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THE UNIVERSITY OF AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
NEW ZEALAND

A Social Realist Case Study of Knowledge and Pedagogy in the First Two Years of Electrical Engineering Education

William (Bill) F. Collis

NZCE, BSc, DipTchg(Sec), PGDip(Ed), ME

PhD Thesis

The University of Auckland

Faculty of Engineering

The Department of Electrical, Computer, and Software Engineering

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Abstract

Sound understanding in electrical engineering requires developing a complex set of linked abstract knowledge about invisible phenomena which are difficult to teach and learn. Often students do not gain abstract knowledge but rote-learn isolated facts instead; and rather than develop the capability to reason using abstract knowledge, they rely on knowing how to use mathematical formulae and procedure. Our modern society however is so dependent upon the abstract knowledge of science, technology, engineering and mathematics, that this is unsatisfactory.

This research involved a case study of undergraduate students' abstract knowledge development in the electrical engineering programme at the University of Auckland. To capture a full perspective of teaching and learning around knowledge of electric circuits I engaged with social realist theories about knowledge, structure, identity and agency; and then immersed myself within four courses in the first two years of electrical engineering. By observing lectures, laboratories and tutorials, and interviewing students, teachers and lecturers, I developed an understanding of the structures of electrical engineering education and their impact on the type of knowledge taught, their interaction with student agency and therefore what students learn.

I developed a quiz and a set of fundamental circuit concept tutorials to develop students' knowledge and investigate their agency. The tutorials engaged students with dynamic visualisations of electric circuits and students began to develop abstract knowledge. Most students however were unwilling to engage with the unassessed tutorials, even when presented with immediate evidence of their misunderstandings. This aspect of student agency was linked to an identity which had proven success in passing assessments through reliance on knowing how to use formulae and fragments of knowledge.

Informed by these findings, I conceptualised and developed a novel educational technology tool called GECKO (Growing Epistemic Circuit Knowledge Outcomes) along *with a framework for integrating it with the pedagogy of direct instruction. These were then used as the basis for redeveloping part of a second year course. Through engaging with visualisations GECKO is used to develop students' epistemic knowledge and capabilities with inferential reasoning. The pedagogic framework supports designing a course that integrates teaching of abstract knowledge using explanations, demonstrations and visualisation, along with a blended formative-summative assessment using GECKO. In a later project-based course, an investigation of students' abstract knowledge and inferential reasoning revealed promising results. These findings can form the basis for wider experimentation and implementation of this approach in other electrical engineering courses.*

To my wife Julie, I would be incomplete without you.
Taku toi kahurangi ‘my precious jewel’.

Acknowledgements

I would like to acknowledge Professor Gerard Rowe, my primary supervisor, for his support and knowledge of teaching and learning in the field of engineering education. His experience in the department, faculty, university, wider world of academia and giving his time to discuss these matters richly informed this work.

I would like to thank Dr Claire Donald for her critical and stimulating insights with the research and the thesis, and for her pedagogical collegiality.

The research was also supported through a joint project involving the Faculty of Engineering and the Faculty of Education and Social Work which was funded by a grant from the Vice Chancellor's Strategic Development Fund. It was through this that I came to know Professor Elizabeth Rata and Dr Graham McPhail; their insights into knowledge and Social Realist theory were pivotal in transforming the research.

Niko Uusitalo, an ex-student of mine, became my teacher and provided guidance around ASP.NET and Azure. Without this GECKO would not have developed so quickly.

This research would not have been possible without the support of the University of Auckland's doctoral scholarship programme; it provided the time and space essential for deep understandings and complex outcomes to fully develop.

I have had the privilege to get to know many academics within the department of Electrical, Computer, and Software Engineering and I would like to acknowledge their professionalism and hard work; they have been generous with their time and expertise.

Over the last 40 years in electrical engineering and secondary school education I have had the privilege of a rich set of experiences. In engineering I discovered how solutions were assessed through the eyes of end-users and in education I discovered how teaching was assessed through the eyes of students. Whāia te mātauranga hei oranga mō koutou – 'seek after learning for the sake of your wellbeing'.

Contents

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Acronyms

ALO – Abstract Learning Outcome

CPLD – Complex Programmable Logic Device

CSE – Computer Systems Engineering

ECSE – Department of Electrical, Computer, and Software Engineering

EEE - Electrical and Electronic Engineering

FPGA - Field Programmable Gate Arrays

GECKO - Growing Epistemic Circuit Knowledge Outcomes

GPA - Grade point average

GTA – Graduate teaching assistant

KCL – Kirchhoff's Current Law

KVL – Kirchhoff's Voltage Law

NCEA – National Certificate of Educational Achievement

NZQA – New Zealand Qualification Authority

SE – Software Engineering

STEM - Science, technology, engineering and mathematics

TA – Teaching assistant

VHDL - VHSIC Hardware Description Language

VHSIC -Very High Speed Integrated Circuit

Glossary

Agency – deciding and acting with purpose, but in relation to structure and culture

Craft – highly informed and competent use of techniques

Culture - our shared values and norms

Episteme - a set of related abstract propositions and models that describe the system of meaning at the core of a domain, our conceptual understanding

Know how – KH, procedural knowledge

Know that – KT, propositional knowledge

KT-propositions - ability to recall isolated or fragmented factual knowledge

KT-inferring –using epistemic knowledge to reason from factual knowledge to unknown knowledge

KH-skills – using inferential knowledge as the basis for follow through with appropriate use of rules and techniques in contextually relevant conditions

KH-techniques - following procedures and rules with little knowledge of their epistemic meaning

Modelling – describing processes in the world as inferential relationships using abstract symbols and language

Pedagogy – the domain of educational theory and pedagogical (teaching) practices

Personal identity –choosing what projects we value to put effort into

Structure –the influential nature of roles of people and institutions

Useful-content – an approach to selecting content for teaching which does not require knowledge to be linked to the episteme

Chapter 1. Introduction and background

This thesis is a case study of the teaching and learning in the first two years of electrical engineering at the University of Auckland. Using theoretical perspectives from social realism and education the study investigates types of knowledge, pedagogy, identity, structure and agency in order to expose their complex interrelationships.

This chapter presents an overview of the research and positions it within theories from social realism. The significance of the research is presented along with details of my own background. The nature of student understanding in electrical circuits is then discussed and followed by an overview of the research stages and questions.

1.1. Research overview

We are at a time in history when our societies have become increasingly dependent upon the outcomes of science, technology, engineering and mathematics (STEM) education. Engineering education programs at the forefront of STEM education are however beset by widespread issues around teaching and learning. This includes students' lack of preparation for university study, their difficulties with the conceptual knowledge involved and consequently their poor performance. More recently writers have begun to express interest in seeing student understanding (and non-understanding) as systemic, as part of complex dynamic systems (Amin, Smith, & Wiser, 2014). In order to capture as full a perspective as possible of the systemic nature of teaching and learning I engaged with the work of social realist theorists in educational sociology and those in engineering education using social realist theory. This led to an extensive case study project which provided a comprehensive analysis of knowledge and pedagogy in the first two years of electrical engineering.

This research was undertaken in the department of Electrical, Computer, and Software Engineering (ECSE) in the Faculty of Engineering at the University of Auckland in New

Zealand. The ECSE department is responsible for three of the nine specialisations in the faculty: Electrical and Electronic Engineering (EEE), Computer Systems Engineering (CSE) and Software Engineering (SE). In the first year of engineering all students take a common set of courses with the ECSE department being responsible for Electrical and Digital Systems (ElectEng101). At the end of the first year students rank five specialisations in order of preference. Grade point average (GPA) is the determining factor as to whether students get into their choice of specialisation. For several years EEE has been the least preferred choice. This has resulted in low numbers in the specialisation and consequently many students with low GPAs in EEE.

In 2015 I immersed myself within four courses. I observed lectures, laboratories, tutorials and interviewed students. In the first semester these were Electronics 1 (ElectEng210) and Fundamentals of Computer Engineering (CompSys201); in the second semester, Electrical and Digital Systems (ElectEng101) and Analogue and Digital Design (ElectEng209). Observations and interviews showed that on entry to engineering, students exhibit an exam-taker identity which prioritises learning of techniques and fragments of knowledge over gaining epistemic (linked conceptual) knowledge and the ability to reason inferentially using it. During the initial semesters of electrical engineering this did not appear to diminish but intensified for many students into a 'get-through' identity. This was often accompanied by a just-in-time approach to their work. On reaching ElectEng209, their first project-based design course, students however were observed to struggle with the challenges in the project that required inferential reasoning with epistemic knowledge rather than the fragments of knowledge and the mathematical techniques they knew. This led students to spend significant amounts of time on their project; this was interpreted by some staff as a need for an increased proficiency with mathematics, and other staff and students that the design course had too much work in it.

Research into the nature and magnitude of student agency was undertaken using a pre-course quiz and a set of fundamental circuit concept tutorials. Through engaging with dynamic visualisation of the fundamental properties of electric potential and charge flow in electric circuits many students indicated significant advances in their epistemic knowledge. The majority of students however were unwilling to engage in unassessed work even when presented with immediate evidence of their misunderstandings. Students related that their identity and agency were tied to the structures and discourses of teaching and learning in secondary schools and the courses within the first two years of electrical engineering which had a teaching and summative assessment focus on fragments of useful knowledge and mathematical techniques.

Informed by these findings and educational theories, I conceptualised and developed an educational technology tool called GECKO (Growing Epistemic Circuit Knowledge Outcomes), along with a framework for integrating it within teaching and learning. GECKO was theorised to work at the intersection of students' epistemic knowledge and inferential capability, student agency, and the structures of teaching and learning. The framework was developed to centre teaching on abstract knowledge through academic abstract learning outcomes. The framework places the disciplinary knowledge expert within the pedagogical practice of direct instruction, engaging students with epistemic circuit knowledge through practical demonstrations, visualisation in GECKO and explanations of relationships between knowledge to meaningfully demonstrate abstract principles in contexts of use. Tangible success criteria and practice are an essential part of developing capability with inferential reasoning with knowledge and the framework engages students with these via a mixed formative-summative assignment. GECKO and the framework were then used as the basis for redevelopment of part of a second year course in microcontroller-based embedded systems. The results from using GECKO and the pedagogic framework within a course show promise for the integration of a knowledge-based tool and knowledge-based educative practice for developing student inferential capabilities with epistemic knowledge.

1.2. Positioning the research

This case study is centred on a social realist view of knowledge, where knowledge is created by humans to express the nature of the world. While created, it is not a personal or subjective view but a contestable view which is critically judged from empirical evidence. It is real or objective in that it does not depend upon those who created or now hold it; at the same time it is 'best-fit' or fallible because a better understanding may be developed in the future (Young, 2010). For instance, in the domain of electrical engineering, the concepts of electric charge and electric potential are objective. This means these concepts are independent of those who study and use them; they are socially produced ideas in that they have been collectively agreed upon as fit for purpose for how we need to use them. Karl Maton (2013, 2014b) states that much current pedagogy does not take this disciplined objective nature of knowledge into account suffering from what he terms 'knowledge-blindness', where knowledge is reduced to the subjective processes of learners (Georgiou, 2016) and their interactions within social contexts. This social perspective of knowledge is not just applied to the target of the research but to the research itself, in order to identify the real aspects of knowledge and pedagogy operating in the first two years of electrical engineering.

A social realist perspective captures how domain knowledge is recontextualised (Bernstein, 1999) - selected and organised into curriculum - by exploring the nature of the knowledge within the discipline and the pedagogical discourse of those involved in the process of recontextualisation and delivery. Social realism also expresses how students need to acquire an appropriate 'gaze' or way of seeing and being within the subject (Bernstein, 2000). This happens through the complex interactions between students and educators, their identities, and agency within the structures and culture of a situation (Archer, 1995, 2002).

While social realist research in education is a developing field, it has been used to describe and explain the nature of knowledge and complex teaching and learning in a number of areas. These include: physics education (Georgiou, 2016), educational technology (Howard & Maton, 2011) and engineering education (Case, 2013; Winberg, Winberg, Jacobs, Garraway, & Engel-Hills, 2016; Wolff, 2017).

1.3. Introducing myself

I have been interested in electronics since the age of 12 when I began tinkering with circuits in my father's shed. I went on to spend 23 years in a variety of electronic and radio communications technical and business roles before transitioning to teaching electronics as part of the New Zealand Technology Curriculum. I taught at a High School for 14 years, developing a teaching programme for students that integrated theory and practice using project-based learning, where students develop microcontroller-based projects aligned to real issues. The window cleaning robot project in Figure 1 was one of these. Within the field of education my roles have involved educating teachers, as well as working with assessment and curriculum at national levels.

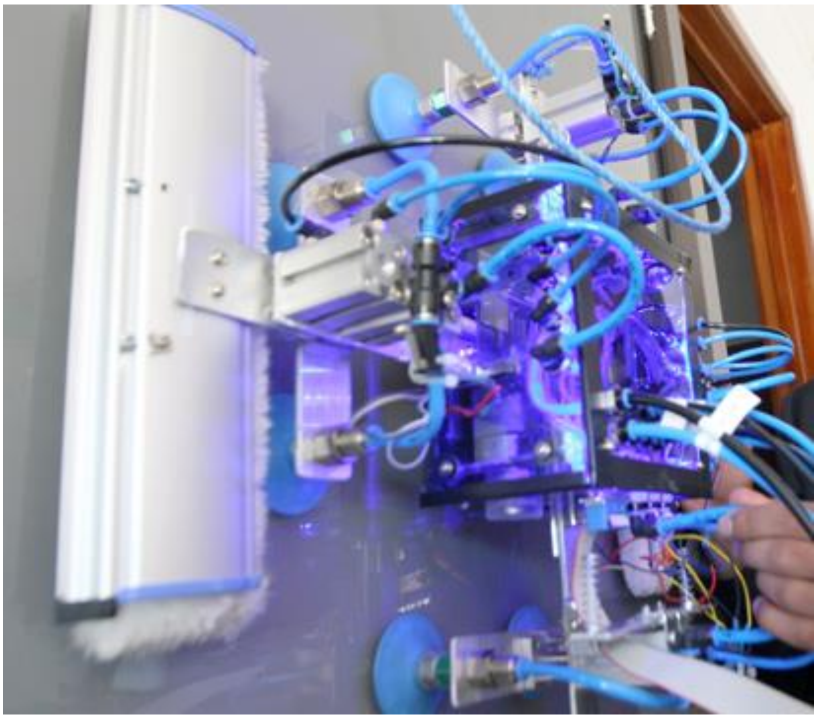


Figure 1: Window cleaning robot, student project, 2013 -www.youtube.com/watch?v=HFI4p4jiMP4

Whilst the discourse around social realist research was new to me, as I began this research it became clear that some of the ideas that it expressed theoretically were already part of my development as a teacher. For example in the early stages of my teaching I realised it was not just the electronics that was hard but there were underlying issues that hindered students doing well in this subject. I realised students were risk averse and consequently lacked confidence in decision making, and that they were primarily focussed on grades and not understanding. I had also engaged with the objective nature of knowledge when I identified the limitations of social constructivist practices which underpinned the New Zealand Technology Curriculum. I implemented a body of knowledge for student work and later when the curriculum changed, became part of the writing team for the body of knowledge for Electronics in Technology Education in NZ schools. Social realism provided not just theory about what I had come to understand from my own practice, but built a clarity about the underlying nature of knowledge, pedagogy and learning.

I have found that this research has enriched my practice as an educator through further engagement with theory. I had previously recognised synergies between the dual identities I had as engineer and an educator, however this research brought new perspectives about the relationship between theory and professional practice. It helped me conceptualise how both education and engineering are professional domains of knowledge in their own right, each being underpinned by a rich body of theory and practice. It is theory which underpins the professionalism necessary to engage with significant problems in both contexts.

1.4. Significance of the research

The extent of student misunderstandings in electrical circuits is well-documented and remains problematic. Using a social realist perspective within case study research I develop a systemic view of the nature of teaching and learning not yet found in electrical engineering education literature. This required synthesizing understandings about: knowledge; student and educators' knowledge practices; educational theory;

educators' pedagogical backgrounds; the identities and agency of students and educators; and the structures and culture operating within the situation.

As well as contributing to research in electrical engineering education, a second contribution is that this research provides an example for those wishing to develop social realist educational research in their domain. GECKO, the new educational technology tool, its innovative approach to engaging students with the hidden epistemic aspects of circuits via visualisations, and the pedagogical framework developed for its use, are another output of this research. The fourth output is the results from integrating GECKO and the pedagogic framework within the systemic constraints of tertiary pedagogy.

1.5. The nature of teaching and learning in electric circuits

There is a significant body of literature in physics and engineering education research that describes how many students fail to gain adequate knowledge about electric circuit theory. This literature reveals a phenomenon that stretches from when students complete secondary schooling (Psillos, 1998) through their tertiary education and even into industry (Carnes & Streveler, 2011). This ongoing concern is something that continues to trouble educators making it a vital area for ongoing research.

1.5.1. The episteme of electric circuits

Electrical engineering students require knowledge of a complex set of scientific principles about electric circuits. These involve knowledge about the atomic level of matter and how energy transformation relates to this. Students need to understand component properties such as resistance, capacitance and inductance and how energy and charge interact with them. They need to know about topology, which describes the pattern of electrical connections of components and that when electric potential is applied to circuits with different topologies different charge flow effects take place. Students also need to understand the abstractions of electric circuits into various models (via symbols, schematics and mathematical models) and importantly how these models describe the interrelationships between aspects of energy, component properties and topology. These in turn are not separate understandings but need to come together in an episteme - a set of abstract propositions with intertwined relationships that exist as a cohesive system of meaning (Rata, 2017). While formal study of electric circuits begins at secondary school level, some students will have been introduced to practical circuits much earlier at home or in pre-secondary school education. Literature describes that while students are familiar with the language of electric circuits, such as: energy, voltage, current, electricity and power, these terms seldom exist epistemically.

1.5.2. Naïve misconceptions

A number of studies have identified a crucial aspect of understanding in electric circuits, the everyday use of scientific terms such as voltage, current, energy and power. This leads to having a naïve framework of physics knowledge (Vosniadou, 1994). The inability to observe force and energy significantly contributes to these issues (Streveler, Litzinger, Miller, & Steif, 2008). Learners bring these naïve misconceptions into formal physics education at secondary school, leaving them unable to distinguish between the characteristics of these core properties, readily interchanging the properties of voltage, current, power and electricity in their language (Duit & Treagust, 2012). The familiarity of students with these terms leads to an unspoken assumption that students intuitively know them when in fact their epistemic knowledge is limited (Jilek, 2010). Many researchers have developed non-calculation type questions in 'concept inventories' to explore these phenomena (Chang, Liu, & Chen, 1998; Engelhardt & Beichner, 2003; Holton & Verma, 2010; O'Dwyer, 2013; Ogunfunmi & Rahman, 2010; Sangam & Jesiek, 2012; Simoni, Herniter, & Ferguson, 2004; Smaill, Rowe, Godfrey, & Paton, 2012).

1.5.3. Energy

Energy is the central theme in electric circuits, as they exist to manipulate energy. Energy however is a concept that is regularly confused and applied inaccurately, even by science educators (Amin, 2009). Because energy is described using words such as transfer, convert and store, students use these words literally rather than metaphorically, often believing that energy is a physical substance (Lancor, 2015) and treat it as an ingredient in circuits (Watts, 1983). One challenging aspect of this conflation with matter is it leaves students unable to account for the different energy and current directions in various parts of a circuit (Duit & Treagust, 2012).

1.5.4. Voltage

> *Voltage! It's got to be the most significant learning challenge for student understanding (Physics teacher, 2015).*

While voltage is the primary concept in a circuit and causes electric current (Liégeois & Mullet, 2002), students regularly think of it as a property of or caused by current (Gunstone, Mulhall, McKittrick, & Case, 2001; Hussain, Latiff, & Yahaya, 2012; Psillos, 1998; Timmermann & Kautz, 2014). One reason for this is that current as a concept is generally taught first in any teaching sequence, because it is conceptually easier to grasp as it can be attributed to some properties of matter (Liégeois & Mullet, 2002). Consequently students do not realise that voltage can exist between disconnected points of a circuit (Cohen, Eylon, & Ganiel, 1983), and perceive that when there is no current there is neither voltage nor resistance (Hussain et al., 2012). Voltage however is often represented by teachers as both cause and effect in a circuit (Gunstone et al., 2001), such as when a teacher includes statements such as 'current causes a potential drop'.

Significant confusion centres around the terms describing the phenomena of energy in an electric circuit: voltage, electromotive force, potential difference, electric potential, electric tension and voltage drop (Sangam, Jesiek, & Thompson, 2011; Timmermann &

Kautz, 2014). These confusions relate to poor definitions of the terms and a failure to see them as the same concept. This is linked to the idea that students cannot physically see energy levels but must interpret them from their effects (Chi, 2005; Gunstone et al., 2001; Reiner, Slotta, Chi, & Resnick, 2000; Streveler et al., 2008). As a consequence these terms become independent fragments of knowledge for students to remember rather than connected (Timmermann & Kautz, 2014) and epistemic.

1.5.5. Current

While students appear to readily grasp current as a concept, as it is most easily likened to matter (Liégeois & Mullet, 2002; Reiner et al., 2000), they attribute matter-like properties to it which are seldom correct. They think of it as resting in wires and flowing from both connections of a battery into a circuit and clashing in the middle (Duit & von Rhoneck, 1998; Osborne, 1983). It is thought of as weakened (Chang et al., 1998), lost (Liégeois & Mullet, 2002), used up or consumed (Holton & Verma, 2010; Zacharia & de Jong, 2014), or a fixed constant in a series circuit (Gunstone et al., 2001). Electric current also has the historical complication of being both conventional and electron based so students confuse its direction (Sharma, 2014).

The term 'current flow' is used commonly in education; however this is confusing for learners as a 'current' is the flow of something. In electric circuits current is the flow of electric charge, so use of the inaccurate term 'current flow' continues to only promote inaccurate mental models (Sangam et al., 2011). Current is often thought of as being caused by electric fields inside wires; in contrast to electrostatics where electric fields are not to be found in conductors but around them (Engelhardt, 1997). Alternating current (AC) is a confusing idea for students as they carry confusions about direct current (DC) into the AC realm, sometimes ignoring the negative part of the AC cycle, or think of charge as distributed spatially along a wire rather than its correct nature which is a function of time (Holton, Verma, & Biswas, 2008).

1.5.6. The components of electric circuits

Some research has been targeted specifically at learners' understandings of core components of circuits. With resistors, students seldom distinguish the relationship between electric potential and resistance or between current and resistance. They apply a power-like property to resistance seeing it as a function of voltage and current or only having a relationship with either voltage or current depending upon which is greater (Liégeois & Mullet, 2002; Psillos, 1998). Capacitors and inductors are commonly confused and how they store energy is seldom understood, particularly their time-varying properties (Holton et al., 2008). Batteries are seen as reservoirs of electric current (Chang et al., 1998) because of their shape (Reiner et al., 2000) and as sources of constant current and not voltage (Engelhardt & Beichner, 2003). While batteries supply energy; charge or charges are primarily described as the carriers of that energy (Sangam & Jesiek, 2012).

1.5.7. Circuit topology

While each component has characteristics, it is topology - the electrical connections of a circuit - that gives an individual component a purpose that it does not have on its own. Figure 2 shows symbols for several components, and Figure 3 shows the electrical connection of these components. These connections are called topology and reveal the purpose of the circuit to those literate in circuit theory (in this case an under temperature indicator).

