicating teachers' focus is consumed on presenting instructions rather than fostering conceptual discussion.

VCEL Conceptual Framework

Existing attempts at innovative digital technologies tend to lack a strong educational strategy or structure. Visualisations within information dense applications are primarily static and two-dimensional. Simulations are limited, lacking a user input-response feedback which would allow full exploration and experimentation. Many mobile applications exist as information databases — a condensed, encyclopedic approach — rather than fostering conceptual understanding of the content. To provide a consistent strategy for educational digital technologies to be designed, we propose the Visual and Collaborative Experiential Learning framework (VCEL). This framework was developed by extending the Experiential Learning cycle with two defined phases and adapting Kolb's perspective of practical experience. *Reflective Observation* and *Abstract Conceptualisation* are compartmentalised with the overarching strategy of *Collaborative Learning*. Conversely, *Active Experimentation* and *Concrete Experience* form their own system, supported instead by the Visual and Verbal aspects of *Visualisation*. Kolb's original interpretation of experience is altered in this model to apply to digital technologies; with simulations of reality replacing physical experiences.

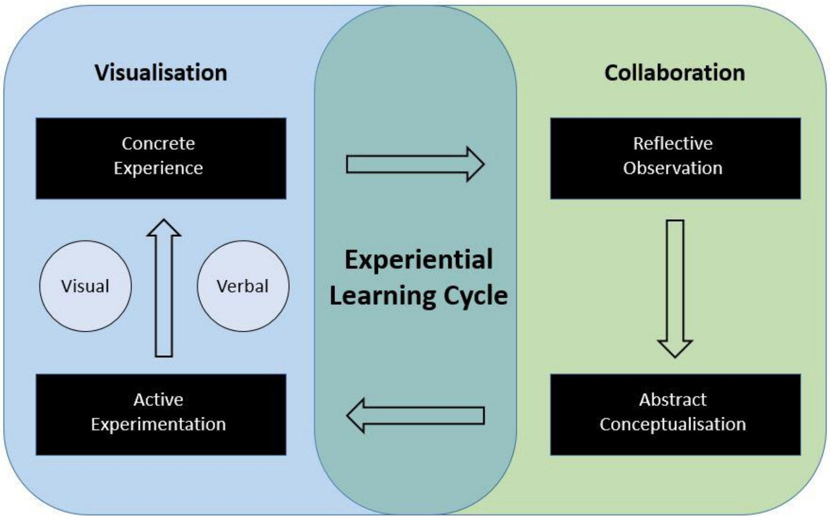


Figure 1: VCEL framework for constructing educational applications

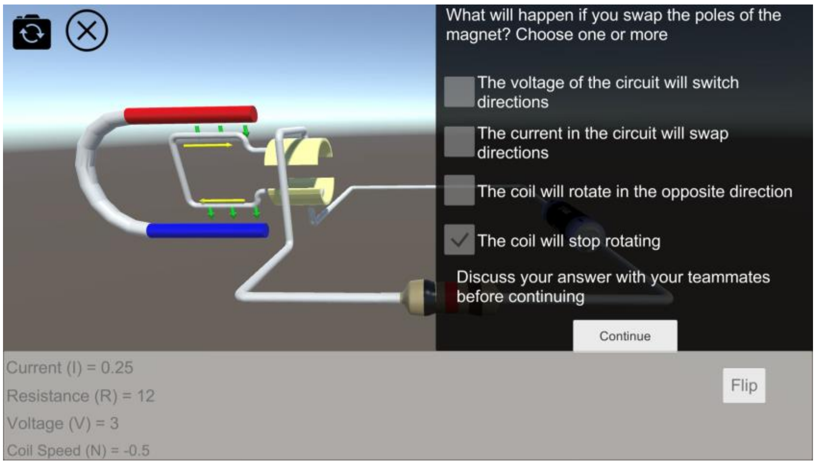
The *Concrete Experience* phase should be supported by a virtual simulation of a real-world experience, applying the visual aspect of virtualisation. Students should be instructed to observe the cause and effect within the simulation. This is built upon in the following *Reflective Observation* phase. Students will be encouraged to collaboratively discuss and reflect on the observations made during the previous phase to strengthen their conceptual understanding. This discussion should continue into the *Abstract Conceptualisation* phase. Students should be developing a social model of understanding by abstracting information from the virtual experiences they have been discussing, which in turn should assist in developing their own mental model. Finally, students should re-examine the virtual simulation during the *Active Experimentation* phase. The simulation should provide capabilities for students to provide input to the simulation and determine its effect. This will allow them to apply their knowledge from the previous phases to predict outcomes before experiencing them in the virtual world, to either consolidate or re-evaluate their current understanding. This cycle can continue indefinitely as students explore and discuss the virtual experience.