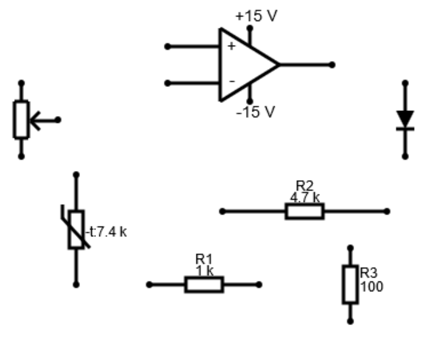


Figure 2: Symbols for some electronic components

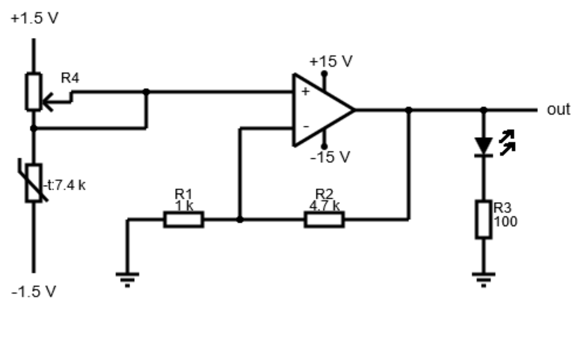


Figure 3: Schematic (circuit diagram)

It is through studying circuit theory that a circuit's function is understood and how each component's contribution to that function is analysed. Topology involves a number of concepts such as open, closed (connected) and short circuits; series and parallel connections, and the subsequent application of foundational circuit laws, such as: Kirchhoff's voltage and current laws (KVL and KCL), and Ohm's law, that express the relationships between electric potential and charge flow.

Research has shown that most high school students seldom present correct ideas about circuit operation within open or short circuit conditions (Liégeois & Mullet, 2002). Further research into university students revealed how they only applied circuit changes such as short or open connection after the change and did not perceive their effect on the full circuit (Carstensen & Bernhard, 2009; Smaill et al., 2012). Topological misconceptions also relate to understanding of series and parallel connections. These are often applied correctly with effective resistance for circuit fragments; however in simple, but complete circuits, students regularly confuse their effect. For instance in both series and parallel combinations more bulbs means more brightness (Engelhardt & Beichner, 2003). Students also struggle significantly when working with combined series and parallel circuit components (Kautz, 2007; Smaill et al., 2012).

Misconceptions about topology can relate to sequential reasoning about circuits (Cohen et al., 1983; Smaill et al., 2012), and seeing a circuit as discrete parts rather than functioning as a complete whole (Liégeois & Mullet, 2002). This leads students to believe that current will divide equally between paths at a junction (Borg Marks, 2012; Duit, Niedderer, Schecker, & Ho, 2007; Engelhardt & Beichner, 2003; Kautz, 2007; Reiner et al., 2000) without any regard to the surrounding circuit. When students miss the multiple factors of influence in a circuit and fail to make links between topology and circuit properties they reveal a significant gap in their conceptual understanding (Chang et al., 1998). Understandings of topology also relate to the issues students have with mapping a two dimensional circuit diagram to a physical circuit (Mazzolini, Edwards, O'Donoghue, & Nopparatjamjomras, 2010; Scott, Harlow, Peter, & Cowie, 2010; Shaffer & McDermott, 1992b).

1.5.8. The interrelationships of circuit components, topology and properties

The concept map for electric circuits in Figure 4 (Sangam, 2013; Sangam & Jesiek, 2015) was developed for research into conceptual analysis of circuit theory textbooks. It was useful for this research because it demonstrates an important complexity of the understandings that students need to develop.

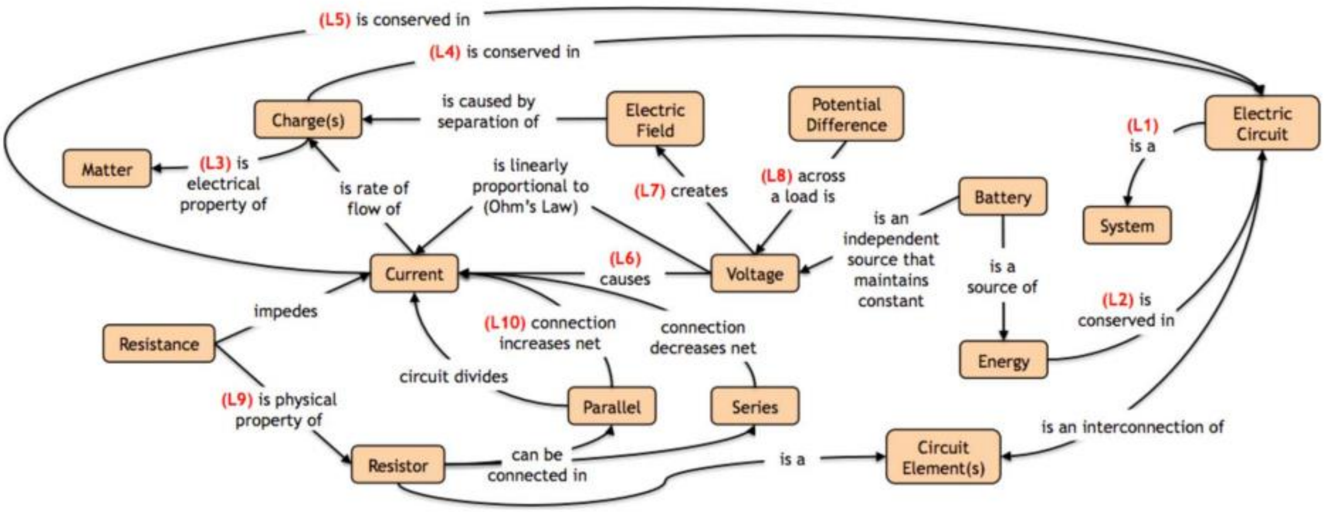


Figure 4: Desired conceptual framework for electric circuit theory.

Reprinted from "Conceptual Gaps in Circuits Textbooks: A Comparative Study" by B. Sangam, B.K. Jesiek, 2015, IEEE Transactions on Education. Volume(58), 197. Copyright 2015 by IEEE.

This complexity is not just the number of elements and number of connections involved; it is at a deeper level. The diagram expresses the interrelationships between different categories or types of items: energy (which is an abstract idea), charge (invisible atomic matter), physical components, and the way they are electrically connected (topology). The diagram expresses the very complex epistemic knowledge about how electric potential can have different effects on charge in a component depending upon the topology.

1.5.9. Analogies

Analogies are common pedagogic scaffolds used to assist learners develop knowledge. Inaccurate understandings however can be caused when analogies of known objects are used to describe the unobservable properties of voltage, current, power and resistance as they cannot fully express the complex relationships exposed in the prior section. Analogies such as water pressure for voltage or queues of people for current, produce unintended effects because teachers (and therefore learners) do not constrain their meaning to the targeted content (Jaakkola, Nurmi, & Veermans, 2011). Due to the propensity of electric water analogies used in teaching many students see electric current as a kind of 'juice' that flows through a wire (Slotta, Chi, & Joram, 1995). This comes about because the learner does not know where or how to differentiate the metaphor from the content (Rankhumise & Imenda, 2014). The use of water for instance as an analogy has been questioned for quite some time due to students' insufficient knowledge of hydrostatics (Mitten, 1937). Unfortunately physics is notorious for false analogies (Laurillard, 2002) and there seems to be a lack of consensus for suitable physics analogies (Mulhall, McKittrick, & Gunstone, 2001). One significant issue relating to analogies is that students often remember the analogy but not the object (Coll, Taylor, & France, 2005; Ugur, Dilber, Senpolat, & Duzgun, 2012).

1.5.10. Mathematical models

Each of the interrelationships in Figure 4 can be expressed using mathematical models. Formulae used in electric circuits include Ohm's law, the conservation of charge in Kirchhoff's Current law and the conservation of energy as expressed by Kirchhoff's Voltage law, Faraday's law of induction, E=QV, formulae used for series and parallel calculations, power formulae (true, reactive and apparent), and formulae for calculating reactance and impedance. The complex interrelationships are so well expressed by these formulae that the nature of the properties and components involved can be reduced to simple variable names. Symbols such as V, I, R, P, X, C, L etc. however can become the focus of rote learning rather than the properties and interrelationships they represent. When this occurs students avoid understanding and resort to the easier path of rote learning, remembering formulae and calculating values (Gunstone et al., 2001).

1.5.11. The widespread nature of circuit misunderstandings

In light of the difficulties with electric circuit theory it is not surprising that many students never expect to make sense of the physics of electricity (Brown & Hammer, 2008) and consequently avoid electrical engineering. Nor is it surprising that studies show that engineering students struggle in electrical engineering courses (Carnes & Streveler, 2011; Cohen et al., 1983; Coppens & De Cock, 2013; Finkelstein, 2005; Sangam & Jesiek, 2012; Stetzer, Papanikolaou, & Smith, 2015). Some students at the end of their electrical engineering degrees were found to be hiding their misconceptions behind a well-rehearsed technical vocabulary (Goris & Dyrenfurth, 2013) or an ability to find the right equation for the numbers they have (Carnes & Streveler, 2011). Nor do all physics teachers or engineers fully comprehend these difficult concepts (Cohen et al., 1983) and when teaching them they sometimes create more serious conceptual problems than existed prior to their instruction (Duit & von Rhoneck, 1998).

1.5.12. Research into student misunderstandings

Amin, Smith and Wiser (2014) describe three periods of research into conceptual understanding. The first involves the identification of domain specific misconceptions which contrasted with prior developmental views of student understanding. The second period builds on the first with its focus of research encompassing conceptual change. This involved developing processes for repairing misconceptions such as reclassification of concepts into correct ontological categories (Chi, 2005, 2008, 2013) or the realignment of fundamental cognitive structures known as phenomenological primitives (diSessa, 1988, 1993). This period includes the critical role of mental models in conceptual change (Jonassen & Easter, 2013; Vosniadou, 1994) and the role of social processes in teaching and learning (Scott, Asoko, & Leach, 2007). The third is a period of exploratory research into conceptual difficulties which takes a systemic view of concepts and conceptual change. This investigates how multiple conceptual elements including mental-imagery, abstract propositions, language and symbols interact with each other, and of significance to this research, how they must be addressed all at once through our pedagogy.

1.5.13. Summary of research about understanding in electric circuits

In summary, misunderstandings about electric circuits are widespread and challenging to resolve. Properties of electric circuits that relate to energy, especially electric potential, are seldom understood. Charge, charge flow (current) and how components influence charge are not understood. The models, particularly the formulae that are used to explain and engineer with, have become surrogates for real knowledge. The links that tie concepts together in electric circuits are troublesome and require transformation of the student to take place for understanding to happen; and a rich body of work exists in identifying and analysing these issues.

The fact that many students have inaccurate knowledge about circuit theory leaves us with significant questions. One of which intrigued me: How is it that many students pass our courses when what they know is so flawed? While the findings from research inform us about specific problems with knowledge, a sole focus on misconceptions is insufficient to answer this question and how we might effectively address students' knowledge issues.

1.6. Research questions and stages

Knowing the limited state of students' knowledge about electric circuits was a starting point for this case study and the following research questions:

- RQ1: What is the real nature of the learning problem?

- RQ2: Can an increased focus on epistemic knowledge help students in first year electrical engineering?
- RQ3: How can theory and understanding of the situation inform the development of a novel knowledge-based educational technology tool?
- RQ4: What is the effect of an integrated approach to pedagogy and educational technology on student knowledge?

The research was conducted in stages. The first stage of observations and interviews was planned at the outset, with subsequent stages developing as a result of the findings. Chapters one, two and three explain the preparatory stages of the research. Chapter one involved developing knowledge of research literature covering the range of difficulties students have in understanding of electric circuits and positioned the research as social realist.

Chapter two addresses theoretical perspectives. This large body of work explores several theories necessary for a comprehensive understanding of teaching and learning. It is broken into five sections: a discussion of knowledge and ways-of-knowing; social realist theories and frameworks about identity, agency, structure, culture and change; the philosophical bases of various educational theories; a heuristic-based approach to selecting pedagogical practices; and perspectives on educational technology development and use.

Chapter three discusses the methodology, positioning the research using social realist theory and case study design. Research methods are described along with explanations of the qualitative and quantitative methods chosen for the data, and the ways in which they were collected and analysed. This includes a discussion of the credibility and dependability of case study research.

Chapter four concerns the first question: 'What is the real nature of the learning problem?' This was aimed at unpacking the nature of student knowledge in the first 2 years of electrical engineering and their influencers using a social realist perspective.

This is a two level investigation aimed at determining the ‘real’ or hidden that lies beneath the ‘actual’ or observable in a situation. At the level of the ‘actual’, students were found to approach knowledge as applying mathematical techniques and remembering fragments of knowledge. At the level of the ‘real’, qualitative observational techniques and thematic analysis identified how the identities of students and educators, and the structures and culture of the situation worked to influence students’ and educators’ agency – what they decide to focus their efforts on.

Chapter five addresses the second question: ‘Can an increased focus on epistemic knowledge help students in first year electrical engineering?’ This stage of the case study evolved out of the understandings gained about issues with knowledge in circuit theory and the nature of the teaching and learning. A short conceptual quiz and a set of fundamental circuit concept tutorials (FCCTs) were developed for students. Two levels of aims were developed for this stage of the research. The first aim was focussed on student conceptual understandings or epistemic knowledge. The quiz was to support students’ self-identification of problems with their understanding and the tutorials were to provide a resource to help conceptual understanding via engagement with visualisations of the hidden properties of electric potential and charge flow in electric circuits. The second aim was to identify whether conceptual work could have an effect within the structures and culture of the situation. This involved developing a fuller perspective on the agency of the students and the influence of structure and culture on their agency.

Chapter six covers the third research question: How can theory and understanding of the situation inform the development of a novel knowledge-based educational technology tool? This question centred tool development on working at the interface of knowledge, agency and the situation. This integrated a range of understandings, including: the specific conceptual issues with electric circuit theory from chapter one, how students engaged with these difficult concepts in the quiz and FCCTs in chapter five, the theoretical lenses on knowledge, educational theory, pedagogical practice and educational technology from chapter two and insights about identity, structure and agency in chapter four. This led to the development of a novel educational technology tool, GECKO, and a pedagogic framework that integrated GECKO with pedagogical practice. While theoretical lenses and the nature of student agency informed the development of this framework, it was the structure and culture of teaching and learning in the situation that made it essential to formalise a best-practice approach to design pedagogy to facilitate understanding.

Chapter 7 covers the fourth and last research question: What is the effect of an integrated approach to pedagogy and educational technology on student knowledge? The use of the quiz and tutorials in chapter five revealed that student agency was centred on a narrow subset of knowledge. This was reinforced by a robust structure and culture that reduced the efficacy of epistemic knowledge in the FCCTs and informed understandings about the nature of making change in the situation. To understand how change to student identity and agency could take place within the culture and structure of the situation the pedagogic framework and GECKO were used to redevelop a unit of teaching on microcontroller-based embedded systems within a second year electrical engineering course. The results indicate a positive impact on student understanding, identity and agency and that change within the situation is required and viable.

Chapter 8 reviews and summarises the outcomes of the four research questions in the case study. This includes how social realism can develop a more refined perspective about the nature of knowledge, and how this perspective can positively influence student engagement with understanding. It also presents limitations of the research and avenues for future research.

Chapter 2. **Theoretical frameworks**

This chapter explores a range of theoretical frameworks that are used throughout the research for both analysis and design purposes. This large body of theory is separated into five sections, each developing a critical lens applicable to this research. Section 2.2 covers knowledge theory. It develops a lens for identifying the various types of knowledge that exist. Section 2.3 introduces social realist theory. This developed the lens needed to critically analyse the knowledge encountered in the situation in terms of development of students' abstract knowledge. Section 2.4 and 2.5 focuses on educational theory and pedagogical practice. Together these sections develop pedagogical lenses to analyse the educative knowledge practices encountered and inform the selection of appropriate practises to develop abstract knowledge. Section 2.6 briefly looks at educational technology and aspects of un/successful use of computer based technology in education. This develops a lens that informed both the development and use of educational technologies that expose students to abstract knowledge.

2.1. Introduction to pedagogy and knowledge

> *It is, of course, possible that one can learn without being taught. Could it not be the case that all learning could take place without teaching? (Winch, 2017, p. 5)*

In this question Winch is not stating his view on teaching and learning; he is encouraging us to engage deeply in the nature of the relationship between them. There are a broad range of views about this relationship. One extreme view is that learning does not require teaching but can be achieved from personal experience and inquiry. Another view uncovered by researchers is that of 'folk pedagogy', where education is founded in personal judgements of valid ways to teach (Booth, 2001; Godfrey, 2014; Torff, 2000; Wankat, Felder, Smith, & Oreovicz, 2002). A further approach to the relationship is to see teaching as a form of craft. Indeed, I was approached by a lecturer who suggested that in engineering there is a need for a ‘recipe’ book’ for teaching. The error of viewing a profession as a craft is expressed by Christoph Niemann (a graphic designer) in the Netflix documentary series ‘Abstract’ (Dadich, 2017). Niemann describes craft as:

> *Like creating a process that allows you to do un-embarrassing stuff on command. It’s like it’s the only way you can do stuff to survive, if you create an armour of craft around you. The one thing that is dangerous about focussing on craft and working very hard is that it can keep you from asking the really relevant questions. ‘I‘m trying to get good at something, what is that thing that I am trying to get good at - the real thing.’*

It is important to engage with education as a profession underpinned by theory and not by anecdote or craft. Theory has increasingly become devalued in teacher education (Orchard & Winch, 2015) and is something regularly missing from engineering education literature (Radcliffe & Jolly, 2003). Without theory engineering educators default philosophical positions are generally positivist, due to engineering being rooted in scientific tradition (Radcliffe & Jolly, 2003). Knowledge in engineering is hierarchical with strong dependencies. In contrast Education is a social science that has a horizontal structure (Bernstein, 2000), where educational theories exist which do not necessarily need to be in relationship with each other, and can even exist in competition with each other (Maton, 2000). For educators in science and engineering this can be a striking and somewhat confusing difference, one which is difficult to come to terms with because of the mind-set created by hierarchically structured scientific knowledge. For engineering educators educational theory seems to have fewer certainties than what might be expected from such a well-established field of research, leading to that

> *nagging feeling that improving teaching and learning might in some odd way be more complex than designing an aeroplane (Case, 2008, p. 2).*

In engineering education, teaching and learning encompasses a broad field, from the academic abstract through to fully detailed and ready to use real-world application

(Case, 2014). It is through application of theory that pedagogical practice develops which gives engineering students access to the breadth of understandings they need (Van Heuvelen, 1991). Theory underpins what we do, by informing us about why we do it.

2.2. Knowledge and ways-of-knowing

A striking issue with the knowledge that students possess in electrical engineering (described in section 1.5) is that students can accurately calculate electric circuit properties yet fail to understand what this means in terms of the circuit's operation. Students have little appreciation of how the mathematics they carry out models or represents the physical world. To reveal what it is that students both know and do not know, a clarification is required about knowledge. The discussion in this section is centred on types of knowledge and the ways an individual comes to hold this knowledge to develop a framework I have called the "ways-of-knowing".

In cognitive psychology the term complex knowledge is used to describe the body of knowledge someone holds about a domain; it has two primary aspects. Know-that (KT) or propositional knowledge, and know-how (KH) or procedural knowledge (Adams, 2009; Anderson, 1995; De Jong & Ferguson-Hessler, 1996; Kellogg, 2011; Winch, 2013b, 2014).

KT or propositional knowledge involves facts, propositions, concepts, principles, schemas, and theories. It involves students progressing from acquisition of isolated facts and propositions to possession of the ability to make inferences and reason using the propositions, concepts and principles within a domain; all with increasing measures of understanding and capability (Winch, 2013a, 2014). KH or procedural knowledge is different; it is practical knowledge and involves learning of techniques, the development of skill, transversal abilities (competencies) and project management abilities (extended competencies) (Winch, 2014). It is often thought of in terms of specific actions for example riding a bicycle or solving a mathematical problem (Chi & Ohlsson, 2005; Ohlsson, 2012).

Winch (2013a) describes a third type of knowledge, knowledge by acquaintance (KA). KA is different, it is not procedural and also lacks the propositions of KT; it is collected through our senses and serves to enrich our understandings about a subject (Winch, 2013a).

These are not three separate types of knowledge as there are complex interactions between them. For this research I developed the diagram in Figure 5 called the ways-of-knowing framework to depict the important relationships described in literature between KT, KH and KA.

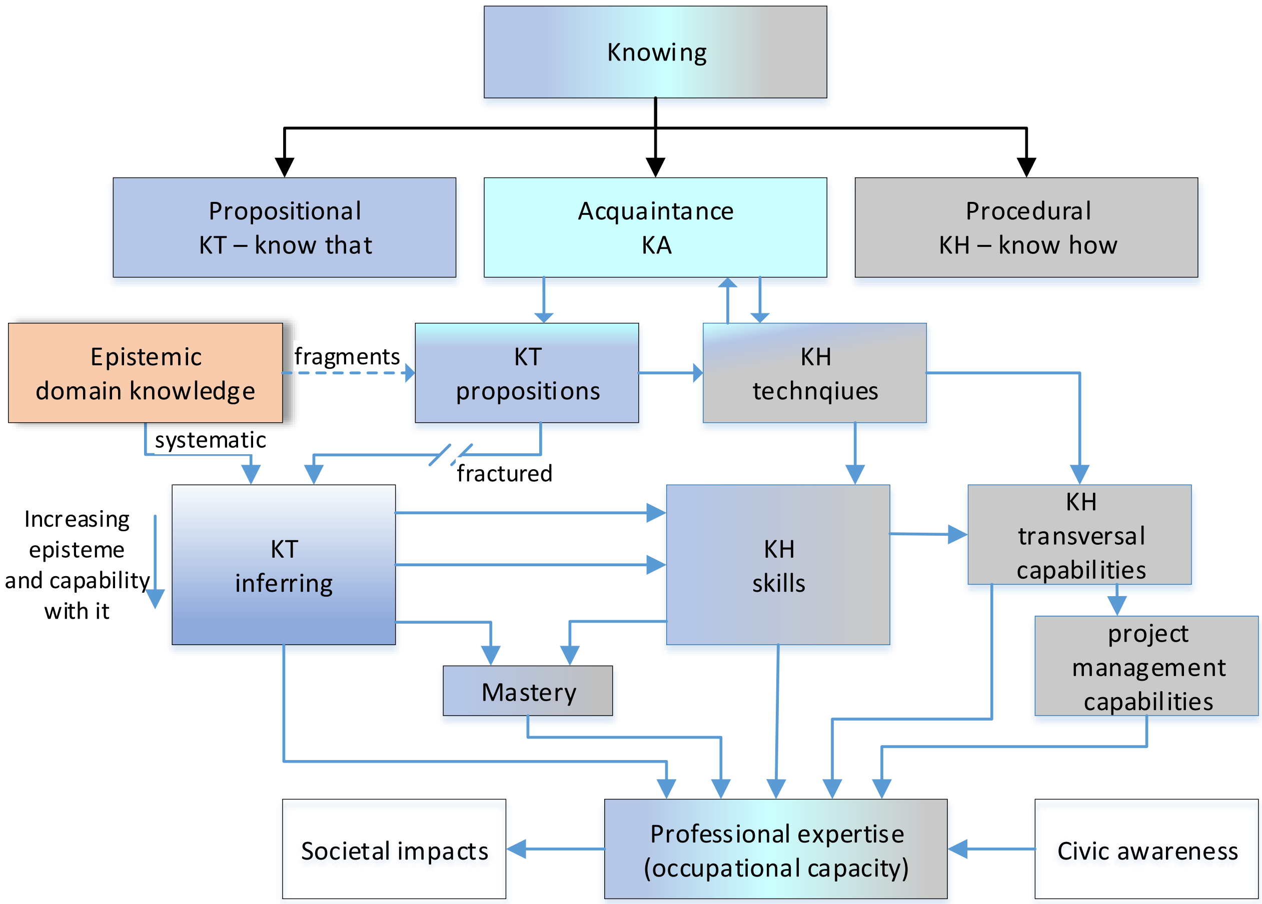


Figure 5: The ways-of-knowing framework

2.2.1. Know-That (KT)

Know-that refers to propositional knowledge. Outside the mind, KT refers to a body of knowledge that has been established by disciplinary researchers, this is referred to as epistemic domain knowledge (Figure 5). The term epistemic is used to reflect the systematic and conceptual structure of the knowledge which makes it coherent and therefore useful by those in the domain (Winch, 2013a). Within the mind, KT refers to knowledge which is integrated and structured as an episteme. This is the term used to describe our knowledge when it accurately reflects the external domain and exists within a 'system of meaning' (Rata, 2017). In cognitive psychology conceptual understanding is the term used to describe the evolving or provisional nature of the hierarchies, networks or schemas of understandings that we develop as we learn (Kalyuga, 2010). Having organised and linked propositions (an episteme) is described as having conceptual understanding, if it aligns with external epistemic domain knowledge (Winch, 2014). Ausubel (2000), an educational psychologist, describes knowledge in a related way. External knowledge is the basis for developing 'advance organisers' which reflect the ideas of the discipline, and meaningful understanding comes from logical connectedness of new knowledge. The term episteme rather than conceptual understanding is preferred for this research to clearly expose the idea that disciplinary researchers create the coherent propositions and the structural relationships between them; and that student knowledge should shadow that of the expert to have meaning within the domain.

As an example, electrical engineering draws from the domain of physics which is a discipline where the epistemic knowledge is hierarchical. The electrical engineer needs core physics knowledge of electric charge and electric potential energy. Above these are knowledge of passive components (resistors, capacitors and inductors) and topology (open, closed, short, series and parallel), and how each influences behaviour of electric potential and electric charge. Going up the hierarchy from the electric circuit, the domain moves clearly to electrical engineering where there are complex active components and systems. Each level in the hierarchy encapsulates and builds upon knowledge below it. A curriculum needs to sequence this hierarchical knowledge so that learners' understandings become coherent (Muller, 2009). Meaning within electrical engineering is lost when the propositions that students develop do not adhere to those of the domain.

Having a shallow level of KT reflects the collecting of single propositions or facts without relating them together (Winch, 2013a). In this research the term used to describe this is KT-propositions. This term recognises these as true facts but distinguishes them from epistemic understandings which are relationally linked. Students develop KT-propositions through rote learning of isolated facts. DiSessa (1988) describes this understanding as knowledge-in-pieces and the fragments as phenomenological primitives. There is potential for these fragments of knowledge to remain as the student's only form of understanding. This is concerning, as it leaves the knower unable to use these to make inferences or carry out reasoning (Winch, 2013a), described in this research as a fractured episteme.

The deeper level of KT is this ability to make inferences using propositions; this requires the propositions to be linked cohesively and correctly i.e. as epistemic. In this research this is referred to as KT-inferring (see Figure 5). The capability for KT-inferring cannot come from fractured understandings as it requires having a necessary level of epistemic knowledge (Winch, 2013a). The requirement to work in a knowledge domain determines the level of episteme students need; there must be a level of understanding commensurate to the work undertaken. For example there are concepts in quantum mechanics that are more complete than the explanations needed (or held) by most electrical engineers, consequently these do not need to be a part of their episteme. There are however concepts in their episteme that electrical engineers cannot do without, e.g. electric potential, charge flow, power, energy, topology, resistance, inductance, capacitance, amplification, feedback and so on. These must exist and be linked correctly for KT-inferring to take place.

KT-inferring was chosen as the term for the research to stress that knowing is more than possessing knowledge, even linked epistemic knowledge, but is also a developing capability to make inferential use of the episteme. The three ideas of episteme (structured propositional domain knowledge), KT-propositions (fractured or isolated domain knowledge) and KT-inferring (ability to reason or make inferences using knowledge) are pivotal and used throughout this case study. Expressed succinctly the development of an episteme rather than KT-propositions is crucial for learners as only through an episteme can KT-inferring develop.

When researchers discuss conceptual understanding of electric circuits, their ideas can also be expressed using these three terms. Jonassen (2006), describes conceptual understanding (the episteme) as the vehicle for testing relations (KT-inferring). Brown and Hammer (2008) describe conceptual understanding as making communication with others in the domain possible - this is because it reflects the episteme of domain experts and researchers. Gilbert & Vick (2004) describe conceptual understanding as providing the ability to ask meaningful questions, i.e. it does not exist as isolated KT-propositions. Moloney (2010) describes the vagueness in student language as the absence of conceptual understanding, and this describes KT-propositions. When students fear having to qualitatively reason about circuits (Engelhardt, 1997) they are aware of their limited KT-propositions. When a knowledgeable student can express why a particular circuit topology exists, why one connection might be more relevant than another, why a specific component value has been chosen and what might be a realistic value to change it to (Slotta et al., 1995) they are using KT-inferring with their episteme.

2.2.2. Know-How (KH)

Winch (2013b, 2014) defines know-how (KH) as a hierarchical set of practical knowledge. This begins at the lowest level of techniques and their application. This is followed by skills, transversal abilities (planning, communicating, evaluating) and project management abilities (the application of transversal abilities over longer periods and in larger projects).

Having KH-techniques describes the correct behaviours demonstrated by students during the execution of procedure and rules. There is considerable concern in the literature that the practice of developing student capability with KH-techniques, specifically mathematical techniques, leads to a limited form of understanding (Bernhard & Carstensen, 2002; Case & Marshall, 2004; Jaakkola et al., 2011; Jilek, 2010; Shaffer & McDermott, 1992b). This occurs when KH-techniques are treated independently of an episteme – even if students demonstrate high proficiency with techniques (Winch, 2013b, 2014). This is not a new problem, as an overt focus on mathematical techniques has long been recognised as inadequate in establishing understanding (Brownell, 1935).

KH-skills is a deeper level of KH, one which expresses a synthesis of KH-techniques with an episteme. KH-skills climbs beyond techniques (and proficiency with them) when actions become intentional, repeatable and contextually appropriate (Winch, 2016). KH-skills relies on KT-inferring - the application of inferential judgments using epistemic understandings and KH-techniques to a problem. Distinguishing between KH-techniques and KH-skills provides one insight into the bimodal distribution of results identified by researchers in electronics courses (Scott et al., 2010). The first peak of such results are students who are proficient with KH-techniques. This however, is insufficient, as students do not have the related KT-inferring about the models they are using to make further progress. The second peak represents the students who demonstrate KH-skills, the ability to make inferential use of their episteme in unknown contexts. In electric circuit theory, making inferences takes place through creation of models or accurate application of models within the boundary conditions of the model.

The conflation by educators of the teaching of simple procedures or KH-techniques to the same level as complex task related KH-skills creates an illusion of understanding and progression (Winch, 2013a). Teaching in physics and engineering is well known for their streamlining of complex tasks (inferential relationships) into algorithmic procedures (Mulhall et al., 2001) in order for students to undertake drill and practice with them. While such practice is critical for developing competence with KH-skills (Hattie, 2009), without an episteme and KT-inferring it leaves students lost. This is demonstrated in the sometimes incoherent and meaningless ways they use their techniques (Engelhardt & Beichner, 2003; Smaill, Rowe, Godfrey, & others, 2008).

The other KH capabilities are transversal abilities such as planning, controlling and communicating. These abilities are not simply students 'going through the motions', but require a high level of KH-skills as they require the learner to be attentive to the factors that lead to success of a project (Winch, 2014). Winch's descriptions of transversal skills and project management abilities are described by other theorists as strategic knowledge (De Jong & Ferguson-Hessler, 1996; Krathwohl, 2002; McCormick, 1997). Strategic knowledge should not be confused with students' calculated choice of material to remember (or not) during their courses. The next level of KH is project management abilities, a deeper set of transversal abilities, used in complex situations to carry out work over significant timeframes with the ability to manage unanticipated complications (Winch, 2013b).

2.2.3. KA – knowledge by acquaintance

Winch (2013a) describes this kind of knowledge as difficult to pin down but that none-the-less it is vital for students' appreciation of the domain. While KA is knowledge about things, it is not enough knowledge to be able to infer what to do with them. KA operates in both directions with KH; we need some KA to allow us to perform KH but at the same time we gain KA when as novice learners we engage with the KH within the discipline, i.e. we learn from doing. Being able to provide opportunities for KA to develop can be difficult as educators are just not able to always bring those things into the classroom or lecture theatre (Winch, 2013a).

Significantly, the amount of content, limited time available and pressure of summative assessment means that a reliance on calculation (KH-techniques) and remembering facts (KT-propositions) dominates teaching. In electronics, KA is the vital but difficult to describe awareness that is gained from building things that we don't understand yet, being gained through handling, manipulating and soldering components. KA informs students in ways which text books just cannot achieve. Laurillard (2002) states that this sort of authentic activity is invaluable because it guides students in engaging with knowledge and so helps them make sense of the "what" they see in the textbook.

While teaching through authentic activities is often described as powerful; activity and the consequent development of KA within a domain is insufficient in itself for learning. While KA is vitally important, it is however not structured or epistemic domain knowledge. For example when teaching students to solder they get acquainted with solder and that it melts and is used to make electrical connections but do not fully need to understand the KT-propositions about solder chemistry and the bonds that form. KA builds an important sensory understanding but it does not build propositional understandings (Winch, 2013a).

Depending on KA to develop KT is unsound. For example the building of circuits without any understanding of them, leads to the development of KT-propositions - fragments of understanding. Some of these KT-propositions may be incorrect e.g. the naïve understandings held by many about electric circuit concepts. Some KA can also be quite unreliable and can lead to failure. For instance a novice learner may know that a light emitting diode (LED) glows when connected to a battery but connect an LED to a 9V battery will destroy the LED. The novice may then find out that a resistor is necessary and get any resistor e.g. an inappropriate value such as 10 ohms or 10 meg-ohms and find that it does not work; or perhaps the novice learner may choose a suitable value by chance and falsely think they now have understanding. KA may well be what is described in this saying:

A little learning is a dangerous thing; drink deep, or taste not the Pierian spring: there shallow draughts intoxicate the brain, and drinking largely sobers us again. (Pope, 1609)

2.2.4. The relationships between KT, KH and KA

The concept diagram in Figure 5 portrays the complexity of knowledge. Importantly, it portrays how KT, KH and KA must not be treated individually, and any teaching that confines itself to KH is as inappropriate as one that focusses only on KT (Winch, 2014). While each is required to develop a student's episteme and eventual expertise, it is the relationships that are crucial (McCormick, 1997), particularly how KT makes KH effective (Glaser, 1984).

One relationship in the ways-of-knowing framework is that KH-techniques rely on KA or KT-propositions; this means that there must be at least some limited knowledge about something to perform a task with it. This is important in framing the high level of mathematical work done that has no link to any need to make inferential judgments using epistemic knowledge. Another relationship has been described; it is how both KH-techniques and KT-inferring are required for KH-skills. One further critical relationship is that KT-inferring develops not just from KT-propositions but from a systematic ordering of the episteme – the knowledge in the domain.

Mastery requires a number of relationships to exist, along with the combination of extended learning and practice (Winch, 2015). Proficiency with techniques is often referred to as mastery but should never be conflated to mastery. Mastery is a combination of KT-inferring and KH-skills that provides a deep understanding of how to relate the knowledge of the domain to the aims of the domain.

Expertise requires another set of relationships. Often these are determined by a professional body; e.g. the Electrical Workers Registration Board (www.ewrd.govt.nz) or Engineering New Zealand. Disciplinary bodies have specific registration requirements for their members which are often legislated by government.

Registration criteria require a degree of mastery which specifies a suitable training programme centred on KT-inferring, a period of acceptable work experience as well as ongoing evidence of learning and practice. It also requires a duty with regard to ethical practices relating to the discipline due to the impacts registered practitioners and professionals have in society.

Professional or practitioner status is linked to the level of KT-inferring. A technician needs a lesser level of epistemic knowledge and more proficiency with KH-techniques whereas a professional will need a greater depth of episteme and ability to make inferences with this to develop the techniques, rules and procedures used by others. The academic researcher often works at an advanced level to a professional, at the level of developing new epistemic knowledge (Winch, 2013a).

Educators are essential to manage the growth of expertise through the ongoing and continual development of the relationships between KA, KT and KH. This presumes two things about an educator's knowledge; their own KT, i.e. their fluency with their subject episteme, and their ability to navigate around its structures. When a knowledgeable educator is able to bring knowledge together in ways that lead to student understanding they have developed what Shulman termed Pedagogical Content Knowledge (PCK) (Shulman, 1986, 2015), the ability to make subject matter comprehensible. The development of the model of PCK was brought about to address what Shulman termed the "missing paradigm" (1986, p. 6) in education in the late 80's; that subject matter (knowledge) had become conspicuously absent and had been supplanted by a generic knowing how to teach (Shulman, 2015).

2.2.5. Knowledge summary

The relationships between the various ways-of-knowing are complex and an appreciation of these leads to the realisation that there is not a single problem with teaching and learning but several problems occurring all at once. One is how KT-propositions are regularly conflated to epistemic understandings and so KT-inferring cannot take place. Another is how KH-techniques are regularly conflated to KH-skills; this is because KH-skills are not understood in terms of their relationship to an episteme. However the last conflation is the most hazardous for student understanding, and the least understood, that of conflating KH-techniques to KT-inferring, where knowing how to do something (even really well) is confused with knowing how to reason. This is what is known as the epistemic fallacy (Bhaskar, 2013), where we believe that what we are seeing is actually what is happening and base our actions upon this false supposition. We do this when we think that more practice will bring things right. However this only leaves students competent with the wrong type of knowing and educators unaware of exactly what is wrong. Energies and resources in this case are piled into only one way-of-knowing and not all of them.

If we see only one problem, then we try only one solution, whereas what is needed is a new way of looking at the multi-facetted problem of student knowledge. The ways-of-knowing framework allows a perspective that interprets the problem, as indeed all problems are, as multi-facetted. Returning to the quotes at the opening of the chapter by Winch and Niemann allows two critical reflections about teaching and learning. Winch (2013a), in answering his own question, describes that student-directed learning cannot lead to understanding. Learning requires others who have gone before and established the episteme, students cannot do this themselves, they need knowledgeable others. Niemann's quote explores something different and very deep. How practice and practice leading to craft leaves us able to do the routine very well, but leaves an empty feeling that something important and illusive is still missing.

The ways-of-knowing framework was developed as the first critical lens for this research as it exposes the need for teaching, and provides the ability to recognise and understand missing and/or mistaken types of knowledge and ways-of-knowing being used.

2.3. Social realist theory

This section of the chapter discusses the social realist view of knowledge (Moore, 2013; Rata, 2012) and the social realist view of the structures and culture where teaching and learning take place, as well as the identity and agency of those involved (Archer, 1995). In integrating these aspects social realist theory can develop a critical lens to further investigate why and understand how a situation came to exist. Not only was a social realist lens applied within the research, a social realist lens was applied to the research as part of establishing methodology and methods in chapter three.

2.3.1. Abstract / academic knowledge

Social realist theory is underpinned by a critical realist view of knowledge (Bhaskar, 2013), where knowledge is created by humans to express the nature of the world. While created, it is not a personal or subjective view but a contestable view which is critically judged using empirical evidence. It is real or objective in that it does not depend upon those who created or now hold it; at the same time it is still fallible because a better understanding may be developed in the future (Young, 2010). For instance, in the domain of physics, 'universal' laws such as the law of conservation of energy represent not literal universality but the best understandings of reality that we currently have. Thus Kirchhoff's Current Law (KCL) was created as the best proposition to represent this phenomenon. Although socially produced this knowledge is not personal belief or subjective as it is empirically evidenced and rationally judged as reliable, and this gives us confidence in it (Moore, 2013). The process of creating this knowledge requires objectification, the removal of its dependence upon any context, making it universal. This means it can exist outside and independent from those who know it and the situation it is used within.

The separation of knowledge from context, gives knowledge a reality of its own, and this allows knowledge to remain even when the content of subjects change. The purpose of education is to help students understand this abstracted or objectified knowledge or "descriptions of the world" (Laurillard, 2002, p. 18). One implication of abstract propositional knowledge such as KCL is that it is not universal; it is bounded by conditions or external propositions. As understanding develops, these boundary conditions must be explored and brought into relationship with a proposition such as KCL. These include for instance, frequency; as at higher frequencies 'stray' and 'leakage' components in a circuit need to be understood as well.

Abstract understandings are crucial, as they give those who have them, the power to use them to create the unknown (Rata, 2015). Abstract knowledge is the epistemic knowledge at the core of a discipline. In the process of becoming abstract knowledge, it is differentiated from the conditions of its existence or situation. This is achieved by isolating the objective properties of it and expressing these using symbols and language unique to a discipline. This language forms the 'thought representations' for operating within a discipline (Rata, 2015).

In electric circuit theory, knowledge in the world is made up of physical components and circuits, for example resistors come in many different types as in Figure 6. These are not abstract as they are 'in the world'. To become abstract they are separated from the conditions of their existence by objectification using symbols such as those in Figure 7. The term 'abstract thought-holders' is used in this research for symbols such as these to express their nature. These abstract thought-holders or symbols for the discipline will not change even when the physical components do.

Figure 6: Various resistor types (http://delli.beriberi.co/resistor-types/)

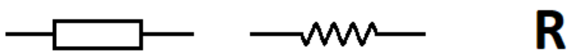


Figure 7: Abstract symbols used to represent resistors

A number of simulation type tools have been developed for teaching about electric circuits at levels that mimic physical reality. Figure 8, Figure 9 and Figure 10 are examples of these, where each operates at the level of the world as they do not use symbolic representations but images of physical components. Resistors (and other components used) however have changed over time and will continue to change in the future, so these tools do not represent objectified knowledge. While the marketing descriptions describe these as 'real', social realist theory describes instead that these exist at the level of the actual. They will not promote the development of abstract knowledge and cannot become abstract thought-holders. The consequence is that they limit students' communicating, reasoning and thinking ability (Moloney, 2010; Rogoff, 2008).

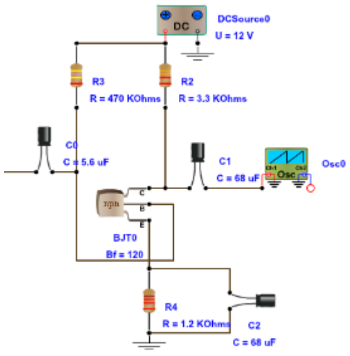


Figure 8: 'Virtual labs to acquire 'real skills' from www.docircuits.com

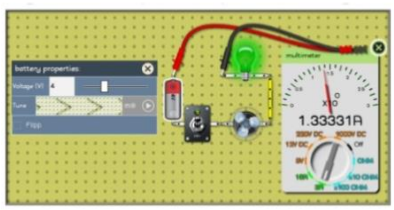


Figure 9: 'Realistic Interface' from www.dclab.com

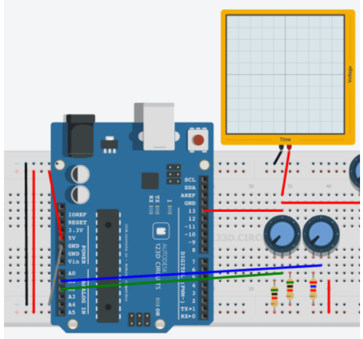


Figure 10: 'The easiest way to learn electronics' from www.circuits.io

In moving away from the conditions of its existence, there are no constraints made upon the user of an abstract symbol from Figure 7 to be limited to any specific instance of a resistor from the range in Figure 6. This is what makes abstract academic knowledge so powerful; it gives those who have it the ability to see beyond that which exists to create new previously unknown instances of it. It is this power of knowledge that is at the heart of sociologists' interest in knowledge; its ability to transform society (Bernstein, 2000). Knowledge gives people the ability to transcend the limits placed upon groups of different social class, gender or culture; with equal access to academic knowledge becoming the basis for a democratic society (Barrett & Rata, 2014; Moore, 2013; Rata, 2015). Without equal access to abstract knowledge, an inequitable situation exists where power resides only with those who have it.

Abstraction of knowledge is not enough. For instance, in electric circuit theory knowledge can be objectified using a schematic as in Figure 11. Students must know more than abstract symbols and schematics (descriptions of the world), they need to learn about how to express the relationships that take place in the real-world using symbolic descriptions as well (Laurillard, 2002). These are conceptual understandings; they can be expressed in mathematical models such as $I_c=\beta I_b$ or the symbolic model in Figure 12; both of which express operational relationships. Symbols and schematics are descriptions of the world; these behavioural abstractions express the inferential relations aspect of epistemic knowledge.

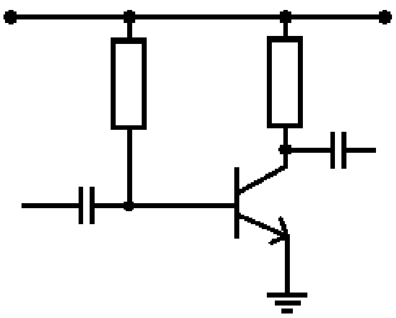


Figure 11: Schematic diagram with generalised/abstract symbols

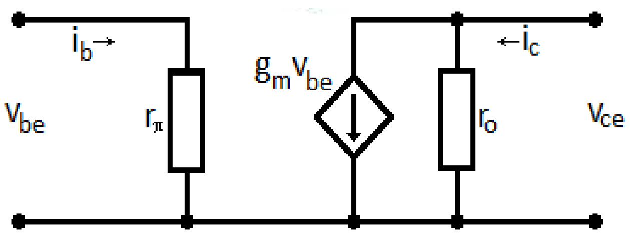


Figure 12: Abstract transistor model for inferential reasoning

Academic teaching and learning operates at this deep level where the things that need abstracting are located not in direct experience, but in the meaning of the experience (Laurillard, 2002). The worldly experience is the KH of building a circuit and the abstract of this is being able to follow schematics and models of circuits. The meaning of the experience is the inferential relationship within epistemic knowledge, which is the realm where engineers work. Importantly the physical contextualised existence, the abstract and the inferential relations, are all required for learners; and any attempt in a professional curriculum to structure teaching and learning for one independent of another will not succeed (Winch, 2014).

2.3.2. Structure, identity and agency

A significant aspect of social realist theory is that of structure and agency, and the relationship that exists between them. In her framework, Archer (1995) describes how agency is not a direct consequence of structure – but neither can it be described independently of it. Figure 13 was produced to describe her framework.

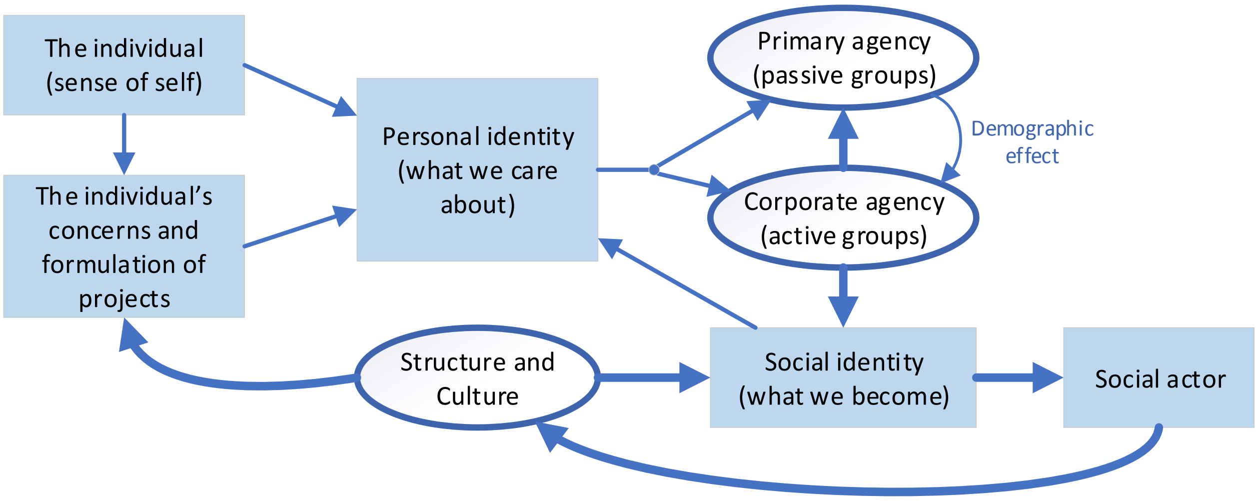


Figure 13: Archer's morphogenetic processes of identity and agency development

The framework describes how personal identity relates to the activities or personal projects that individuals focus their efforts on. One example of this is the change in student identity as personal projects change during school education. Harlen and Crick (2002) in their systematic review of the impact of summative assessment found that prior to secondary school, most students are open and willing learners with intrinsic motivations (have a personal project) aligned to learning; this could be called a 'learner' identity. In secondary school, the emphasis on summative assessment produces students with a strong extrinsic orientation; and a new personal project develops, one centred on results and accreditation. In New Zealand this has become known as 'credit farming' (PPTA, 2015; TEU, 2017). In this research a student's personal project around credits is referred to as an exam-taker identity. When students enter tertiary education this identity with its orientation towards grades is well established. This description of identity is not an all-encompassing view, as students will have alternative projects in different areas of their life (e.g. sports, music and hobbies) and identities quite different to that of passing in them.