Electromagnetism VCEL Application

An implementation of the framework has been developed as a means for evaluation. The topic of Electromagnetism was chosen, a difficult concept within Electrical Engineering due to its abstract nature. A smartphone application was developed, which gave students the ability to explore simulations of real world scenarios involving electromagnetic experiences. Students are able to explore these scenarios from any perspective in three dimensional space by rotating, panning or zooming on their device. This establishes a basis for visualising the *Concrete Experience* and *Abstract Conceptualisation* phases. Students are able to interact with simulations by altering the state of individual components and experience the effect of these changes. The collaborative aspects of the application lay the groundwork for the

Reflective Observation and *Abstract Conceptualisation* phases. To encourage users to reflect on what they are doing, questions are prompted when the user interacts with different components in the activity, as seen in Figure 2 While the development of this application is focused on electromagnetic concepts, other STEM subjects could easily be targeted with this approach, following the VCEL framework.

Figure 2: Example of a question displayed after user interacts with a magnet



Identifying common misconceptions in electromagnetism

Based on research by Smaill et al. (2012), Maloney et al. (2001) and Saglam & Millar (2006) defining common electromagnetism misconceptions, a set of electromagnetic activities were created. Magnetic forces on charges, induction and its correlation to changing flux, vector directions, generators and motors were identified as key concepts where misunderstandings were common. To support these findings, an analysis of New Zealand's national curriculum, the National Certificate of Educational Achievement (NCEA), was also conducted. This analysis was completed on course paper '91173 - Demonstrate understanding of electricity and electromagnetism', by analysing the assessment reports from 2007 through to 2014 to identify misunderstandings. Similar misunderstandings were found with induction (2007), moving charges (2010,2013), generators and motors (2010) and vector directions (2011,2012) all directly referenced. Two secondary school Physics teachers were also consulted. They specifically highlighted that demonstrating the function of a commutator and the concept of changing flux in motors and generators was difficult as they were often limited to drawings or relied on gestures to explain three dimensional concepts

Activities targeting electromagnetic misconceptions

Five core activities were established based on the identified misconceptions. The activities range in difficulty, dependent on the misconception(s) targeted.

Activity one demonstrates the link between the current through a wire and the circular magnetic field that is generated around it. This concept is often difficult to portray in two dimensions due to the perpendicular field direction compared to current direction.
Activity two shows how current and solenoid size will affect the magnetic field generated around the solenoid. This is also difficult to express with a two dimensional medium.
Activity three contains a circuit with a solenoid and a voltmeter, with a bar magnet that users are able to insert into the solenoid. This demonstrates the cutting of the magnetic field, change in flux, and the resultant electromotive force as an induced voltage.
Activity four seen in Figure 2 simulates the direct current motor that was specifically highlighted as a difficult concept by secondary school teachers and literature. This activity explains how a coil will experience a force as a current passes through it in a magnetic field. The coil is placed in a magnetic field to demonstrate how the resultant force is affected by the current and magnetic field, as well as demonstrating how a commutator functions.

Activity five is the reverse process to what is explored in the previous motor example and should help users define the difference between a motor and generator. Users are able to simulate the coil being turned to see it interact with the magnetic field to induce a voltage.

Methodology

An evaluation was conducted with two classes at a New Zealand secondary school, studying the NCEA Level 2 Physics course, a standard typically taken by students in their penultimate year. The classes consisted of 23 and 17 students, with a different teacher leading each class. The students were also divided into subgroups with two smartphones in each subgroup, resulting in four to five members in each subgroup. The evaluation had the following structure:

Introduction (5mins)
Preliminary Test / Diagnostic Test (10mins) - 10 multiple choice questions with 4 options
Application Usage (85mins) – Self-driven, guided by the application, 5 activities to complete
Post Test (10mins) - Same format as preliminary test, with isomorphic questions.
Questionnaire (10mins) - A set of Likert scale questions and open-ended questions.

Each class was allocated two, one-hour lessons for the evaluation. The students involved in the evaluation had recently completed the electromagnetic section of their course and had knowledge of the basic concepts of electromagnetism. The diagnostic test questions were inspired by those proposed by Maloney et al. (2001) and the NCEA Level 2 Physics curriculum.

Results

Diagnostic test statistics

A two tailed paired t-test was carried out to determine the statistical significance in the difference between the pre-test and post-test marks of the students. Conducting the two tailed paired t-test found a p-value of 0.030 meaning we can reject the notion of there being no difference in mean score between pre-test and post-test marks and consider that a significant difference has been found. Observing the confidence interval, we can recognise a lower bound of 0.0950 and upper bound of 1.405. These values indicate that we can say with 95% certainty that the mean difference in score lies between 0.0950 and 1.405, and hence it is likely the difference will fall in the positive region. This is statistically significant evidence that the use of this application has positively impacted students' understanding of electromagnetic concepts.