While individuals have identity, Archer (1995) describes agency as a function of groups rather than individuals. In Figure 13 the rectangular blocks relate to individuals and the oval shapes to groups. Groups with primary agency are passive and have little influence, for example when students perceive education as something that is 'done to them'. Primary agents are not however completely without effect, for instance Archer (1995) describes them as having demographic influence, either as large or small groups. In tertiary education, primary agency is exhibited in demographic 'push-back', when students are described as only doing directly examinable work (Godfrey, 2003; Smaill, Godfrey, & Rowe, 2007). The primary agent demographic effect is described by Merrow et al. (2005) in the documentary Declining by Degrees as a 'non-aggression' pact between professors and students:

> *Don't ask too much of me and I won't expect much from you.*

In this research, the term student agency is used to capture the effect of how personal identity informs individuals as a group to respond in similar ways to the structure and culture of a situation. Where people come together to work in ways to change society the group has corporate agency. These individuals develop social identity and become social agents who hold roles in the situation and in turn influence structure and culture (Archer, 1995). For example, students can have corporate agency and social identities within their communities.

Allied with student identity in literature are characteristics such as personality types and learning styles (Felder & Silverman, 1988). Approaches to teaching using learning styles however are less useful than they appear (Coffield, Moseley, Hall, & Ecclestone, 2004; Hattie, 2016), perhaps because they view these student traits as immutable. Identity however can be learnt (Hattie, 2014) and is influenced by structures, cultures and corporate agents rather than just a sense of self (Archer, 1995). The role of educators is to find ways to develop learner identity (Hattie, 2014; Laurillard, 2002).

2.3.3. Structures and culture

Social realist theory places students and educators as social agents or social actors with unique identities existing within social structures and culture. The social realist framework of Margaret Archer (1995) is drawn from to explain the nature of stability and change in structure and culture. Structure describes the influential nature of the roles of people within institutions, and culture describes shared values, norms and ideas. These should not be reduced to our activities and practices (Archer, 1995), but they underpin our 'we do things this way' type of thinking (Godfrey, 2014). Teaching and learning does not take place independent of the relationships between personal identity, agency, structure and culture. Where there is incongruence or misalignment between parts of the system, learning may become impoverished. Archer (1995) developed ideas about order within social structures and cultures as existing within states of morphostasis (stability) or morphogenesis (change). Change taking place in structure or culture over time is termed the morphogenetic cycle. Change depends upon whether structures or ideas are compatible/incompatible and necessary/contingent as to whether there will be movement or stability in a situation as in Table 1.

Table 1: Situational Logics for Structural and Cultural Factors

	Compatible Complementary	Incompatible Contradictory
Necessary (must exist together)	1. Morphostasis Maintenance of the status quo	2. Morphogenesis Leads to compromises for the purpose of stability
Contingent (can exist independently)	3. Stability with some elaboration, new opportunity for advancement	4. Elimination There is a winner or loser

Note: Adapted from "Realist Social Theory: the Morphogenetic Approach" by M. S. Archer, 1995, Copyright 1995 by Cambridge University Press

Where aspects of culture or structure are compatible, the logic within situations determines stability (quadrant 1) or perhaps some elaboration (quadrant 3); however when there are incompatibilities the logic of the situation describes either change (quadrant 2) or elimination of one conflicting aspect (quadrant 4). Applying a social realist perspective in this research involves identifying the structures and cultural factors that have bearing upon students and educators and the various ways of knowing; and then considering which aspects might lead to morphogenesis (change) and which act for morphostasis (maintenance of the status quo).

2.3.4. The researcher-educator identity

While the structure and culture of learning and student results are linked to educators (Hattie, 2009, 2012; Laurillard, 2002), Hattie makes the statement that "teachers are tired of being measured, accounted, and told what is wrong with them" (2014, p. 4). He takes this sentiment through into complimenting the many successful teachers found in schools. In this research a similar compliment is made to the highly capable and professional group of academics that were encountered, a number of whom are recognised internationally in their disciplines. The tertiary academic however, has a different role to that of a teacher; they are both researcher (creator of epistemic domain knowledge) and educator. To reflect this duality, the designation of researcher-educator is used in this research; in this way the perspective is one of capturing the relationship between the researcher-educator identity and students' knowledge and identities. To capture this relationship Figure 13 from page 38 has been extended to develop the diagram in Figure 14.

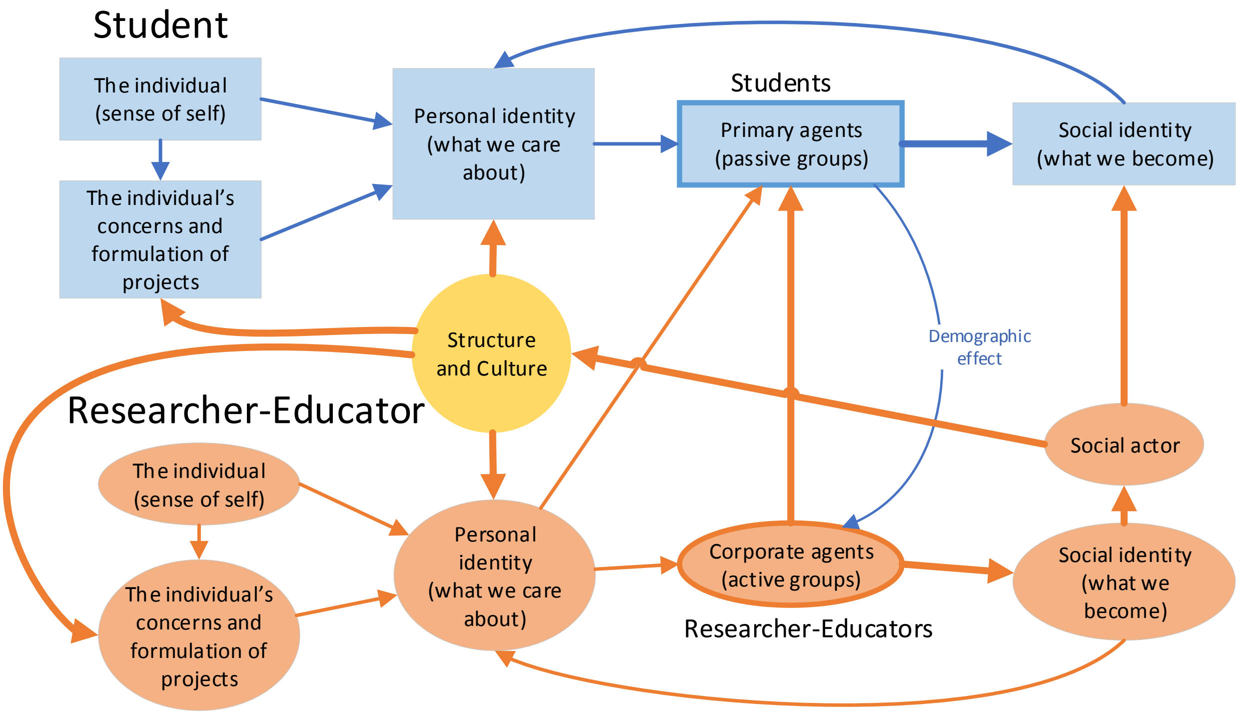


Figure 14: Identity and agency of researcher-educators and students

The colours and shapes represent the two identities and personal projects of the researcher-educator and the student. The researcher-educator has corporate agency and a developed social identity. The arrows indicate their influence on structure and culture, and consequently the personal projects and identity of students, and students' primary agency. The structure and culture element of the model is shaped similarly to that of the world of the researcher-educator. As corporate agents their role is necessarily one of driving the process of student becoming.

While Figure 14 is complex, it is further complicated by the dual nature of researcher-educator identity. The researcher has a mandatory aspect to their work within the university. This is high stakes as it reflects in personal standing and promotion (Mills & Treagust, 2003), and for institutions' ranking and funding[1]. Researcher-educators do not perceive their efforts in improving teaching are rewarded (Graham, 2018) and

[1] In New Zealand, the Tertiary Education Commission administers the PBRF - Performance Based Research Fund where an institution's ranking is based upon each individual's contributions to an institutions' research outputs.

quickly learn to use their resources for rewards that matter most, i.e. promotion (Godfrey, 2003). The description of where lecturers focus energy and efforts – or personal projects - captures the identity of 'researcher'. Alpay and Verschoor (2014) describe how the researcher identity overshadows the educator identity leading to institutions finding ways to support the researcher role by reducing or removing educational work load. Applying these descriptions from literature to Archer's (1995) situational logics in Table 1 on page 40 reveals a contradictory and incompatible situation, where one identity overshadows another (quadrant 2) or where one 'wins' over and eliminates the other (quadrant 4).

Applying the incompatible researcher-educator identity back into Figure 14 reveals how the researcher-educator identity influences the situation. When looking into learning, Godfrey (2003) identified the influence of the researcher-educator as having a focus on teaching centred on: mathematics (KH-techniques), useful content (KT-propositions), problem-solving and design (but lacking problem-framing) and on making students work hard to develop their ability to 'take it'. Understanding these influences and the way they are applied both directly to students and indirectly to them via structure and culture is a useful model for the analysis of teaching and learning.

2.3.5. Social realism summary

This section of the chapter explained social realist frameworks and theories. These encompass a critical realist view of knowledge, where knowledge is abstracted from the conditions of its existence and stands on its own. This abstract knowledge forms the episteme at the core of a discipline, and when students develop an episteme they become capable of operating within the domain. A social realist framework describes how structures and culture influence where teaching and learning take place and the identity and agency of people within a situation and how these in turn influence structure and culture. These frameworks provide a critical lens through which the 'real' or hidden within a situation can become visible.

2.4. The gamut of educational theory

Pedagogy has two constituent aspects: educational theory and pedagogical practice. There are many different educational theories, and this section discusses several different theories that have a bearing upon teaching and learning. These are described in how they differ ontologically and epistemologically and how they have bearing upon the ways-of-knowing. Educational theory is the third critical lens for the case study.

2.4.1. Why educational theory is important

Theory is essential for professionals as it provides the ability to analyse and critique designs and to communicate valid reasons for why things are done the way they are. Radcliffe and Jolly (2003) however, make the statement that educational theory has not been evident in much engineering education literature, as Mills and Treagust (2003) discuss, because engineering educators are not taught of its importance. The need for a theoretical underpinning, however, is as valid for educators as it is for engineers (Shulman, 2015). For example a technician has less need for theory or epistemic knowledge and consequently has a lower ability in KT-inferring, as their work is more prescribed whereas an engineer's work is more ambiguous. Without educational theory, the question is raised by Orchard and Winch (2015) as to whether the educator should be considered a professional or a technician. Orchard and Winch (2015) propose that educators need to be professionals, as a professional has the ability to take part in the important debates that shape practice. This aligns with the ways-of-knowing framework where a civic awareness and societal impacts are professional responsibilities and just as important for educators as engineers (Shulman, 2015). This level of engagement with debates about educational theory is complicated in education because it is a social science, where theories exist in a horizontal structure with differing philosophical positions. It is this horizontal structure which underpins the major debates in education.

2.4.2. Epistemology and Ontology

Engineers do not usually engage with discussions about the nature of knowledge because engineering has a positivist scientific tradition centred on empirical data and scientific methods (Radcliffe & Jolly, 2003). Engineering knowledge exists in a hierarchical structure, where concepts are subsumed into higher order concepts (Bernstein, 2000). Education on the other hand is a science involved with the nature of people and society; and different theories of education have contrasting philosophical underpinnings about knowledge and consequently exist in a horizontal structure (Bernstein, 2000). This gives rise to a complex set of links between educational theory, knowledge, ways-of-knowing, pedagogical practices and the need for a heuristic for choosing pedagogical practice. These are explained in Figure 15.

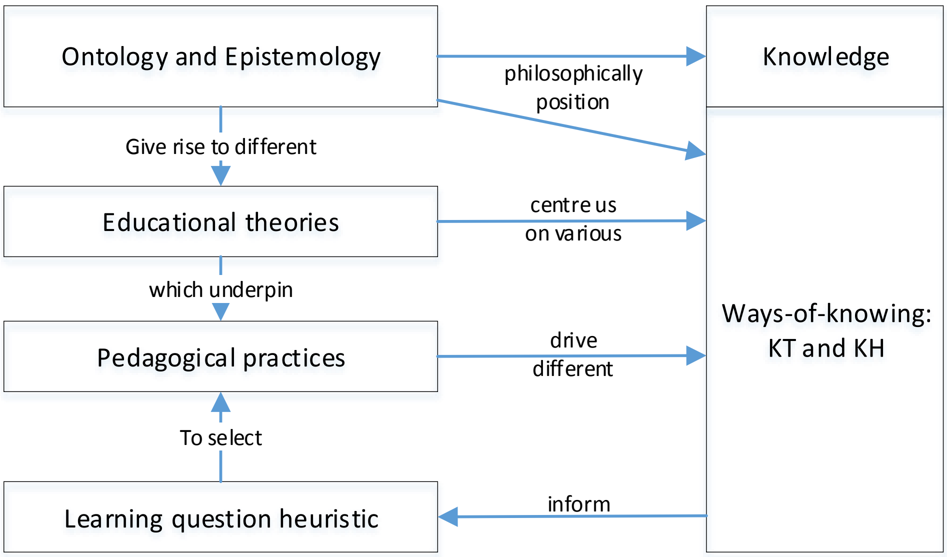


Figure 15: Interrelationships between educational theory, knowledge and pedagogical practice

Different philosophical positions represent differences in ontology and epistemology. Ontology (Figure 16) refers to the nature of reality and ontological positions of educational theories relates to the nature of where knowledge exists. Epistemology involves looking at how different educational theories describe the way people come to know and learn.

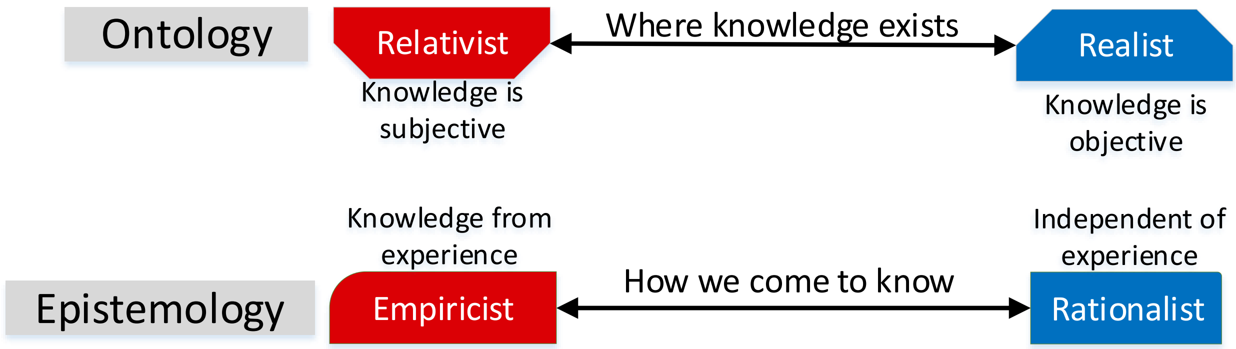


Figure 16: Philosophical positioning of our beliefs about knowledge

The chapter opened with Winch's question about whether all learning could take place without teaching. This directly points us toward epistemology with its two different positions about how we know: these are the empiricist and the rationalist (Ertmer & Newby, 2013; McCormick, 2006; Sternberg, 2010). Empiricism is a view that our knowledge comes via experience. Theories and practices that are empiricist place the environment as central to learners' experience (Ertmer & Newby, 2013). Theories and practices that are more rationalist rely on knowing coming from reasoning, and this places the students' mind as central to understanding (Ertmer & Newby, 2013). Ontology (Figure 16) precedes epistemology in that it relates to truth or existence of facts and objects. The opposing ontological positions are relativist and realist. Relativist means knowing is only subjective or with reference to the individual; from a relativist point of view students create their own truth or knowledge (Boghossian, 2006). The other position is realist; this means knowledge comes only from absolutes or laws that exist outside the individual and experience is not to be trusted. Being aware that different philosophical positions about knowledge and understanding exist helps educators recognise the basis for the debates in education.

Figure 17 structures the full discussions in this section on theory and the next section on framing practice. Its purpose is to illustrate how educational theories differ from one another because of their different epistemological and ontological positions on knowledge and in turn how these positions give rise to different pedagogical practices.

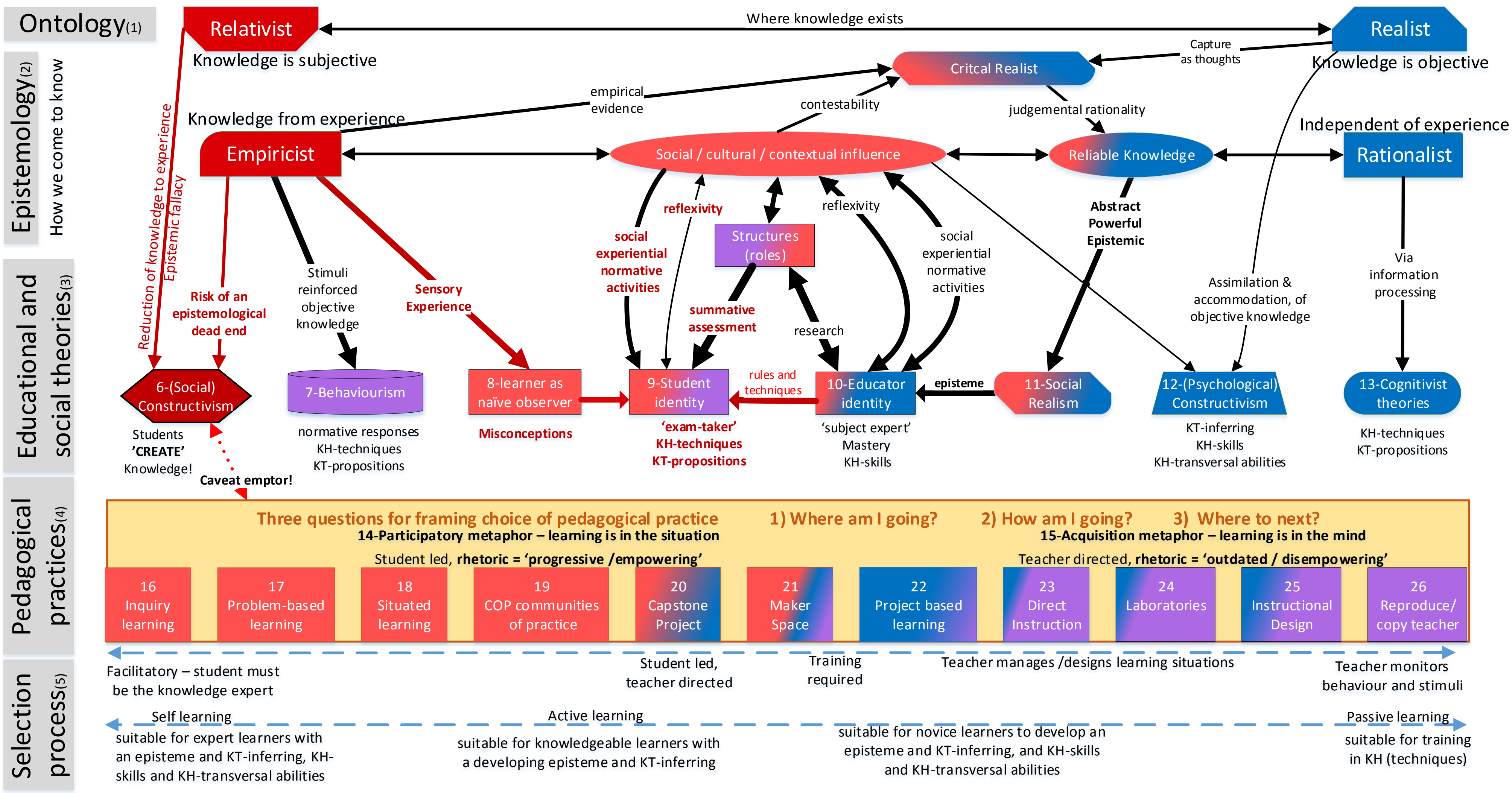


Figure 17: Philosophical positioning of educational theory and pedagogical practices for the case study

A philosophical view is important to educators, because choosing or arguing for a particular teaching method is not atheoretical; it implies epistemological and ontological positions about the nature of knowledge and ways of teaching. As Maton says "there is no such thing as having no theory" (2006, p. 11). Education should never be opinion-based (Hattie, 2014); it is a profession, and professions are based upon having theoretical understandings (Orchard & Winch, 2015).

2.4.3. Behaviourism

Behaviourism (Figure 17 #7) is one educational theory. It is rooted in an empiricist or knowledge-from-experience view (Ertmer & Newby, 2013) where learning is an association between correct response and environmental stimuli (Schunk, 2012). To the behaviourist, knowledge is ontologically real, external and objective, never subjective (Boghossian, 2006) where the teacher is active in manipulating stimuli and the learner passive (Mayer, 1992). While the teacher holds the objective knowledge and sets up the events where learning takes place, it is not the teacher doing the teaching, it is the environment (Schunk, 2012). Williams (1999) describes behaviourism as having limited effect, because students have volition - they are not automata. Archer's (1995) descriptions about the nature of primary agency agree with this as structure does not fully describe behaviour. Behaviourist strategies in mathematics and science, such as drill and practice (KH-techniques), are designed by educators to teach on their behalf, and are especially useful with large cohorts, where they are unable to provide any form of individual contact (Smaill, 2006). However behavioural drill and practice work leads to tightly constrained understandings that students are not able to generalise into novel situations, though they can exhibit excellent performance in standardised testing (Thornburg, 1994).

In New Zealand secondary schools, behaviourism (Figure 17 #26) was the hallmark of pre-1995 Technology Education, where teachers taught students to reproduce the same product (e.g. Cheval mirror) in exact detail as that provided to them (Harwood & Compton, 2007). These rote learning practices were popular as they supposedly led to KH-skills and were viewed as suitable pathways for 'non-academic' students into trades. However this teaching approach was recognised as highly limited (Compton, 2007), as students learned KH-techniques, with limited epistemic knowledge or KT-inferring of why, where or when their techniques were best used. Changes to the curriculum sought to change the place of Technology Education in New Zealand education by displacing this model of learning. However the educational facilitators tasked with implementing change found moving teachers pedagogically was difficult, with most teachers remaining firmly fixed in their behaviourist traditions (Harwood, 2002; Harwood & Compton, 2007; Mawson, 1998).

Tertiary lecturers who have less educational training than teachers and ever present research commitments, are also difficult to move pedagogically, preferring to teach in the pattern once used on them (Phillips, McNaught, & Kennedy, 2012), one which centres on the assumption that doing lots of problems will lead to understanding at some later time (Case, 2008). This is then translated into the textbooks they write, which rely on definitions, formulae, examples and practice but have deficient conceptual frameworks (Sangam & Jesiek, 2015; Sangam et al., 2011). In tertiary education, the turn toward outcomes based education has been criticised as a return to behaviourism; particularly in engineering education where the outcomes are directed by professional bodies and industry with a focus on what graduates can do rather than know (Case, 2014).