Likert scale results

The Likert scale section of the questionnaire had 18 questions in total, with the questions and results shown in Table 1. The students responded positively to the questions targeting conceptual understanding. There was strong agreement that the application benefited their understanding of the content, and in a rapid fashion. Their confidence in the course material after using the application, while still strong, was the weakest result in this category. The visualisation aspects had the strongest overall result. Students were very appreciative of this new perspective on the content they had been taught and agreed that this transferred into their mental visualisation when answering test questions. The responses on collaboration were not as strong, though still very positive. While most found the application encouraged discussion, it is clear from these results that the implementation of the framework could have provided further avenues for discussion. The application encouraged students to discuss their answer when proposed with questions, though future implementations should seek other, active means of fostering discussion to better reflect the collaborative learning aspects of the framework. The engagement and enjoyment question also received strong results, though slightly more polarised, with a larger percentage than previous categories falling outside the Strongly Agree/Agree options. This indicates that these styles of innovative learning may still face teething issues with a small percentage of students. Despite this, many students indicated their willingness to use this application both within and outside of the classroom, across various subjects. While ease of use does not directly reflect the impact of the conceptual framework, it is an important factor to consider when developing digital technologies. Despite the application being designed with common user controls as a reference frame, many students struggled with this aspect. This highlights a potential barrier with the difficulties involved when simulating three-dimensional content with a two-dimensional interface. There is room for improvement in this aspect, demonstrating that developers need to consider usability during design, potentially through student agency or positive feedback loops to improve confidence.

Table 1: Likert scale question responses

Conceptual Understanding Questions	**SA**	**A**	**N**	**D**	**SD**	**X̄**	**σ**
Using the mobile application helped deepen my understanding of the subject	52.5%	45%	0%	2.5%	0%	4.5	0.63
I did not find the using the tool was a distraction in the classroom environment and positively impacted my understanding	55%	37.5%	7.5%	0%	0%	4.5	0.63
The mobile application helped me to understand concepts presented in class a lot faster	52.5%	32.5%	12.5%	2.5%	0%	4.4	0.79
I was more confident about the course material after using this mobile application	27.5%	62.5%	7.5%	2.5%	0%	4.2	0.65
Visualisation Questions							
Viewing the visual aspects within the application helped me understand the concepts	57.5%	4%	2.5%	0%	0%	4.6	0.55
The ability to interact with the visualisations within the application helped further my understanding of the concepts	62.5%	35%	2.5%	0%	0%	4.6	0.54
Using the mobile application helped me to visualise concepts when answering questions	60%	37.5%	2.5%	0%	0%	4.6	0.54
Collaboration Questions							
The mobile application encouraged me to discuss my understanding with my peers	42.5%	37.5%	15%	5%	0%	4.2	0.86
I enjoyed using this application collaboratively with my peers	42.5%	50%	5%	0%	2.5%	4.3	0.78
Engagement/Enjoyment Questions							
I would like this application to be used in my other subjects	57.5%	27.5%	10%	5%	0%	4.4	0.86
The mobile application helped improve my engagement/interaction in the classroom	40%	50%	5%	5%	0%	4.3	0.77
I would like to use this mobile application in my own time	50%	35%	10%	5%	0%	4.3	0.84
I would like to use this mobile application during class time	57.5%	32.5%	7.5%	2.5%	0%	4.5	0.74
Ease of Use Questions							
I found it easy to interact with the visualisations (e.g changing components, rotating the view)	30%	27.5%	27.5%	12.5%	2.5%	3.7	1.1
I found it easy to find the activities for concepts I wanted to learn	35%	45%	15%	5%	0%	4.1	0.83
The tool was simple and easy to use	37.5%	45%	7.5%	10%	0%	4.1	0.92
The tool was unstable, crashed a lot and frustrating to use	12.5%	40%	35%	12.5%	0%	3.5	0.87
The tool should support more features to make it more powerful	42.5%	35%	17.5%	5%	0%	4.2	0.88

Thematic analysis

A thematic analysis was performed to extract common themes in the open-ended questions. This determines which themes were most common and identifies the strengths and weaknesses of the smartphone application in relation to the conceptual framework.

What was the best part of using this mobile application? (Question one): Themes extracted from this question, shown in Figure 3, mirror the proposed conceptual framework. 28 of the 40 participants identified the visual aspects as the best part, related to Visualisation in the framework. Interaction was also highlighted, and relates strongly to the experiential learning cycle, most specifically the Concrete Experimentation and Active Experimentation phases. Discussion, related to Collaboration in the framework, was only mentioned by two participants. Hence more focus should be placed on the collaborative aspects of the app to benefit from the improvements this offers to conceptual understanding. Participants also found the change in approach, from the standard whiteboard learning, to be beneficial, applauding the fun and easy style. The 'question and answer' mechanic was also identified as the best part, which could be utilised to develop the collaborative aspects of the application.

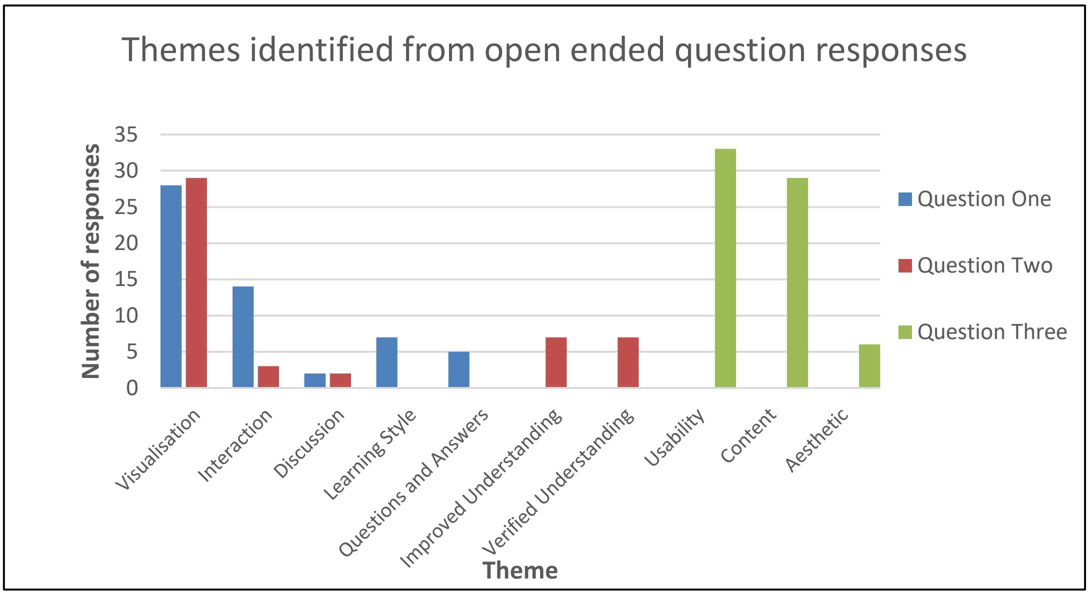


Figure 3: Themes identified from open ended question responses.

In what way, if any, do you feel the application assisted your learning? (Question two): As seen in Figure 3 the themes of Visualisation, Interaction and Discussion, were outlined again. Visualisation was again the most popular theme in the responses. Interaction was considerably lower, indicating that students do not consider it as impactful despite enjoying this aspect. Discussion remained at low response numbers for this question. The participants also identified that the application assisted their learning by both improving and verifying understanding. The verification of understanding is achieved by the application's question and answer features, as well as visualising how the simulation is altered after user input.

What improvements would you like to see in the tool? (Question three): Aesthetic appeal was the least highlighted theme, referring to the colours and designs used in the app. Content was identified as an important area for improvement with participants encouraging the addition of more content, in the form of questions and activities. Usability was the most requested improvement for the application. Navigation controls were the primary offender, despite efforts to maintain industry standards for touch control. Three dimensional simulation through a two dimensional interface will always face these challenges. This demonstrates that usability is important and must be considered to prevent distractions from conceptual learning.

Conclusions

Existing educational theory was investigated to identify an innovative approach to teaching electrical concepts. Informed by this, a conceptual framework, VCEL, for the development of educational software applications was proposed. As an extension of Experiential Learning theory, this framework redefines Kolb's original concept of practical experience to a virtual simulation based theory and incorporates Visualisation and Collaborative Learning strategies. An educational smartphone application targeting common electrical misunderstandings was developed using this framework and evaluated against a cohort of secondary school students in their penultimate year. The results demonstrated, with statistical significance, that the usage of the application had a positive impact on the students' conceptual understanding. A thematic analysis of student responses indicated the themes of the VCEL framework were recognised by students, with Visualisation having the most significant mentions. Students were mostly appreciative of this innovative approach to learning electrical concepts and showed interest in using this content both outside of the classroom and for other subject matter. This introduces future work, to utilise this framework to create more applications for electrical engineering education, among other subjects, to evaluate the consistency and flexibility of the framework.

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