Behaviourist practice can be used when enriched by epistemic knowledge and KT-inferring. For example I have used behavioural type practices in situations with students at secondary school, one of which is learning the epistemic knowledge and KH-techniques of soldering. After providing an introduction to some of the conceptual knowledge of tools, materials, how good and bad shapes of solder joints happen, and some chemistry, I have students place one resistor in their printed circuit board and solder it. They then form a line in class and I have each student in turn present their first solder joint to me. Using a fine pointer I condition them by asking about the features of the solder joint using external stimuli (reference images about shape) and the influence this has on the suitability of the solder joint. Each student is then directed to do one, two or three more components depending upon the accuracy of their first joint, and then to join the queue again. Within 50 minutes each student knows what is expected, is generally conforming and there are few issues with student's soldering technique in the future. In this situation, epistemic understanding and the ability to infer from concepts about soldering are exposed to students. The goal is not to develop engineers who can design soldering machines and procedures for others; it is the training of knowledgeable soldering technicians. These technicians must be able to reliably apply the techniques across the range of situations they will come across when soldering wires, components and PCBs, and so need a level of episteme. These relationships include how temperature, stability, cleanliness, the solder and flux impact upon the chemical bonds that form which determine the conductivity, strength and reliability of the solder joint – this is inferential knowledge. Before using this process I had used a completely behavioural process with no connected knowledge of the chemicals and bonds that formed. However without this knowledge I found students to have a narrow perspective on the quality of their solder joints and a lack of concern about for instance cleanliness of the components. With more epistemic knowledge came the ability to infer what would happen if joints were not clean. Introducing the knowledge through context-of-use is part of the systemic (third period) approach described by Amin, Smith and Wiser (2014) toward addressing issues with conceptual understanding as described in section 1.5.12.

2.4.4. Cognitivism

Cognitivist theories (Figure 17 #13) are epistemologically rationalist rather than empiricist focusing on internal processing and mental representations (Ertmer & Newby, 2013) and position the student as having an active role in developing understanding (Mayer, 1992; Schunk, 2012; Williams, 1999). Cognitive teaching techniques involve developing KH-techniques for selection, processing, organising and retrieving knowledge (Ertmer & Newby, 2013) and KH-skills such as problem solving (Schunk, 2012). Cognitivist theory is found in research into conceptual knowledge issues in physics and includes: how experts and novices organize their knowledge differently, the miscoding or mislabelling of concepts, fragmentation of concepts and learners misinterpreting conceptual relationships (diSessa, 1988, 1993; Streveler et al., 2008).

Cognitivism is prominent in the field of instructional design (Figure 17 #25) - although instructional design has its early roots in behaviourism; and recently has drawn from constructivist theory (Ertmer & Newby, 2013). The goal of instructional design is to make teaching and learning efficient (Merrill, 2008), portraying education as a scientific discipline (Merrill, Drake, Lacy, & Pratt, 1966) where the acquisition of knowledge takes place after the development of appropriate teaching strategies (Ertmer & Newby, 2013). This involves identifying variables that influence learning and strategizing about controlling and testing them (Jonassen, 1997). A critique of instructional design is how concepts are treated discretely rather than relationally (Jonassen, 2006), for instance a concept can be defined through the process of attribute-isolation, which highlights individual characteristics that define whether a concept is a member of a class or not (Merrill, Tennyson, & Posey, 1992).

While the understandings gained from cognitivist information-processing approaches are highly valuable, treating concepts in isolation can lead to fractured understandings or KT-propositions. Concepts in a discipline are better described as evolving constellations (Georgiou, 2016) or systems of meaning (Rata, 2015). PCK (section 2.2.5) was developed to avoid the "blind spot" (Shulman, 1986, p. 9) concerning knowledge from an increasing focus on pedagogical practices. PCK also provides expert educators flexibility in adapting to learners and situations (Hattie, 2014) which is something that cognitivist approaches avoid in their view of learners as cognitive-information processors.

2.4.4.1. Mental models

The mental model (Johnson-Laird, 1983; Vosniadou, 1994) is one valuable output of cognitivist theory. Mental models are the underlying psychological structures and representations in our minds, and are focussed on building KT-inferring. Mental models are symbolic or iconic simulations, so are dynamic rather than static abstracts of ideas, objects and events and their propositional or unifying relationships (Kellogg, 2011). They allow us to explain and predict behaviour (Rickheit & Sichelschmidt, 1999) and take action (Johnson-Laird, 1983). In engineering and computer science, mental models are closely linked to building students' understanding of electric circuits (Frederiksen, White, & Gutwill, 1999; Tarciso Borges & Gilbert, 1999), and computer programs and algorithms (CAÑAsf, Bajo, & Gonzalvo, 1994; Ma, Ferguson, Roper, & Wood, 2007). In electric circuit theory, inaccurate mental models lead to false predictions about circuit behaviour (Chi, 2008). Students' models of circuits are seldom accurate or complete, and do not agree with those held by experts (Jaakkola et al., 2011). Students with sound mental models demonstrate efficiency in new learning compared to those with less adequate ones (Frederiksen et al., 1999; Mayer, 1989).

To enable learners to build mental models, 'conceptual models' are used, which can include words, diagrams and animations (Mayer, 1989) and computer simulations and games (Schunk, 2012). Conceptual models for electric circuits are often poor analogies and students develop understanding constrained to that depicted in the model, for instance they might think of electric wires as empty pipes and electric current as a liquid (Coll et al., 2005; Jaakkola et al., 2011; Ugur et al., 2012). This makes much conceptual modelling ineffectual as it produces incorrect KT-propositions rather than the epistemic understandings needed.

Incorrect models are resistant to change, but change can happen by exposing students to cognitive conflict where models that contrast theirs are demonstrated (Chi, 2008). Students, however, often rote learn the right answer and later revert back to their previous incorrect models (Amin, 2009). More often students' inaccurate models are never exposed to them and their ideas become synthesized into understanding that lacks coherency (Vosniadou & Skopeliti, 2014). Rosengrant, Van Heuvelen and Etkina (2009) found an association between a lack of coherent understanding and students' avoidance of the use of qualitative representations when solving physics problems. Students move directly from an abstract problem to an even more abstract mathematical representation. Without linking these two representations with an intermediate model such as a sketch or graph, their mental models become deficient. They argue for the importance of creating 'representation-rich' learning environments that feature a focus on the missing qualitative understanding.

2.4.4.2. The Variation Framework

Students need to be able to not just articulate the complex interactions in circuits (described by Figure 4, page 13), but how one relationship will have an effect on another; these are termed 'co-varying' relationships (Jonassen & Easter, 2013). When phenomena co-vary, such as when changes to topology change the way a component reacts to electric potential, it is difficult for students to discern their individual character. The Variation Framework (Marton & Pang, 2007) describes how co-varying relationships can be understood by varying one relationship and holding others constant, in this way students can discern the critical attributes of each in reference to others (Fraser, Allison, Coombes, Case, & Linder, 2006). This means that removing complexity by hiding non-varying relationships ultimately hinders understanding. For example circuit fragments are often used to reveal the relationship between topology and either current or electric potential, and the unused electric potential or current is assumed so not shown. The variation principle indicates that the unused property should not be taken for granted but brought into students' awareness to develop the epistemic relationships in a circuit.

2.4.5. Constructivism

The term constructivism has become widely used in education, so much so that it is now not well understood (Leach & Scott, 2003; McPhail, 2015). The term has expanded to capture more views than it was originally theorised for. Liu and Matthews (2005) and McPhail (2015) describe it as now having become hegemonic in educational discourse. Constructivism was theorised by Piaget and Vygotsky as a psychological theory of individual learning which is influenced by the social world (Matthews, 1997; McPhail, 2015; D. C. Phillips, 1995) (Figure 17 #12). Confusion exists between the different philosophical underpinnings of psychological constructivism (which is a theory of epistemology that describes how people come to know) and social constructivism (Figure 17 #6) which is to do with ontological theories about where knowledge comes from (Matthews, 1997; McPhail, 2015, 2017).

2.4.5.1. Psychological constructivism

In this section the term psychological constructivism (PC) is used to concentrate on the development of student knowledge. PC (Figure 17 #12) moves away from some of the ideas of cognitivism (e.g. information processing) toward a situation where the teacher is less dominant (though not less important) and the student becomes more active as they must cohesively construct knowledge frameworks and mental models for themselves (Leach & Scott, 2003; Liu & Matthews, 2005; Williams, 1999). With its primary focus on the active engagement of learners with material, PC has received some criticism in terms of it being inefficient for learners' knowledge development (Winch, 2016). Also it places excessive demands upon educators to construct learning environments (Ben-Ari, 2004). It has also been criticised as not effective in building student understandings. For example, laboratory sessions (Figure 17 #24) aimed at constructing understanding have been found to be viewed by students as simply mechanistic exercises (Feisel & Rosa, 2005).

The key ideas of PC are that knowledge exists outside the learner and must be actively engaged with. This requires a 'knowledgeable other' in education to bring the objective knowledge to the fore. PC is important for developing understanding as it places the emphasis strongly on conceptual understanding and signals a definite move away from transmissive assumptions about teaching (Booth, 2001). Instructional design (Figure 17 #25) that promotes a PC approach requires creating meaning through being active with knowledge rather than a direct 'mapping' of knowledge into students' minds (Ertmer & Newby, 2013).

2.4.5.2. Social constructivism

Social constructivism (SC) is a sociocultural theory of learning centred on the person situated within a social setting and is a quite different theory to PC (McPhail, 2017).

Before entering into a discussion on SC, it is important to recognise that not all theorists hold similar views about it. For example Hattie (2012, 2014) and Kirschner, Sweller, and Clark (2006) attribute lesser worth to participatory learning practices while Hmelo-Silver, Duncan, & Chinn consider them not ill-structured and highly powerful (2007). Bernstein describes these contrasting views as the volatility associated with weak grammars in horizontal structures (1999). In horizontal structures where theories exist separate to each other, there can be disagreements between theories and even disagreements within theories, because they have weak grammars - are weakly defined. This thesis presents SC as the radical constructivist approach of von Glasersfeld which rejects the objective reality of science as independent of the knower (Cardellini, 2006). In doing this SC is described as having a relativist position. The discussion presented then seeks to find a place for SC within the teaching and learning situation of the case study.

Sfard (1998) describes two metaphors at work in education. SC falls within the metaphor of participation with PC being acquisition (e.g. behaviourist and cognitivist theories). In psychological constructivism, students construct an episteme, whereas in SC, the knowledge they create may not be epistemically related at all. This reflects SCs specific commitment to an ontological stance about knowledge being subjective and relative to the knower (Cardellini, 2006; Maton & Moore, 2010; Rata, 2012). Epistemic knowledge is not created by novices, it is created by academic researchers, and novices need to learn this knowledge. As a learner becomes more adept at KT-inferring (wielding this knowledge) they can learn to create using it. The range of literature relating to students' misunderstandings in science education includes much discussion about the complications created by learners' naïve assumptions about the world (Vosniadou, 2002). SC however considers the student is the only active agent in the learning process and that their experience is more important than anything else (McPhail, 2015). Teachers therefore should adapt curricula to student interests (Schunk, 2012) and become facilitators (Ben-Ari, 2004; Magrini, 2009; Perkins, 1999) rather than activators of learning (Hattie, 2014).

In engineering education, Felder describes 'two competing paradigms', the positivist and the constructivist (2012). The positivist is viewed as 'traditional' with its teacher-centred transmissive lecturing using a deductive process of instruction from fundamentals to application. The constructivist (SC) is viewed as 'emerging' in its stand against the traditional through its learner-centred inductive process of specific to the general. This view has become synonymous with increasing student engagement and reducing the downward trend in student numbers caused by traditional methods (Felder, 2012; Prince & Felder, 2006). While lecturing has been shown to produce insufficient understanding in students (Biggs & Tang, 2011; Hake, 1998; Laurillard, 2002), Sfard describes SC's easy acceptance as an alternative in this climate not because it offers a better solution but because it brings about

> *immediate relief from the old headache (Sfard, 1998, p. 8).*

A reductive binary view is insufficient because it conflates too many ideas from within such a complex field. For example, lecturing or direct instruction is a pedagogical practice, while SC is an educational theory. This inaccurate conflation between epistemology and ontology is one aspect of the epistemic fallacy (Bhaskar, 2013) where what is seen is misinterpreted as something else.

This binary model highlights the trend in general education which is toward the marginalization of teacher-centred pedagogies as traditional and elitist, while student-centred practices involving SC are promoted as progressive and democratic (Moore, 2013). Sfard describes this approach as risking leaving education up-to-chance, and where students can be left at an "epistemological dead-end" (1998, p. 8); where the student is left not knowing the abstract concepts that they need to be able to function satisfactorily within the domain. Hattie (2014) describes that there is a regular rediscovery of these student-centred ideas in education, referring to them as a dogma that will not go away.

Sfard (1998) also raised an important question, one that is at the heart of sociologists' concerns about knowledge and education, as to whether SC could fulfil its promise of democracy to students. Rata (2017), describes that when knowledge becomes subjective and experiential, it lacks its epistemic nature, and without epistemic knowledge students are unable to inhabit the intellectual world of the abstract and so do not have the ability to take an informed, active and democratic role (Barrett & Rata, 2014). Sfard's warning about an epistemological dead-end seems extendable to a democratic dead-end as well.

Teaching experience and further study in educational theory have contributed to my own gaze on SC. In 1995 there was a shift to an SC learning focus called 'Technological Practice' in the New Zealand Technology Curriculum (Ministry of Education, 1995) to replace inadequate behavioural practices in New Zealand Secondary technology education (as described in section 2.4.3). Knowledge in technological practice changed to a situated-learning paradigm where teachers were facilitators and students had to learn for themselves. This resulted in significant issues for students' knowledge (Compton & Jones, 2004; Turnbull, 2002) as epistemic or taught knowledge that was not directly used within student practice was not rewardable with grades. During professional development sessions, facilitators described to teachers the overarching need for all knowledge to be situationally based. Ultimately this did not lead to the desired outcome and students' contextually bound understandings were determined to be shallow without any critical relationship with knowledge (Compton & France, 2006). Technology within the subsequent curriculum (Ministry of Education, 2007) was changed to complement SC practice by creating a parallel strand for the curriculum called Technological Knowledge; this promoted the teaching of domain specific epistemic knowledge. I became involved directly with issues relating to both behaviourist and SC practices when working with teacher trainees and teachers, in assessing and moderating work at a national level, and as part of the writing panel for the body of knowledge for electronics within the Technological Knowledge strand.

The danger with SC is seeing it as the only valid approach for transforming knowledge and understanding. Kirschner, Sweller and Clark (2006) and Hattie (2014) clarify where SC theory can inform educational practice. This is when students have sufficient prior understanding; i.e., students need a sound episteme. This describes the current approach of engineering courses which culminate with a capstone project where students must work with minimal guidance. The multiple ways-of-knowing required for a capstone project have been built up over progressive learning cycles of discipline related theory courses and project-based courses.

Hattie's (2012) description used earlier, about how these ideas keep getting 'reinvented', is apt again here. In 2017, the curriculum area of Digital Technology in New Zealand was redeveloped. It has two strands, one relating to practice, and the other to knowledge. However, suitable pedagogy for both strands has been defined as inquiry learning and outcomes for both strands begin with the statement:

> *In authentic contexts and taking account of end-users, students… (Ministry of Education, 2018)*

In effect a full cycle has taking place, the original curriculum which centred on experiential learning was counteracted via the introduction of epistemic knowledge (the Technological Knowledge strand), and in this latest curriculum, experiential learning is again the focus.

2.4.6. Educators discourse around education theory

In the same way that student discourse exposes understandings about circuit theory, an educator's discourse exposes their understandings about educational theory. Bernstein (2000) describes this in terms of an inner regulative discourse and its resultant external instructional discourse. Regulative discourse represents our values around pedagogy (Kinchin et al., 2016) and brings order to instructional discourse (Bernstein, 2000). If an educator has a limited regulative discourse, their instructional discourse centres on enrolment, assessments, useful-content (KT-propositions) and efficiency (Kinchin et al., 2016). This in turn can lead to pedagogic frailty, a vulnerability to minor events or change (Kinchin et al., 2016). Pedagogic frailty is the same as student's frail understandings in electric circuits. When student understanding is based upon KT-propositions and KH-techniques, a minor change made to a circuit reveals the students' lack of understanding (Smaill et al., 2007) and this represents their inability to make inferential judgments. Just as students need an epistemic foundation in circuits for KT-inferring to avoid susceptibility to change in circuits, educators need theory to pedagogically align their regulative discourse around educational theory to avoid susceptibility to minor change.

2.4.7. Educational theory summary

This section of the chapter has discussed a range of educational theories from the perspective that they differ ontologically and epistemologically. The focus of this discussion was to position the role of theory in relation to the development of the different ways-of-knowing and explore how some theories contribute to the development of epistemic understanding and KT-inferring and how some might have the opposite effect. The understandings of the nature of educational theory has revealed that teaching is a crucial aspect of learning, that Winch's question as to whether all learning could take place without teaching should be answered in the negative, that teaching is most definitely necessary. However more than this, the discussions of educational theory begin to address the call by Niemann at the start of the chapter for us to engage with our profession not as a form of craft, but theoretically as professionals, and to search for and identify 'the real thing we are trying to get good at'. This involves a change in the purpose of education, often described as a move from being teacher-centred toward becoming student-centred. The lack of definition of the term student-centred is of significant concern, as it exposes those who lack formal backgrounds in educational theory to potentially making significant errors in pedagogy. This discussion on educational theory therefore provides a further critical lens for the ensuing case study research.

2.5. Pedagogical practice

This section uses the lenses of knowledge, social realism and educational theories to discuss what teaching practices might be a best-fit with the development of students' epistemic knowledge and KT-inferring needs. The term best-fit is used as teaching and learning situations are so diverse that there should be a wariness to any prescriptive approach to teaching (Fullan, Hill, & Crévola, 2006); instead effective principles need to be applied to educational practice (Hattie, 2014). This describes all practice in professional disciplines, as professionals often work with ambiguities not certainties. It is the application of epistemic principles and not codes of practice that makes unknown and difficult problems solvable. Laurillard (2002) describes this uncertainty between theory and practice in education as 'fuzzy', which precludes the writing of detailed 'recipe books' for teaching. This reflects the need to apply a certain flexibility to pedagogical practice; a social realist perspective describes such an approach, as it is contestable, is based upon empirical evidence, and is rationally judged for best fit.

Describing teaching practice in this way as fuzzy is useful as this allows the application of fuzzy logic. This is where not all variables are known and the assignment of probabilities is more useful as there is seldom a defined right approach. In education, these probabilities have been established through Hattie's research (2009, 2012, 2014), and these can provide educators with a degree of confidence when choosing practices. A heuristic is needed when applying probabilities with fuzzy logic; and in education such a heuristic exists. This heuristic was developed to describe how feedback should work in educational situations. The heuristic consists of three simple questions; these are:

> *Where am I going? How am I going? Where to next? (Hattie & Timperley, 2007, p. 86).*

These three questions view teaching and learning from a learner's perspective, as if in response to Winch's question, students were asking us to teach them. They begin to develop a definition of what student-centred teaching might look like.

2.5.1. Three questions for guiding pedagogical practice

This heuristic does not centre on particular practices but on making the teaching and learning process completely transparent to the student and not just something the educator knows about (Hattie & Timperley, 2007). As Case (2013) writes, the morphogenesis of agency comes from knowledge; in an educational setting, this takes place by providing knowledge to students about the processes being applied to them.

2.5.2. Pedagogical question 1: Where am I going?

In section 2.3.2 students were described as often driven by assessment. The first pedagogical question involves realigning students toward epistemic knowledge. This includes defining the curriculum, a goal for student literacy, development of knowledge-based abstract learning outcomes, and the development of challenge to guide student identity.

2.5.2.1. Where am I going? - Curriculum

Educational systems have curricula that establish the direction and knowledge for teaching and learning. This involves recontextualisation – teachers making decisions about what knowledge will move from the subject's episteme into the curriculum (Bernstein, 1990). Recontextualisation is not purely an academic process, it is informed by the ideology and agency of dominant groups with whom power resides (Barrett & Rata, 2014; Bernstein, 1990; McPhail, 2015), as described with the New Zealand Technology Curriculum in section 2.4.5.2.

The production of knowledge and consequently what students learn within the university has been under the influence of those within the university (Laurillard, 2002); increasingly though recontextualisation is being informed from outside the university, from industry and professional bodies. This has given rise to two sometimes conflicting forces at work in education; the first aligns with the position of the discipline within the university and relates to what students 'know'. The second relates to the position of the discipline within the culture of practice and is concerned with what students 'can do'. This can be seen in recent changes at the University of Auckland in terms of its graduate attributes (The University of Auckland, 2017a) compared to its prior graduate profile (The University of Auckland, 2003). The earlier position was knowledge based; the profile beginning with 'specialist knowledge' and included terms such as: body of knowledge, mastery and philosophical basis of knowledge. The newer profile centres on practice along with disciplinary knowledge and includes lists of KH-transversal abilities skills that employers are seeking (The University of Auckland, 2017a). Along with this, the group working on academic programme development at the University of Auckland recommended having every course of undergraduate studies include a capstone type project (The University of Auckland, 2017b).

This inward and outward focus is a hallmark of engineering education (Case, 2013). In New Zealand, Engineering New Zealand (ENZ, formerly IPENZ, the Institution of Professional Engineers New Zealand) accredits engineering education faculties; ENZ is a signatory to the Washington Accord for international accreditation purposes. ENZ sets the standard for entry to the engineering profession and monitors engineering faculties' standards in terms of: the body of knowledge, graduate outcomes, aspects of programme design, admission levels and completion rates, assessment, staffing, facilities and even culture (IPENZ, 2017). Study in engineering, therefore, already integrates the important relationship between student knowledge and its use in industry. Winberg et al. (2016) investigated this model of engineering education by canvassing the opinions of experienced engineers. Their research confirmed the critical importance of establishing epistemic knowledge as the basis for curriculum development; with a transition at higher levels that engages students in specific practice-based 'can do' knowledge.

The shift in emphasis by the university as whole to embrace a more 'can-do' approach to teaching is not a weakening of academic disciplines; it strengthens epistemic knowledge through context-of-use. It can, however, weaken disciplines if taken to excess. This is the debate encountered in teacher education where educational theory has become less and less valued compared to learning on the job (Orchard & Winch, 2015). In a keynote at the Australasian Association for Engineering Education Conference, the director of Professional and Community Engagement at an Australian University, made the statement that the resounding success of their practice-based initiatives for undergraduates in the university indicated that it was preferable that all learning:

> *starts with practice rather than theory (Clark, 2017, p. 41).*

This goes beyond an integration of 'can do'; it is a turn toward ontological relativism. The practice of putting teachers into schools without adequate theoretical preparation is exactly the same issue as putting students in their first year of engineering into a consultancy and expecting them to understand what is happening. The ways-of-knowing framework clarifies what takes place when knowledgeable tertiary students enter the work place, their episteme of theoretical knowledge becomes engaged in a context-of-use, and KT-inferring capabilities begin to develop through this engagement. Engaging knowledge within a situation can result in such an overwhelming epiphany of understanding that the full awareness of all the factors that led to the awakening become lost and the situation is seen as the reason for the change. This happens when early career teachers look back and see their growth as educators not from the combination of theory and practice but from the practice because that is where they developed this awareness. This is the epistemic fallacy; believing what you are seeing is what is actually happening; when what is happening is the culmination of many factors at the level of the real. To make the leap to ontological relativism demonstrates that the important place of epistemic knowledge and the way know-that informs know-how is not understood. The epistemic fallacy was demonstrated by a comment made in the keynote, that those who disagreed with this progressive way of learning were 'naysayers'. Unfortunately those who might see the flaw in the logic – the engineering educators - do not usually have the episteme of educational theory (Radcliffe & Jolly, 2003) to mount an argument against the epistemic fallacy in terms of the epistemological and ontological nature of knowledge and understanding. Orchard and Winch (2015) describe this essential ability, being able to argue the epistemic knowledge at the core of the discipline, as the difference between a professional educator and a technician type educator.

Curriculum designers need a theoretical lens through which they can analyse the ideologies at work in learning and design a curriculum that builds epistemic knowledge and underpins it with practice. While challenging, this is a critical process, as through precisely framing the 'where am I going?' question students know their direction because educators know why they are teaching students what they are teaching them, and can argue for it.

2.5.2.2. Where am I going? - Literacy

It is in the curriculum that specific goals for students are found, and these goals are not only involved with knowing; in schools they are wrapped within competencies involving thinking, contributing and relating to others (Ministry of Education, 2007). These become goals for student literacy, for example scientific literacy, technological literacy or numeracy (mathematical literacy). It is important not to describe literacy as a shallow form of know-how or 'can-do', as it is a deep know-how goal (KH-skills). Being literate is an abstract ability, to be able to use what has been learnt in the abstract in new and novel situations. Literacy requires KT-inferring and is not an invitation to start and finish teaching with KH-techniques. When engineering educators complain about students' inadequate mathematical skills, they are indicating a failure of numeracy, as students can carry out highly complex mathematical procedures when presented to them in a cut-and-dry way.

Learners who do not have an awareness of the abstract nature of the domain cannot develop a literacy goal for themselves. This makes social constructivism (Figure 17 #6), with its focus on students discovering for themselves through inquiry (Figure 17 #16) or problem-based learning (Figure 17 #17), inadequate as students do not have the insight yet within their domain to create a goal for their learning. Of note, Ausubel (2000) removed the chapter on discovery learning from his revised work because educators were disappointed with its potential for saving education. This makes inquiry or discovery learning as something only suitable for knowledgeable learners. Working with a literacy goal also has strategic benefit in moving the emphasis of students and educators away from grades, encouraging students in the process to develop an intrinsic motivation with the domain (Harlen & Crick, 2002).

2.5.2.3. Where am I going? – Academic Learning Outcomes

Beyond an overarching goal, the student needs academic goals that will develop the epistemic structure of their knowledge; these are referred to in literature as learning intentions, outcomes or objectives. In the Bloom's Taxonomy (Krathwohl, 2002) the term is educational objectives; Biggs and Tang (2011) in their model of constructive alignment describe how they initially called them 'curriculum objectives' then changed to calling them 'intended learning outcomes'; Shirley Clarke (2001, 2005, 2008) refers to them as 'learning objectives' as do Ambrose et al. (2010) and Laurillard (2002), while to Hattie (2009, 2014) they are 'learning intentions'. Sometimes writers use intentions, outcomes and objectives to signal a student or educator perspective, although generally this distinction is not made. For this research 'learning outcomes' was chosen. The term used however is less important than how it is used and what it expresses. This relates to the integration or separation of context and content within the learning outcome. For example, Biggs and Tang write context and content directly into learning outcomes e.g., “define the key values of Hong Kong culture” (2011, p. 141) as do Ambrose et al. “articulate and debunk common myths about Mexican immigration” (2010, p. 247).

When writing about learning outcomes in primary and secondary school education Clarke (2001, 2005, 2008) recommends that they should exclude context to help students focus on the purpose of their learning and not the content or context, a practice now promoted by Hattie (2014). This has particular relevance in tertiary education as it is well known for its content ‘tyranny’ (Prince, 2004) where courses are developed based upon lecturers’ own textbooks and a culture which conforms to doing things the way they have always been done (Wiggins & McTighe, 2005). Knowledge that is bound to context or explicit content in a learning outcome does not align with the goal of abstraction. It follows that Clarke’s decontextualisation of learning objectives for primary and secondary school learning is perhaps even more important for tertiary education in the promotion of learning as the development of abstract thought-holders, that give the owner of such understanding the ability to design the unknown (Rata, 2012).

Learning outcomes are often written based upon the six educational objectives from the original Bloom’s Taxonomy (Bloom, Engelhart, Furst, Hill, & Krathwohl, 1956) or its revision (Krathwohl, 2002). Writers in education often state that objectives such as ‘understand’ from the taxonomy are not useful for writing learning outcomes as they do not focus on student actions (Ambrose et al., 2010) nor the level of performance required (Biggs & Tang, 2011). However, when writers promote learning outcomes that are action oriented (describe or explain), they centre student knowledge on KH-techniques dealing with descriptions of the world and not abstract epistemic knowledge. The strategy used by educators to unpack knowledge from the concrete into the abstract has not been successful as a strategy in electric circuits as demonstrated by the naïve conceptions students continue to demonstrate.

Karl Maton, an educational sociologist, has developed Legitimation Code Theory which includes the theory of semantic gravity as expressed by semantic waves (Maton, 2013, 2014a; Maton, Hood, & Shay, 2016). Using his theories, a range of research has been carried out to identify processes for the development of powerful knowledge across diverse domains. These include thermodynamics (Georgiou, 2016), teacher education (Macnaught, Maton, Martin, & Matruglio, 2013) and engineering (Wolff, 2015). This theory promotes conceptualising abstractness and concreteness as a continuum where teaching practices have relative strengths of 'semantic gravity' from weak (abstract) to high (concrete). Semantic waves that describe levels of semantic gravity, can be depicted in graphs of abstractness as shown in Figure 18.

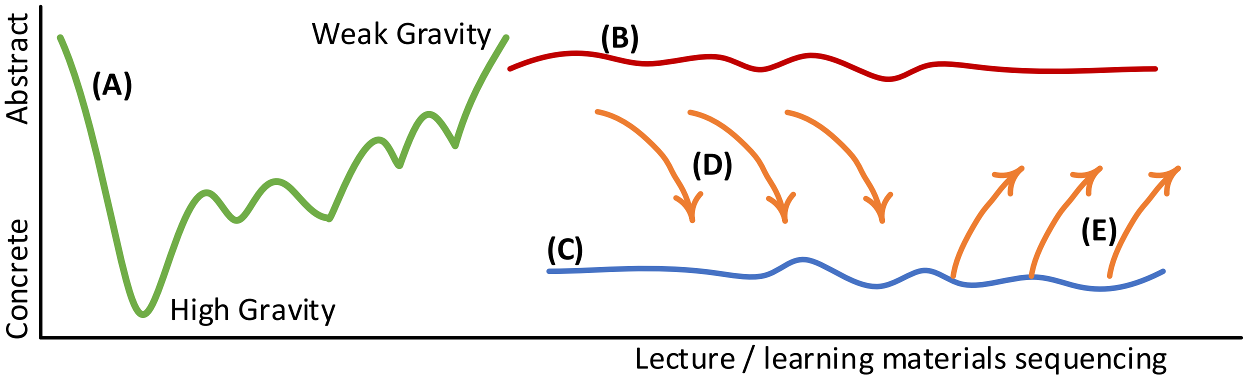


Figure 18: Various semantic wave profiles from Legitimation Code Theory

The most powerful processes identified in teaching have a semantic wave such as Figure 18(A). Teaching begins with low gravity abstract concepts followed by explanations involving authentic and rich contextual applications with high gravity. Scaffolding follows in a sequence of steps that build a hierarchy of understandings from concrete back into the abstract. One possible approach to teaching is a semantic wave where knowledge is only aligned to abstract ideas as in Figure 18(B), but this misses the important requirement of using knowledge in authentic contexts, something we need to avoid (Winch, 2014). The opposite is where only contextualised examples are ever used as in Figure 18(C). This wave represents the participatory models of pedagogy based upon social constructivist theory where understandings can too easily be constrained within the high gravity of the contexts in which students learn, limiting students' ability to build abstract meaning.

A great deal of course work involves limited waves as in Figure 18(D). Teaching begins with decontextualisation of a device, technology or process e.g., a circuit fragment in electric circuits or a formula. Decontextualisation is insufficiently abstract; it still has too high gravity, as it has no link with abstract thought-holders. This process is then reinforced by providing practice with calculations. These teaching strategies are seldom contextualised enough (given enough gravity) to create meaning. This equates to an emphasis on KT-propositions with KH-techniques with little epistemic development or ability with KT-inferring.

In engineering literature, binary paradigms such as the deductive and inductive are often quoted (Felder, 2012; Felder & Silverman, 1988; Prince & Felder, 2006) and promoted as the two alternatives available for engineering educators. The deductive method is top-down, a theory-first methodology where content is presented without context (Anderson, 1995; Arends & Kilcher, 2010) e.g. Figure 18(D). The inductive alternative is Figure 18(E), a bottom-up or context first approach; the disadvantages of context centred teaching have already been identified as limiting the ability of students to develop abstract understandings. Maton's theory of semantic waves is not an attempt to find a neutral position between two binary exclusives, it expresses how education needs to operate over the full continuum rather than within the constraints of either the deductive or inductive models.

It is crucial that teaching begins and ends in the abstract with abstract thought-holders. In this research the term Academic Learning Outcomes (ALOs) was chosen to express a fully abstract or 'zero-gravity' learning goal. This term was not found in literature to have any special meaning and is used to stress the importance of abstract, rather than contextualised or even just decontextualised learning goals. Being high level abstractions, ALOs serve an 'advance organiser' (Ausubel, 2000) purpose by directing students to the important nature of the learning, bridging the gap between known ideas and new knowledge. An ALO has no gravity tying it to context, it cannot easily be 'looked-up', and novice learners could not be involved in setting these because they do not recognise what they do not know. Using ALOs requires knowledgeable experts who can develop processes for identifying the abstract thought-holders of their discipline and unpacking these for students using suitable teacher-activated pedagogical practices. This centres on direct instruction which can then be powerfully enriched through project-based learning (Figure 17 #22 and #23).

Argyris and Schön's (1974) theory about professional effectiveness describes double loop learning. A single loop centres on 'doing things right, e.g. learning outcomes that express content and context focus on this. A double loop describes how 'doing the right things' precedes 'doing things right'; an ALO only describes doing the right things; while doing things right is a different educative practice relating to the second pedagogical question. When students are regularly reminded of where they are going (or doing the right things) they recognise what learning is about and begin to drive it for themselves (Argyris & Schön, 1974; Clarke, 2008; Hattie, 2014; Schön, 1987). This awareness or visibility is at the core of students knowing where their learning is going.

2.5.2.4. Where am I going? –Blooms Taxonomy and knowledge

Education has been heavily influenced by the work of Benjamin Bloom and his taxonomy for classifying educational goals which was initially developed for building a consistent approach to writing educational outcomes (Bloom et al., 1956; Krathwohl, 2002). Developed in 1956 and revised in 2001, the Bloom's Taxonomy has been highly influential in education and has 'stood the test of time'. This does not mean that because we have always used it we always should, instead it reflects a critical realist position that Bloom's Taxonomy is 'reliable knowledge' that is contestable by the academic community; and having been scrutinized against empirical experience it continues to be valid and reliable. Applying such a critical view to the taxonomy led to the revision where the highest two levels were swapped (Krathwohl, 2002).

There are six levels in the revised taxonomy's cognitive process dimension (see Figure 19). This dimension equates to the single dimension found in the original Blooms taxonomy. Remembering is the lowest level with its recognition and recall of facts, this denotes KT-propositions in the ways-of-knowing framework.

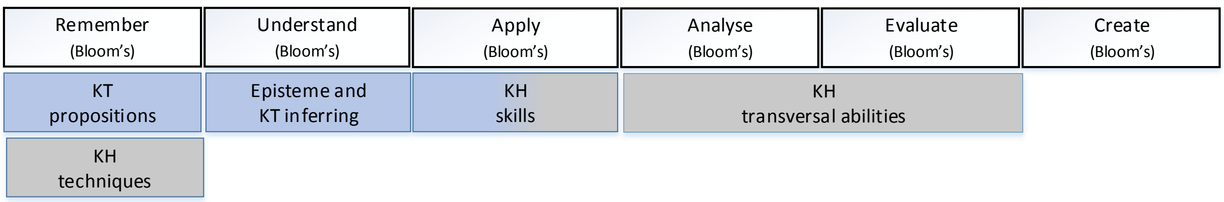


Figure 19: Relationship between Bloom's Taxonomy and the ways-of-knowing Framework

Understanding is next which relates to epistemic knowledge and KT-inferring. Applying is third and is the ability to use the information learnt within new contexts; this is KH-skills.

Often encountered in engineering education is the sequence of practicing mathematical problems before understanding, leaving understanding for some later stage (Case, 2008). This is the conflation described earlier of KH-techniques to KH-skills; while students develop proficiency it does not lead to being able to apply knowledge to unknown problems. KH-techniques is aligned alongside KT-propositions at the lower level of 'remember' in the Bloom's taxonomy; i.e., 'remembering' including knowing how to mathematically differentiate or use a technique such as node voltage analysis. Seeking congruence between the ways-of-knowing framework and the Bloom's brings perspective about how different ways-of-knowing must not be treated in isolation, and how the order in which they should come together is crucial within the full sequence of teaching.

2.5.2.5. Where am I going? - Challenge

In Hattie's research (2009, 2009, 2014) into practices that have the greatest effects on student learning, challenge factors along with feedback as one of the two essentials required for learning. Developing challenging tasks, however, is not an easy process and Hattie (2014) describes getting it correct as the hallmark of expert teachers. Biggs and Tang (2011) describe it as striking a balance between chaos and cut-and-dried work. While it is recognised that developing challenge in large lecture environments is difficult, research into questions asked in large lectures reveals them to consistently be at low levels of cognitive challenge. They are generally rule oriented (Ellner, 1983; Larson & Lovelace, 2013) i.e., aligned with KH-techniques, and seldom 'why' in nature which would emphasize KT-inferring. The questions presented to students not only ally with challenge, but are deterministic; they develop the level of student thinking. If questions are always at the lowest levels of KT-propositions or KH-techniques, that is what students become. Biggs and Tang (2011) present successful practices for lifting challenge in lectures through use of functioning knowledge – which relates to developing capabilities with KT-inferring in conjunction with the development of epistemic knowledge.

2.5.2.6. Where am I going? – Focus on techniques or understanding

With the prevalence of teaching related to techniques in engineering, Case and Marshall's (2004) comparative analysis of their two studies contains important advice for engineering educators. Their work clarifies a crucial aspect about agency in teaching and learning relating to techniques and understanding. Their analysis begins with the identification of the relationships between procedural/conceptual knowledge and surface/deep understanding leading to students taking different approaches to problem solving as in Figure 20.

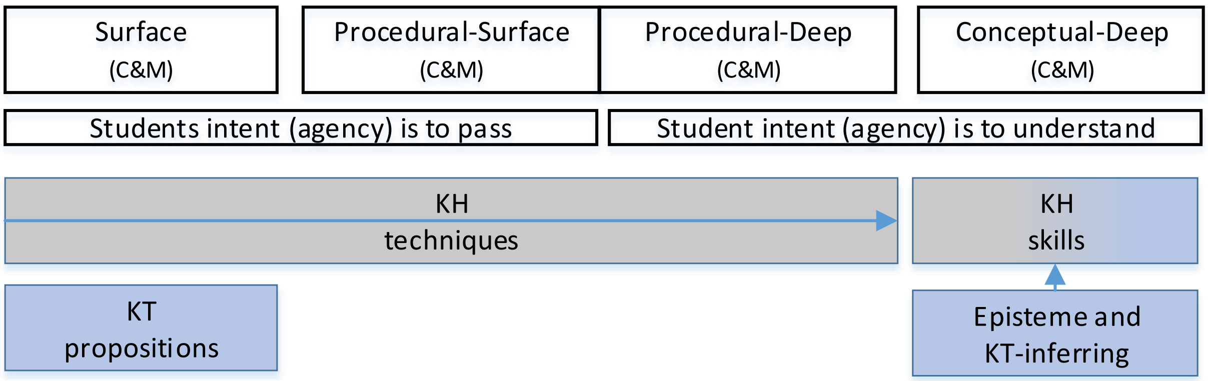


Figure 20: Approaches to knowledge and understanding identified by Case and Marshall (2004)

The lowest level is a surface approach which entails teaching algorithmic procedures (KH-techniques) and/or surface information (KT-propositions) in order for students to pass tests and examinations. When a student takes this approach in electrical engineering, they memorize the properties of a BJT transistor characteristic and the procedures for identifying its operation as either active, saturated or cut-off; or they memorise characteristics of an ideal OpAmp and the formulae for its various feedback configurations. In each case, a student's goal is often to be able to use the information and the associated procedures to pass a test or examination.

In the centre of their model there is a separation of procedural-surface and procedural-deep, where students use procedure but change their intent from passing to understanding. This transition of intent indicates student agency at work. To get to the final level of conceptual-deep however, requires students to change more than their intention; teaching and learning must be gone about quite differently. Students however, are primary agents and their approach to learning is driven (or constrained) by what they perceive the values of the course to be. These values are set by those with corporate agency; and when corporate agents place value in procedure, students follow procedure. Case and Marshall concluded that teaching which highly values procedure (even procedural-deep) is not likely to develop a conceptual-deep approach in students – a different approach to teaching is required – one that is underpinned by epistemic domain knowledge and requires KT-inferring. In terms of the pedagogical question about where a student is going, it must therefore be asked in relation to the values of the course and what is expected, not in terms of the intent of the students (Hattie, 2014).

If educators value and teach KH-techniques and KT-propositions, then the question about where a student is going is constrained to a narrow set of outcomes. This concern is noted in the many comments made by researchers about a reliance on KH-techniques; from it being counterfeit knowledge (Borg Marks, 2012), to providing false confidence to both learners and teachers and as masking real ability (Clement, 1982). An overt reliance of educators on drill and practice is not a new concept, for instance Brownell states it

> *merely afforded opportunity for practice and increased efficiency with undesirable procedures (1935, p. 11)*

Such a numerical-only approach to circuit theory is easily recognisable when students resort to blind application of formulae in confusing ways (Kautz, 2007; Smaill et al., 2012). However it is still the predominant methodology found in textbooks and courses (Sangam et al., 2011). The high use of drill and practice, and the reliance on learners gaining the ability to carry out decontextualized calculations in electric circuits feeds students' tacit belief that engineering is simply mathematics (Gunstone et al., 2001).

A grounding in mathematics is none-the-less essential if students are to gain the rich circuit knowledge they need to transcend 'technician' understandings (Vandewalle, 2009). While a singular approach to teaching as drill and practice is inadequate, drill and practice is in itself not poor pedagogy, as it is essential for building proficiency. The expert educator is able to recognise when deliberate and relevant practice is aimed at mastery of understandings (Hattie, 2009) i.e., developing students' capability of KT-inferring with epistemic knowledge, rather than cut-and-dry drill and practice of KH-techniques. When students undertake drill and practice activities before they understand the mathematical models, they see only the mathematics as their goal, and end up looking for formulae that fit variables (Laurillard, 2002) and fail to see the phenomenon being modelled. To achieve mastery, drill and practice work should occur in the later proficiency stage of teaching after the understanding stage (Burns, 2004).

Relevant to this research is establishing how drill and practice can be bought into teaching so that it works powerfully for educators and students. Remaining focussed on learning goals is critical (Luik, 2007); if an educators' focus promotes academic learning outcomes, student practice becomes grounded in the abstract. Drill and practice must be recognised as helping students make and explore inferential relationships using their epistemic knowledge and not as just efficiency with mathematical procedures.

2.5.2.7. Where am I going? - Identity and agency

Whilst social realist theory around identity and agency was discussed in section 2.3.2 on page 38, this section frames student identity and agency in relation to the philosophical positions of educational theories in Figure 17 and how these might influence pedagogical practice selection. Figure 21 is a portion of Figure 17. Students (#9) and educators (#10) are represented separately as they have different identities, personal projects, and agency in the situation.

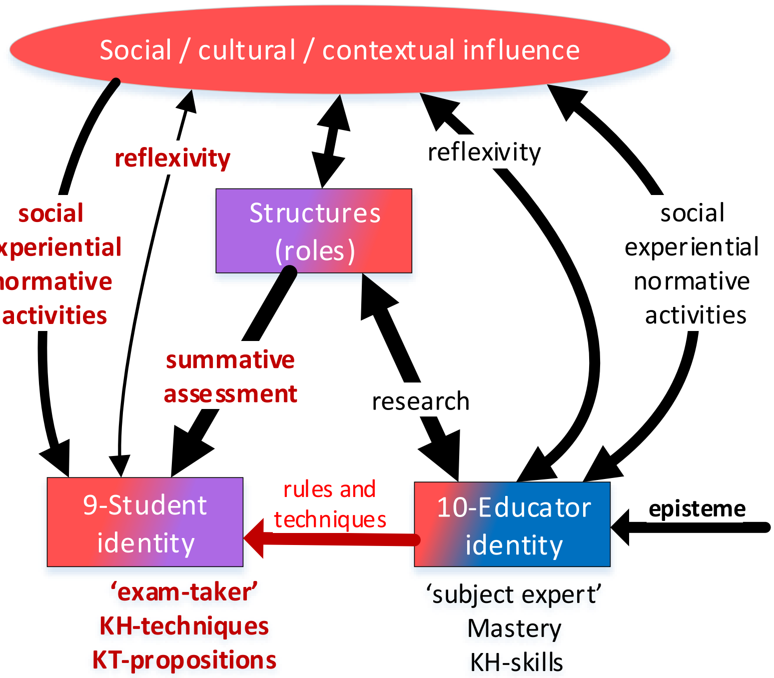


Figure 21: Student and Educator identities (extract from Figure 17)

The arrow sizes and direction reflect the different influences acting upon each and their primary or corporate agency within the structures around teaching and learning. Educators' corporate agency is expressed by the solid black arrows feeding inwards to them which impact on their social identity; these include epistemic knowledge, research and reflexive relationships within the research community. Educators however interact with students in quite a different way. The arrow coming from the educator to the student in Figure 17 (#10 to #9) is the result of filtering of knowledge exhibited by a useful-content approach (Godfrey, 2003; Laurillard, 2002), the reduction of concepts to formulaic processes (Case & Gunstone, 2002; Mulhall et al., 2001) and transmissive approaches to knowledge (Harlen & Crick, 2002). This filtering explains how student identity remains aligned with the one they had when entering tertiary education.

This raises the question about why this filtering exists, as there seems no congruence between the critical engineering researcher who is amongst those at the very top of their field and the educator whose teaching work is transmissive and formulaic. One aspect of Archer's framework is that agency is not all encompassing. Educators can have both corporate agency as researchers and primary agency within the university. Laurillard (2002) expresses this primary agency when she shifts the responsibility for the incongruence in lecturers' work onto the culture and structures of their educational institutions where in general lecturers are not required to know about teaching, nor rewarded for it (Godfrey, 2014; Graham, 2018) – the normative activities arrow.

When it comes to educators choosing pedagogical practices, the use of a social realist perspective of structure, agency and knowledge is informative. Practices that are student-centred (Figure 17 #16 to #21) inherently require intrinsic motivations that are not found within primary agents. Also if KT-inferring and KH-skills are left up to situations to develop via student-led practices, a narrow subset of knowledge can too easily develop. This was found in the changes made to Technology Education in the New Zealand Curriculum (described in section 2.4.5.2) – where an unsatisfactory situation developed, one that was ineffectual in bringing about the desired change in students and even resulted in lower student levels of KH-techniques as well.

While students need to be active in learning, they need guidance (Hattie, 2009). It is important to clarify the commonly used term, 'active learning'; it is used here in the way Prince (2004) defines it, as an approach and not as a single method. Practices that involve active learning methods include direct instruction and project-based learning (Figure 17 #22, #23). These practices require teachers to teach, and to have a goal of developing epistemic knowledge and the building of capability with KT-inferring that uses epistemic knowledge. Student's identity can be positively influenced through these practices.

2.5.2.8. Where am I going? – Inquiry and problem-based learning

The discussion on social constructivism as a theory of learning in section 2.4.5.2 revealed the ontological issues that are often hidden with the way social constructivism is presented in education. This leads to confusion around terminology such as problem-based learning (Prince, 2004) which leads to it being used interchangeably with project-based learning. To clarify their individual meaning it is helpful to identify their distinct ontological and epistemological positions. Mills and Treagust (2003) and Case (2014) distinguish project-based learning (Figure 17 #22) as the application of taught knowledge and problem-based learning is where students need to identify and acquire the knowledge for themselves. In project-based learning the curriculum retains its familiar teacher led epistemic hierarchy – and is realist. In problem-based learning, knowledge is linked to the situation and if students do not have an episteme it will not develop (Perkins, 1999; Perrenet, Bouhuijs, & Smits, 2000; Rata, 2017). Problem-based learning therefore should not be used with students who lack sufficient knowledge in a subject (Hattie, 2016). Biggs and Tang's (2011) treatment of problem-based learning is highly informative, typifying it as real world professional practice and the need for students to have prerequisite functioning knowledge or KH-skills, before it should take place. Referring to Figure 17, this reflects the placement of problem and project-based learning toward different ends of the pedagogical scale of practice. Perrenet, Bouhuijs and Smits (2000) concluded that the limitations of problem-based learning made it unsuitable as a strategy for all engineering education. Borrowing from Sfard's (1998) description of a caveat concerning the participatory metaphor of learning; social constructivism in Figure 17 (#6) has been given a 'caveat emptor' warning with regard to choosing pedagogical practices.

2.5.2.9. Where am I going? – Direct Instruction

Lecturing to large classes in universities has attracted much criticism as being simple transmission of information to a passive audience (Laurillard, 2002); with lecturing even becoming known as "content tyranny" (Prince, 2004, p. 229). Lecturing has been called teacher-centric; in education a single alternative to this view is often promoted, that education needs to be student-centric (Felder, 2012). Lecturing however is not about the teacher, as it is a pedagogical practice with epistemic knowledge at its base, and falls under the pedagogical practice of direct instruction, which has one of the largest effect sizes of educational practices (Hattie, 2009). It is powerful when centred on learning outcomes, has a 'hook' for student attention, when concepts are fully explained, practice is guided, and there is a way to check understanding through independent practice in a new context (Hattie, 2014). Direct instruction exposes knowledge using explanation, demonstration and engagement which is the requirement for basic concepts to emerge (Winch, 2013a).

As many lectures are delivered to large cohorts, there is seldom an opportunity to assess and provide feedback about students' understandings, which can lead to errors in judgement about how long students take to develop understanding. A number of aspects of lectures need addressing to improve them pedagogically. Pace and amount of content appear to drive much lecturing, with lectures being likened to building a brick wall; the faster the bricks are put on top of each other the faster the wall gets built (Brown & Hammer, 2008). Adequate time for learning directly influences student understanding (Alton-Lee, 2003) especially in concept rich areas such as electric circuit theory (Sen & Ammerman, 2006). One aspect that needs work is the lack of real context (Tobias & Hake, 1988), something students need as described by Maton's work on semantic waves (2014a). Demonstrations of phenomena are one way that lecturers can make content relevant and accessible to students (Hattie, 2014; Laurillard, 2002); although the pedagogy in use must engage students meaningfully with the demonstration (Miller, Lasry, Chu, & Mazur, 2013). Models such as the predict-observe-discuss method show good results; with students much more likely to remember what happened if they make a prediction about a demonstration before it occurs (Sokoloff & Thornton, 1997) - just as they are if they predict the outcome of calculations before they make them (Kautz, 2007).

Much work has been done to improve lecture outcomes by using reflective writing (Kalman, 2017), setting readings before the class, creating concept maps to track progress (Kinchin et al., 2016), work along exercises, incorporating think aloud modelling, using strategic breaks, and finishing with consolidation and review activities (Laurillard, 2002). Educational technology has also been used to increase and monitor student participation. Importantly there is an immediate need to improve pedagogy around lecturing, rather than remove it from our repertoire. This can be achieved by focussing it on the practices of direct instruction, centred on epistemic knowledge and development of the capability of KT-inferring through demonstration of reasoning.

2.5.2.10. Where am I going? - Laboratory work

Laboratory work is primarily aimed at students learning to use theories and models and linking them to real events and artefacts (Carstensen & Bernhard, 2009). While motivational (Vandewalle, 2009) most students leave laboratories with little understanding of what they did (Coppens & De Cock, 2013) as they focus on getting the work done and not gaining understanding (Duit & Treagust, 2012; Zacharia & de Jong, 2014). Gauld (2012) found that laboratory work revealed little cognitive change with high school students in electric circuit understanding, many returning to their old understandings after doing experiments on electric current, some even changing their memory of what happened in the experiment to suit their prior naïve theories. Because of these findings, laboratory work in Figure 17 (#24) is generalised as a passive rather than active mode of learning.

In terms of students having a direction for their learning, a critical aspect of laboratory work is the training of students in the methodologies for acquiring and validating disciplinary knowledge (Winch, 2013a). Laboratory work becomes useful in answering the pedagogical question about where a student is going in terms of understanding the correct use of tools and techniques within their discipline.

2.5.2.11. Where am I going? – Understanding of modelling

Modelling is a uniformly accepted concept in engineering (Rossouw, Hacker, & Vries, 2010) yet is notoriously difficult for students in electronics to understand (Harlow, Scott, Peter, & Cowie, 2011). A model is an analogy or simplified representation of a natural object or phenomenon that captures its central structural relations (Amin et al., 2014) in ways that words cannot (Oh & Oh, 2011). Models are used to create a subset of the properties and relationships needed for the problem at hand. For instance, when modelling component function, symbols are used; and when modelling PCB design, 2D line drawings of component footprints are used. Electrical circuits are expressed using schematics made up of component symbols to express circuit behaviour, though not model it, as this requires formulae.

The engineer can accurately place these models in relationship with the whole of reality. Students however, struggle to realise the importance of the models used in electric circuit theory (Harlow et al., 2011) because educators predominantly present only the calculation of formulaic models (Frederiksen et al., 1999; Shaffer & McDermott, 1992a). Students need explicit instruction about the ontological or true-to-life aspects of models (Oh & Oh, 2011) so they can appreciate them as descriptions of reality. Confusion develops when these aspects of reality are left out.

2.5.3. Pedagogical question 2: How am I going?

The second of the three questions for framing practice is directed at the need for both students and educators to evaluate the progress of learning. Bernstein wrote:

> *Curriculum defines what counts as valid knowledge, pedagogy defines what counts as valid transmission of knowledge, and evaluation defines what counts as valid realization of this knowledge on the part of the taught (2003, p. 203)*

A 'valid realisation' of students' understanding must avoid formulaic or rote learnings which are only an appearance of understanding with little substance (Winch, 2013a). Research by Marton and Säljö (1976) differentiates these surface approaches from deep meaning-oriented ones. Answering the 'how am I going' question involves taking a deep, not a shallow perspective. This question is not just about student learning, for in encouraging students to ask and answer this question, it challenges educators to reflect on their practices and whether they are developing opportunities for deep or shallow learning.

2.5.3.1. How am I going? - Success criteria

Students need concrete actions against which progress can be measured. These are known as success criteria and are the evidence statements teachers develop for a course (Clarke, 2001, 2005, 2008). They are derived from the literacy goal and ALOs (abstract learning outcomes). These include content and may include context. Many learning outcomes in courses look similar to success criteria, which can lead to the question as to why both are necessary. When courses are written with a focus on content-based learning outcomes, any content for the course becomes valid, and teaching can operate at a useful-content level which does not require knowledge to be linked to the episteme. When success criteria are written in response to ALO's the focus shifts to how the content and context link to the abstract goal.

When success criteria are referred to regularly, students become adept at identifying what is still needed and what is not working for their understanding (Hattie, 2012). Importantly the student no longer needs to guess what learning is about as they are fully aware of the double loop of both 'doing the right things' and 'doing things right'. Success criteria help develop students' authority over, and responsibility for, their learning (Clarke, 2008).

2.5.3.2. How am I going? - Feedback

Feedback is about progressing students' epistemic knowledge through revealing gaps in it. It features as one of the strategies that has the greatest effect on student understanding (Hattie, 2009). Laurillard (2002) describes that students' work is unproductive without it. Feedback given during teaching is called formative assessment, while evaluation for the purpose of awarding grades is called summative assessment. If the pedagogical question is centred on how the student is going in terms of their epistemic knowledge rather than how they went, it usually indicates formative assessment. However Brookhart (2001) found that successful students also made good use of summative assessment results to improve their understanding.

Feedback can be focussed on one of three ways: on the student, on tasks or on processes. Feedback which is aimed at the student should be in the conative domain (Herrington, Reeves, & Oliver, 2010), this is feedback directed toward the students' will, desire, drive and determination; this is aimed at developing their self-efficacy and self-regulation (Feisel & Rosa, 2005; Hattie & Timperley, 2007) and agency. Feedback aimed at the student which is personal, rather than conative, is not useful; if negative it lowers self-efficacy and if positive may have a negative effect on engagement even though students personally like it (Hattie & Timperley, 2007). Conative feedback can help students develop an identity that focuses on learning rather than results.

Feedback on tasks is layered depending on students' agency. Confirmation of in/correctness is sufficient for engaged learners, for less engaged students it does not make visible what is required for changes to understanding. This requires making strategies explicit or giving directions to students that they could pursue (Black & Wiliam, 1998). Often comparisons with other students are useful, and sometimes the provision of less explicit cues is highly beneficial (Hattie, 2009). Feedback should also be timed to align with student effort; this for instance can make computer-assisted feedback powerful (Hattie & Timperley, 2007).

2.5.3.3. How am I going? - SOLO Taxonomy

Bernstein (2003) describes evaluation as a valid judgment of what has been taught, and it was from seeking a valid way to recognise what students know that Biggs and Collis (1982) developed the Structure of the Observed Learning Outcome (SOLO) Taxonomy. A student's cognitive structure is not directly accessible, however their efforts are, and the taxonomy quantifies the quality of knowledgeable understandings in use and whether these uses are fragmented or integrated. There are five levels; the lowest is pre-structural, then uni-structural, multi-structural, relational and extended abstract, see Figure 22.

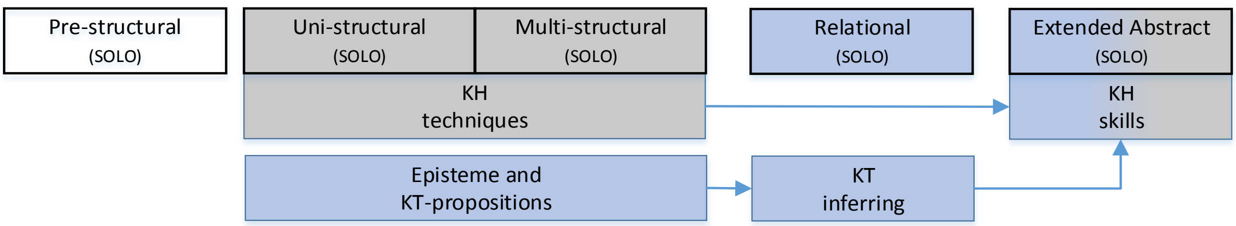


Figure 22: Alignment of the SOLO Taxonomy with the ways-of-knowing framework

Pre-structural understanding is where the student needs full guidance on how to approach a task. A uni-structural response to a task indicates a student's ability to use a single identifiable aspect of knowledge; this surface approach could indicate a low level of KT-propositions or KH-techniques. A multi-structural response demonstrates the ability to link several relevant aspects; this still indicates KT-propositions and KH-techniques. The most powerful aspect of the SOLO Taxonomy is perhaps that it clearly identifies the difference between fragmented multi-structural or KT-propositions and how relational (or linked) understandings are applied in use, which is KT-inferring. This is where most students' problems appear to lie in electrical engineering. The extended-abstract response shows students as capable of applying linked understandings into new problems or unknown situations, which are KH-skills. In design courses, students need relational understandings and in problem-based capstone projects, extended-abstract ability is required.

The SOLO Taxonomy is used extensively in education, and it seems to share the same critical realist standing as Bloom's Taxonomy, that of being valid and reliable through its ongoing use and scrutiny against empirical evidence. The core difference of the two taxonomies appears to be the purpose each was developed for: Bloom's to guide teaching through setting up expectations of intended learning (Krathwohl, 2002) and the SOLO Taxonomy to measure the observable outputs of student understanding. This does not mean that one cannot be used for the purposes of the other, but the distinction is carried through in this research with Bloom's Taxonomy being used to support the 'where am I going?' first pedagogical question and the SOLO Taxonomy with the second 'how am I going' pedagogical question.

2.5.3.4. How am I going? - Threshold Concepts

The work by Meyer and Land (2003, 2005) on threshold concepts has important implications for educators. Threshold concepts are significantly troublesome knowledge for novices and stall their development of epistemic knowledge until overcome. They are conspicuously transformational (Meyer & Land, 2003), and once a student is transformed, the concepts may not be unlearnt, as the way the student 'sees' or reasons about the world is now quite different (Atherton, Hadfield, & Meyers, 2008; Quinlan et al., 2013; Scott et al., 2010). Transitioning toward understanding of threshold concepts is a non-linear process and marked by 'liminality', an unstable state where the novice has left behind the previous knowledge but not yet attained the new (Harlow et al., 2011). A liminal state is also characterised by some back and forth fluctuation in understanding (Biggs & Tang, 2011; Quinlan et al., 2013; Scott, Peter, & Harlow, 2012).

In electronics Scott and Harlow (2012) have identified modelling, dynamic resistance, reactive power, feedback, and dependent current and voltage sources as threshold concepts. Threshold concepts from school physics include holistic current flow (Kirchhoff's current law – conservation of charge), mapping between circuit and real components, and drawing conclusions from graphs. Reflecting on the complexity of what we seek students to understand from the work of Sangam (2013) shown in Figure 4 on page 13, it is perhaps reasonable to expect students to have significant trouble comprehending some, if not most electric circuit theory. While both the identification of threshold concepts and how to transition student understanding is difficult, identifying when a threshold in understanding has been reached is clearly evident by whether a student is able to demonstrate performances of understanding (Biggs & Tang, 2011).

With threshold concepts being troublesome, the risk exists in our educational systems for these to be "quietly dropped" (Meyer & Land, 2003, p. 6) in favour of a KT-propositions or rote learning that students can more easily achieve. Because some courses have many threshold concepts in their early stages there has been pressure to move some of them to later parts of courses (Scott et al., 2010), something that should be rejected so as not to weaken students' epistemic foundations.

Perkins (1999) importantly describes troublesome knowledge as coming about because it is ritualised, foreign, conceptually difficult or inert. All four of these concerns have been identified in section 1.5 on the problems identified with understandings of electric circuits. Ritualization describes the preeminent focus of formularising and practicing isolated circuit patterns, such as the formula for resistors in series and parallel. Fundamental circuit properties such as voltage, current, energy and power are effectively foreign, even though they are in everyday use, as learners find their true meanings quite alien. Circuit properties are conceptually difficult because they are invisible. Inert knowledge is a consequence of our pedagogy, how so much of the circuit theory is based on circuit fragments and formulae that are kept distant from the reality in which they are used. These four aspects of troublesome knowledge encourage learners to maintain their focus on KT-propositions and KH-techniques. Seeing threshold concepts as aligned to ways-of-knowing provides signposts for us in selecting pedagogical practices centred on knowledge development through direct instruction followed by project-based learning (Figure 17 #23 - #22), and avoiding practices that require students to identify knowledge for themselves from the context in which they work.

2.5.3.5. How am I going? - Scaffolding

Scaffolding is the term used to describe how educators frame their teaching into manageable chunks. Scaffolding is often related to Vygotsky's (1980) concept of the zone of proximal development (ZPD). While his theory is one of development, his ideas have been widely applied to teaching (Chaiklin, 2003), particularly his idea of a proximal zone for learning. The proximal zone represents the gap that exists between what students can do and what they could do with external support. Any gap in knowledge that students can cross on their own is beneath the proximal zone and may lack sufficient challenge. Any gap in knowledge that lies beyond students' proximal zone is too challenging, and is unreachable even with assistance. This latter issue is important in electrical engineering where there is considerable difficulty in bridging gaps in understanding. In their work on threshold concepts, Scott and Harlow (2012) identified that researchers need to distinguish between a threshold concept and the situation where students have weak underpinning concepts. The latter indicates students do not have KT-inferring of prerequisite chunks. Instead their KT-propositions and proficiency with KH-techniques hide the fact they are well back from the proximal zone for the concept they need to learn.

To progress students across the proximal zone, the required epistemic knowledge is broken into chunks. The term steps is avoided, firstly because electric engineering is often treated in textbooks like sequenced steps in a recipe (Jilek, 2010) and secondly because electric circuits are not sequentially organised but part of a hierarchical knowledge structure (Bernstein, 1999) where higher order chunks subsume lower ones. Often educators do not realise how tacit these subsumed understandings have become, and the density of knowledge condensed within a single term. This can make identifying the chunks required for scaffolding difficult. When scaffolding does not take into account how one aspect of understanding subsumes or links to another, students build isolated clusters of knowledge (Winch, 2013) - a fractured episteme.

Pedagogical expertise is required to flesh out a domains hierarchy and density, and then build a sequence for knowledge progression.

2.5.3.6. How am I going? - Conceptual change

In the situation where students have existing knowledge which conflicts with new knowledge, a conceptual change process needs to take place. Conceptual change is problematic; Chi (2008) describes three approaches to it, each relating to a different type of incorrect understanding. When misunderstanding exists as a single unlinked instance, i.e., as KT-propositions, confrontation with a clear contradiction can lead to belief revision. For example, when a student incorrectly identifies a capacitor on a circuit board as a resistor, correction takes place by showing them how to recognise the differences. The next two issues of misunderstandings are more troublesome with regard to change as they are held as collections of beliefs - as an incorrect episteme. These are incorrect mental models or conceptual miscategorization. Both are prevalent in research around student understandings in electrical engineering. For example, the mental model of current held by students is often incorrect, as current is referred to as ‘used up’ in a circuit; and energy is often miscategorised as a substance rather than a process (Chi, 2008). In these cases, students cannot be ‘told’ or shown what is wrong, change must take place at a conceptual level (Duit & Treagust, 2012). This requires using practices such as visualisation to correct mental models (Finkelstein et al., 2005) and the development of concept maps such as that of Sangam’s (2013) in Figure 4 on page 13 to build correct categorisation.

2.5.3.7. How am I going? - The relationship with context

One of the important aspects of teaching is the relationship of understanding with context (Finkelstein, 2005). While context on its own leads to naïve understandings, as described by the literature on misconceptions, it is important to link abstract understanding with the real world (Laurillard, 2002; Maton, 2014a). There are however two alternative views about context in literature. The first is where concepts need to be grounded in experience before abstraction (Laurillard, 2002) and the second where abstraction needs to precede context (Maton, 2014a). The second view is preferred as it specifically informs students about what to look for in a context, avoiding the misleading nature of observations (Rata & Taylor, 2015), which once established, require a difficult conceptual change process.

Context is powerful when it is authentic because it activates non-verbal components, one of the essential parts of the systemic view of understanding (Amin et al., 2014). Once students are taught to analyse a context in terms of the abstract knowledge underpinning it another context can then be put forward for students to identify the principles within that. After several opportunities to recognise the abstract within context it becomes generalised and forms the basis for KH-skills. Context is important because abstract thought-holders are propositions and words, and words take on meaning within context (Hattie, 2009). The word resistance can be defined but until a resistor is placed in series with an LED and its brightness affected, the concept of resistance has little meaning. In electrical engineering, authentic contexts are often thought as too complex for novice learners; however abstract concepts or thought-holders such as resistance can be expressed in very simple circuits using multiple resistors, battery and LEDs.

2.5.3.8. How am I going? – The role of graduate teaching assistants

The graduate teaching assistant (GTA) is recognised as holding a key role in tertiary education. They are often the person closest to the student as they run laboratories, take tutorials, write course materials, oversee online forums, write tests and examinations and grade them. Positively, the GTA role is viewed as an important way of providing funding for post graduates studies (Chism & Warner, 1987). However some academics view it as a means to increase research output by alleviating pressure on themselves (Park, 2004); for instance the excessive use of GTAs has been criticised as “education on the cheap” (Chism & Warner, 1987, p. 9). There is, though, a growing dependence upon GTAs in tertiary situations, and in some countries undergraduate courses are taught solely by GTAs (Park, 2004). One issue with this is that GTAs are not as adept as lecturers at recognising common difficulties that students have (Maries & Singh, 2016).

While universities are increasingly investing in training programs for GTAs (Park, 2004) the model of learning applied to them is usually an apprenticeship model rooted in behaviourism (Chism & Warner, 1987; Park & Ramos, 2002; D. E. Williams & Roach, 1992). Initially GTAs' activities are closely monitored and corrected; as confidence increases in their ability to copy their role model, supervisory requirements made upon them reduce. An outcome of this model is that GTAs often develop the need for performance feedback, in contrast to feedback on their success as an educator (Park & Ramos, 2002). This is observed through their focus on procedural matters such as grading correctly and classroom management (Benveniste & Berry, 1991). This aspect is further strengthened by the GTAs' view that while they are part of long term course planning, they are reactively called upon only when needed (Park & Ramos, 2002).

There is research that can inform GTA development, and this relates to beginning teachers and mentoring them through their first years in the classroom. The important focus for coaching is to shift to helping new educators reason about their performance rather than focusing on the surface performance of students (Timperley, 2001; Tomlinson, 2001). This aspect of GTA development is crucial so that they can contribute to the development of student understanding.

2.5.4. Pedagogical question 3: Where to next?

The third pedagogical question is 'where to next?' This is not the question 'what do I do next?' – a question I have spent many hours in classrooms directing students away from. The question is about the next steps in understanding, and relates to helping a student develop metacognitively.

While metacognition is considered a property of students, its development requires a significant change to occur in the way they view knowledge, and this requires a morphogenetic cycle to take place (Archer, 1995). As educators have corporate agency and students have primary agency, the onus is on educators to set up situations where the incompatibility between any inferior knowledge practices and the goals become visible to students. Then students will begin to recognise that their current agency is incongruent with the situation. In Archer's terms, this would be educators developing a situational logic of necessary contradiction that stimulates morphogenesis. This process is not one which comes easily; as it stands in contradiction to the observation by Merrow in his documentary about tertiary learning where educators and students can exist in a stand-off of compromised expectations (section 2.3.2).

In the early stages of developing metacognitive awareness, training students away from dependence can be achieved by rephrasing the three questions. For example: 'Which learning intention does this task relate to?' 'How do you see what you are doing in relation to the learning outcome?' 'What questions do you still have about your own understanding?' After a period of time students will begin to stop asking 'what do I do next?' and begin to develop the awareness and metacognitive control they need for themselves, then ask and answer the question about where their learning should go next.

2.5.5. Pedagogical practices summary

In Figure 17, several pedagogical practices are presented. This is not supposed to be an exhaustive account of practice; rather they were discussed in terms of informing this research around the three pedagogical questions heuristic. The discussion centred on the point of view by Orchard and Winch (2015) that teachers need to develop a critical lens to understand the conceptual dimensions of their practice. Practice should not be approached as some form of craft but professionally, just as engineers would approach practice. Educators with a formal background in theory can develop a social realist perspective about practice, one that is critically aware of the social nature of learning but not driven by personal beliefs or situations. They are able to empirically and critically judge alternative theories to establish the best-fit. These are important understandings if education is to have the academic effect it needs to have on students' abstract knowledge development. It is also crucial if educators are to engage with the topic of the next lens used in this research, educational technology.

2.6. Educational Technology

While some benefits of educational technology have been claimed since personal computers began to appear, doubts and questions have been raised about the efficacy of using computers and technology to improve student outcomes (Higgins, Xiao, & Katsipataki, 2012; Luik, 2007; OECD, 2015). One concern is the lack of educational theory in courses on developing educational technology (Ertmer & Newby, 2013), which leads to designers who lack awareness of the emergent properties of information technologies. One example is the organisation of data within databases, which once in use are resilient to change, and consequently have controlling effects on teaching and learning structures (Mutch, 2010).

The purpose of separating this section from the discussion on pedagogy is not to identify it as different, but to distinguish its place in pedagogical structures and educational cultures and thus avoid several issues with educational technology, including: the lack of theoretical grounding of much research into learning technology (Gunn & Steel, 2012; Howard & Maton, 2011), and the expending of valuable resources only to achieve more of the same (Renken & Nunez, 2013).

2.6.1. More (or less) of the same

With dwindling numbers in small group tutorials and increased class sizes, some universities have replaced face-to-face tutorials with online questions (Scott, Harlow, & Peter, 2014; Smaill, 2006). This has benefits for lecturers by reducing their workload, benefits for universities by reducing staff to student ratios, and benefits for students as results are returned immediately and the accuracy of their calculations can be tightly controlled (Hussmann & Smaill, 2003; Smaill, 2005). While educational technology tools may appear successful through automating drill and practice type work the transformative potential of using educational technology in this way is reduced (Kinchin et al., 2016). As discussed in sections 1.5.11, drill and practice based understandings are unsatisfactory. These further encourage students' unsatisfactory exam-taker identities (section 2.3.2). The question arises then as to whether educational technology drill and practice tools are helping with the learning problem or contributing further to it. In this case, educational technology could be said to be achieving 'more of the same' – though with an increase in efficiency.

There is a practice by educators to jump into the educational technology arena by putting existing teaching materials online. However when those materials are used in class, the teacher unpacks them for students determining if the required epistemic knowledge is being developed. Online, the situation is very different as the learner works with the materials on their own without the teachers' support (Teo & Gay, 2006). This content focussed approach to using educational technology (Kinchin, 2012) leads to a situation where students actually get 'less of the same'.

A significant factor with realising the potential from educational technology is the role of knowledge in education. There are concerns about the 'knowledge-blindness' (Maton, 2014b) driving educational technology development, as this tends to focus educational technology development on pedagogy (Higgins et al., 2012). Howard and Maton (2011) identified the limited way educational technology was used in Mathematics classes to build KH-techniques and in English classes as ways of expressing oneself using KH-transversal abilities which led them to conclude that there needed to be a stronger emphasis on the knowledge being taught. Educational technology that centres on replicating existing limited pedagogical practices rather than knowledge represents a 'more of the same' approach.

2.6.2. TPCK

A prominent model in education often used to describe teaching is that of PCK (Shulman, 1986) which, with the growing use of education technologies, has been extended by Mishra and Koehler (2006) into TPCK - technological-pedagogical-content knowledge, as shown in Figure 23. TPCK extended the goals of PCK to focus educators on knowledge and the representation of concepts, not the replication of existing pedagogy (Kinchin, 2012).

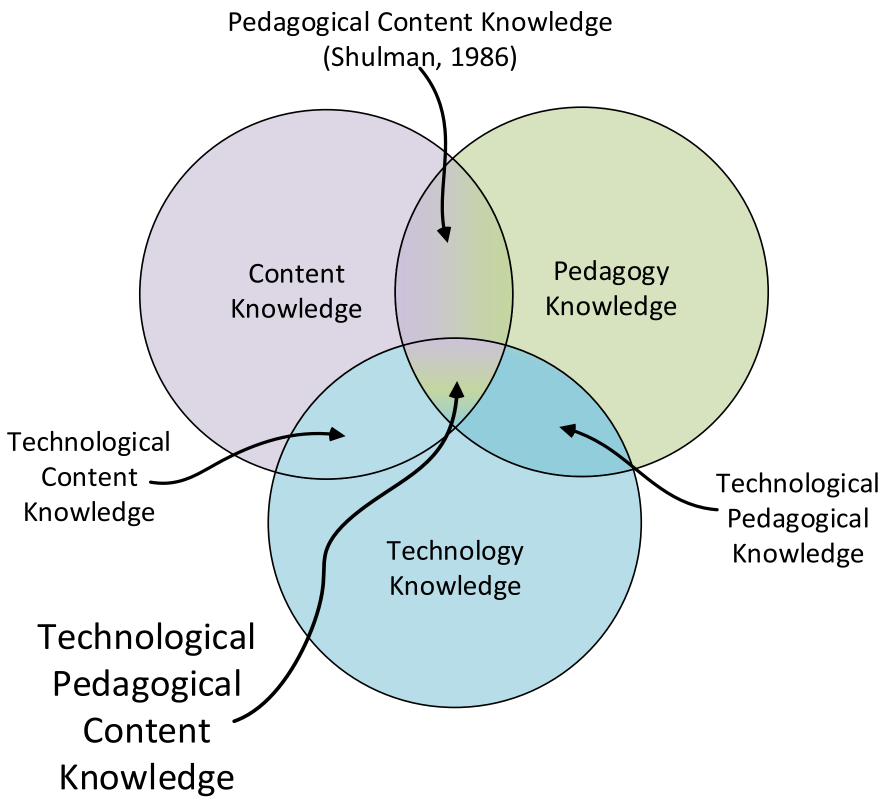


Figure 23: Technological Pedagogical Content Knowledge

Adapted from "Technological pedagogical content knowledge: A framework for teacher knowledge" from The Teachers College Record (p. 1025) by P. Mishra and M. Koehler 2006.

Being able to manage the demands of teaching and learning requires resolve by an educator to develop their identity as a professional educator – to develop their PCK - the way in which expert educators synthesize knowledge and pedagogy to bring about student understanding (Shulman, 1986). To develop TPCK however, does not just add one more aspect to PCK. Mishra and Koehler(2006) describe four more aspects that TPCK requires: technology knowledge, which describes the knowledge needed to operate and create learning artefacts; technological-content knowledge (TCK), about how subject knowledge can be changed by technology; technological-pedagogical knowledge (TPK), how educational practices can be influenced by use of educational technologies; and the overall combination of technological-pedagogical-content knowledge. These added layers place significant burdens on establishing a theoretical underpinning to educational technology in ways that can positively influence student knowledge and avoid more or even less of the same; what Kinchin describes as "technology enhanced non-learning" (2012, p. 46).

2.6.3. Visualisation

With circuit theory there is little chance of students implicitly making understanding for themselves as the epistemic knowledge of electric circuits (electric potential, charge flow and their interrelationships, as expressed through Kirchhoff's and Ohm's laws) are only visible by proxy. In contrast the properties of mechanical and civil engineering disciplines such as velocity and acceleration are more easily observable and are more easily conceptually grasped (Engelhardt, 1997; Jaakkola et al., 2011). Relying on sensory experience for understanding of the hidden nature of circuits is impractical and leads to misunderstandings. In Figure 17 #8 the term 'Naïve Observer' was used to describe students with misunderstandings formed from sensory experience about electric circuit phenomena.

Visualisation is one aspect of educational technology that has shown to be powerful in helping students learn about the nature of unseen reality (Chen, Hong, Sung, Chang, & others, 2011; Hundhausen, Douglas, & Stasko, 2002; Naps et al., 2003; Urquiza-Fuentes & Velázquez-Iturbide, 2009). To be effective in helping correct misconceptions, visualisations must animate the content or conceptual metaphor to be learned (Amin et al., 2014; Höffler & Leutner, 2007). Animation of electric current and voltage therefore might be deemed useful with students who hold existing misunderstandings in electric circuit theory, specifically: open and closed circuits, Kirchhoff's Current and Voltage Laws, series and parallel component combinations; and more difficult concepts such as constant current sources, and the electric current properties of OpAmps where there may be no input current but there is an output current. Visualisation can provide a holistic view of the way phenomena act (Eilam & Gilbert, 2014). This could be strategically important to students of electric circuit concepts in that they often exhibit localised thinking about changes to circuit components. Animation would allow students to predict and then 'see' the full effects on the circuit. The Variation Framework (section 2.4.4.2) is informative about how visualisation can be leveraged in electric circuits where voltage and current are co-varying.

2.6.4. Model based instruction

Educators, and some students, have voiced concerns about simulated learning environments replacing real environments and students therefore loosing valuable practical experience and real skills (Dobson, Hill, & Turner, 1995). While simulation tools cannot fully replace real situations, they can perform a powerful function when used with students to develop mental models. The development of mental models is a key aspect of cognitive educational theorists which centres on using model-based instruction (Frederiksen et al., 1999; Seel, 2006). Models that portray dynamic relationships allow the student to sense change and trends that are otherwise hidden (Gibbons, 2008), and this helps develop viable mental models – accurate epistemic knowledge of these unobservable phenomena and their temporal relationships (Eilam & Gilbert, 2014; Papadouris & Constantinou, 2009; Rutten, van Joolingen, & van der Veen, 2012).

Model based instruction has been successful in complementing teaching especially when used in addition to experimental work (Jaakkola et al., 2011; Rutten et al., 2012). When comparing real and virtual environments, Finkelstein (2005) found that students who used real equipment had issues building simple closed circuits, yet where students used a simulation as well as real equipment they did not have the same difficulties. Benefits from using simulation in conjunction with the practical were not short lived effects but carried over into their overall course results as well (Kollöffel & de Jong, 2013). Benefits of mixing the real with the visualisation may be due to the increase in fidelity, i.e., the focussing of students' attention on the real nature of the experiment by reduction of the amount of 'noise' in the environment caused by the confusing array of new equipment and processes that students need to cope with (Zacharia & de Jong, 2014).

To have educational benefit, students must engage with visualisations in meaningful or scientific ways (Eilam & Gilbert, 2014; Keilson, King, & Sapnar, 1999; Steinberg, 2000). Even in controlled situations, students are prone to engage at a surface level, ignoring instructions and aimlessly playing (Keilson et al., 1999). A useful method for teaching using simulations is to have students predict and then observe contradictory phenomena (Dori, 2005; Tao & Gunstone, 1999; Weyten, Rombouts, & De Maeyer, 2009; Wylie & Chi, 2014). Naps et al. (2002) developed a taxonomy for engagement with algorithm visualisation: viewing, responding, changing, constructing, presenting. They found students do not generally engage with viewing simulations satisfactorily enough but do engage when asked to respond, change, construct or present.

2.6.5. Designing educational technology models

Students have difficulty going beyond the superficial aspects of visual representations and models to interpret their real meaning, and teachers tend to assume too higher levels of student understanding from the diagrams and images they use (Eilam & Gilbert, 2014). An important aspect of using diagrams and models involves taking time to explicitly help students understand the syntactical elements and meaning of them. Cognitive scientists have explored maximising learning from media design. These are relevant when using educational technology to model and visually represent phenomena when the teacher may not be present to unpack the meaning for students, and the educational technology must do most of the teaching. Cognitive scientists found that experiencing new media can easily create a great deal of cognitive load due to the significant amount and complexity of unknown information that must be processed by learners (Paas & Sweller, 2014). For instance, having too much new complexity to deal with at any one time can create an overload of our working memory, which has a limit of 7 +/- 2 items (Kellogg, 2011). Media or components of media that are familiar already, exist in long term memory, which can be accessed without these limits. Educational technology design, therefore, should begin with a clear appreciation of the number of new understandings that students need to cope with.

Mayer (1989) identified seven cognitive characteristics of models that are useful when designing educational technology materials (Table 2) to manage cognitive load.

Table 2: Summary of Mayer's Characteristics of Good Models.

Complete	All needed elements, actions and associations for learning a concept are present.
Concise	Capped at five or so tasks to avoid excess information
Coherent	Sense making, showing interactions and rules for those interactions
Concrete	Depiction should be familiar to the learner
Conceptual	Shows the system operation meaningfully
Considerate	Student level vocabulary and organisation
Correct	Major analogies used are correct

Note: Adapted from "Models for Understanding" by R. E. Mayer, 1995, Review of Educational Research, Volume 59(1), 43-64. Copyright 1989 by SAGE Publications

These can provide useful tools for educational technology design not just in terms of reducing cognitive load, but in making educational technology tools as powerful as possible with regard to developing students' epistemic knowledge and KT-inferring. For example, a lack of coherence makes materials difficult for students to follow, a criticism levelled at textbooks when diagrams and explanatory text are not linked causing a student to have to move backwards and forwards in the text to find the explanations for diagrams (Eilam & Gilbert, 2014).

In electric circuit theory, the predominant means of engaging students with epistemic knowledge is through circuit diagrams or schematics, which are the conceptual models which express circuit behaviour. The schematic however, as a conceptual model, lacks many of the seven characteristics for good models described by Mayer (1989) in Table 2 on page 94. One of these is completeness, as not all actions and associations in an electric circuit are present within schematics so they are insufficient in developing a student's episteme of understanding. For example, the foundational epistemic properties of electric potential and charge flow that students have significant trouble with, are absent and must be inferred. Also lacking is coherency, as the rules and interactions taking place are not visible e.g. the interrelationships between component values and electrical potential or charge flow. Concreteness is another characteristic lacking as there is little development of what circuits really do in the world when looking at a schematic.

2.6.6. Benefits of educational technologies on feedback

Feedback for learning purposes was discussed in section 2.5.3.2; strategically there are benefits to both lecturers and students when educational technology tools involve feedback on student progress and learning behaviour. Students can receive immediate formative feedback provided by an e-tool as it responds dynamically to student input. In both real time and after use, educators can receive analytics or statistical information that can inform them of their impact on student understanding (Choquet, Iksal, Levene, & Schoonenboom, 2009; Siemens, 2013). Another benefit of analytics arises from the issue that educators' buy-in is the single most important factor in the success of new educational technology environments (Jaakkola et al., 2011; Naps et al., 2003). Buy-in cannot be separated from the identity and agency of educators and the structure and culture of the situation. While agency and structure may make educators reluctant to change existing pedagogy, when faced with the amount of feedback that students can receive and the data that learning analytics can provide to educators, refuting benefits is difficult.

There is also the potential for analytics to provide benefits in terms of summative or high-stakes assessment if useful data were incorporated into an overall strategy for assessing learning outcomes (Smaill, 2005). Many students fail to collect marked assignments, suggesting that they do not regard the marked script as valid feedback; e-feedback however does not need to be collected as it can be immediately delivered. Students can become engaged with feedback on summative (marked) tasks if given resubmission opportunities. Jiao (2015) found that awarding marks encouraged students to not only take time to correct errors but it also reduced similar errors in subsequent tasks.

2.7. Chapter Summary

This chapter has reviewed literature relating to a diverse range of theories. This was essential as the field of learning in engineering education is very broad with its transitions from core science to engineering science to project-based work, and these learning processes are deeply embedded in the institutional structures and culture of engineering faculties and universities. Engineering education entails a wide ranging development of engineering students' episteme, KT-inferring capability, KH-skills and KH-transversal abilities to allow them to begin to work with complex problems. The pedagogy behind this requires a cohesive and multi-faceted approach and the negotiation of competing factors relating to the identity and agency of both educators and students that significantly influence success or failure.

Engaging with what is understood about types of knowledge was depicted in the chapter through the ways-of-knowing framework followed by a discussion of the ontological and epistemological roots of various educational theories and how these interact with student knowing. In turn, having a critical understanding of theory and a heuristic to apply theory can inform thinking about various pedagogical practices and reveal how each can contribute to student knowing. Through these discussions an answer to Winch's question at the beginning of the chapter, about whether all learning could take place without teaching, became clearly evident; learning most definitely requires teaching and teachers with a high level of professional knowledge. Niemann's comment about craft, also from the beginning of the chapter, is important as it encourages educators to go beyond seeing their role as craft, to become professionals who engage with difficult theoretical concepts. This engagement will have rewards in terms of student understanding and avoid the epistemological dead end.

Chapter 3. **Research lens, methodology and methods**

3.1. Introduction

Teachers' and engineers' problem solving skills come as a direct consequence of their ability to apply core principles (Hattie, 2009; Winberg et al., 2016). I aspired to undertake worthwhile and meaningful research into a significant issue, and this chapter establishes the research principles necessary for this. It begins with a discussion that frames the research as realist, making use of the lens from discussions about social realism in section 2.3. Following this is a description of the research as case study methodology; then the overarching strategy and the methods for each research question are explained.

3.2. The research questions

The case study research was conducted in stages. Only the first stage of observations and interviews was planned at the outset. The first two research questions took form early in this process, and as a result from these the second two questions were developed:

- RQ1: What is the real nature of the learning problem?
- RQ2: Can an increased focus on epistemic knowledge help students in first year electrical engineering?
- RQ3: How can theory and understanding of the situation inform the development of a novel knowledge-based educational technology tool?
- RQ4: What is the effect of an integrated approach to pedagogy and educational technology on student knowledge?

3.3. Overview

The final or summary plan for the case study is shown in Table 3. This collates the research questions with the methods and data collection undertaken at each stage.

Table 3: Case Study Research Investigations and Data Collection Overview

	2015 Semester 1	2015 Semester 2	2016 Semester 1	2016 Semester 2	2017 Semester 1	2017 Semester 2
RQ1:	The 'real' nature of learning investigated in EE201, CS201, EE101, EE209. OASIS evaluation using McKenney and Reeves (2012) criteria: soundness, institutionalization, effectiveness and impact					
RQ2: FCCTs focus on epistemic knowledge	FCCTs development and focus group trials carried out	Conceptual quiz and FCCTs use with EE101 (0% course mark)	Changes to FCCTs based upon student feedback	FCCTs use with ElectEng101 using GECKO. (4% course mark)		FCCTs use with ElectEng101 using GECKO (0% course mark)
	Development of GECKO using McKenney and Reeves (2012) criteria					
RQ3: GECKO Development	Soundness: pilot testing of circuit visualiser in FCCTs	Feasibility: liaison with IT department, development of database and applications	Local viability: Ongoing development FCCTs move to GECKO, pilot	Local viability: testing in EE101 and ongoing development		
				Analysis of GECKO using McKenney and Reeves (2012) criteria		
RQ4: GECKO integration				Redevelop CS201 course	Institutionalization: CS201: GECKO	Effectiveness study in EE209
Data collection	EE201, CS201 observations and interviews (N=12), course results analyses	EE209, (N=64), observations interviews (N=5), EE101 quiz (N=468), FCCTs (N=242)	Interviews (N=19)	EE101, usage analytics, course results, FCCTs (N=834), EE209 observations	CS201 usage analytics, course results analysis(N=218) interviews (N=10)	EE101, usage analytics, course results. FCCTs (N=307). EE209 observations and survey (N=55)

3.4. Positioning the research as realist

In Chapter 2, social realism was presented and discussed in terms of theoretically framing knowledge and situations. The same lens of social realism became the perspective applied to this research. McPhail and Lourie (2017) describe the three dominant research paradigms as interpretivist, positivist and critical, and that the realist research paradigm is often overlooked because its place in relation to the other three is not well understood. This research uses a realist approach aimed at identifying the level of the 'real' and to avoid the epistemic fallacy (Archer, 2002; Bhaskar, 2013) - believing that 'what is seen is what is actually happening'.

In educational research, a positivist approach can be used to develop objective understandings, to quantify, isolate and test human variables, just as might be done with the variables in an electric circuit. This approach is used to avoid confounding by the many interactions within a situation. When speaking with a lecturer about educational software research, a positivist view was promoted: "oh it's easy, just split the course randomly into two groups. Test the first group in one way with one, the other way with the second group and there's your data, write it up and that's your research". There are however, learning structures and culture, as well as identities and agency that influence the validity of this sort of test and processes such as sampling cannot control for all these confounds.

This does not indicate that positivist methodology is poor, indeed this research uses the analyses by Hattie (2009, 2012, 2014) of over 1200 meta-analyses of many thousands of rigorously conducted studies that measure and quantify learning phenomena. Hattie (2014) describes that the results of the studies do not make them direct predictors of success, and that the probability of success for student outcomes is realised only when an expert educator fully understands their unique situation. Hattie's comments recognise the critical importance of bringing the 'real' or hidden into perspective when using empirical results. A positivist lens therefore did not seem to provide access to the hidden aspects of the situation.

In the early stages of the research, an interpretivist phenomenographic approach (Marton, 1981) was considered. This is where the points of view of how people perceive events and situations are collected and analysed. While entirely valid research, an interpretivist view can leave us without an idea about how to improve the situation (Case, 2013), because it does not always produce generalizable knowledge (McPhail & Lourie, 2017). This should also not be interpreted as a criticism of interpretivist methodology; indeed phenomenographic research has identified highly important understandings about teachers (Kinnunen, McCartney, Murphy, & Thomas, 2007), students' perceptions of software (Kinnunen & Simon, 2012), learning in physics (Ramsden et al., 1993) and electric circuits (Prosser, 1994). It also led to Variation Theory (Marton & Pang, 2007) which is leveraged in this research. What was needed was a way to take an interpretivist research approach further within the situation of the learning problem.

A third perspective is research aligned to a critical view. This seeks to identify the nature of the hidden in a situation. This refers to power relationships between groups and change refers to altering social relationships between those groups (Case & Light, 2011; McPhail & Lourie, 2017).

Realism is a different perspective; it integrates aspects of the previous three. It is explicative, creating knowledge to explain the nature of the world. It is objective in that it does not depend upon those who create or hold it. It can develop causal understandings about the systemic way that the identity and agency of people interact with the ways-of-knowing, and the social structures and cultures of the organisations that they are a part of (Archer, 1995).

A realist theory aligns with thinking by educators that learning exists within highly complex systems (Amin et al., 2014; Hattie, 2012; Laurillard, Oliver, Wasson, & Hoppe, 2009). An understanding of systems is an important part of modern engineering. Importantly, a systems approach in engineering differentiates between taking a systematic as opposed to a systemic view of a system (Storey, 2017). For instance, when engineers take a systematic approach to design, large systems are broken down into smaller and smaller subsystems. This is a reductionist view that sees systems simply as the sum of their parts. As Storey (2017) describes, a systematic level of analysis cannot express the 'feel' or 'ride' that a system such as a car has, as these characteristics exist due to complex interactions between many components. The better approach is a systemic one; this is a holistic view of a system that describes the complexities of the whole system in full operation, giving us an understanding of its 'feel'. When a situation is viewed systematically, it is seen at the surface level or the 'actual', and as the sum of many parts. A systematic view does not acknowledge the synergies or antergies (negative synergies) of the interrelationships between knowledge, structures, culture, student and teacher identities and agency. Social realist research seeks to find a systemic perspective, one in which the situation is viewed in full operation, to achieve the perspective at the level of the 'real'.

3.5. Case study research

In this research a qualitative methodology, the case study, was chosen to carry out the investigations of knowledge and pedagogy in the first two years of electrical engineering. The case study is a way of developing important 'insider' knowledge about a single phenomenon at a single point in time (Hancock & Algozzine, 2006), and for resolving what is happening in great detail (Case & Light, 2011). The power of qualitative research methodologies such as case studies are that the visible aspects of people, structure and culture can be used to build theory (Stake, 1995). The case study therefore operates at the level of the 'actual', and the theory it develops at the level of the 'real'.

While case study is a powerful research methodology it is important to ensure that it is conducted in a robust manner to ensure its usefulness (Golafshani, 2003) or trustworthiness (Guba & Lincoln, 1989). Lincoln and Guba (1989) propose that trustworthiness is established through criteria of credibility, transferability, dependability and conformability. Credibility can be used as a qualitative research criterion equivalent to internal validity for quantitative research, and dependability as the criterion equivalent to reliability. Several criteria were used to clearly define the case study to develop its credibility and dependability.

Stake (1995) describes case studies as intrinsic or instrumental (or collective if multiple cases involved). The focus of an intrinsic study is directly on the study of the issue(s), whereas the instrumental case study seeks to develop theoretical explanations as to the reasons behind the issue(s); instrumental was identified as most suitable for this research. An instrumental case study requires a recursive process of developing rich descriptions using multiple sources of information to develop comprehensive understandings about situations.

The second criteria Hancock and Algozzine (2006) and Thomas (2015) stress is developing the purpose of the case study. Purpose can be exploratory, descriptive or explanatory. The study had an initial exploratory stage which involved informal discussions with several students and lecturers along with reading over notes from various courses. At this stage, the analysis of literature took place to identify what was known and not known about learning in electric circuits (see in section 1.5). Subsequently, the case study entered an explanatory stage to identify why the situation existed and how various learning processes were influential within it. This led to a broadening of the research and seeing the issues not just as those aligned to electric circuits.

The next criteria was approach, which was aimed at increasing the study's power to develop theory about the unique situation under investigation. This involved identifying boundaries or delimiters for information gathering (see section 3.6) and the identification of participants who could serve in the role of 'member-checking'. These people were used to discuss the legitimacy of results identified as the research progressed (Yanow & Schwartz-Shea, 2015).

The last criteria was whether the case study should be retrospective, a snap shot or diachronic. Whilst initially envisaged as a snap-shot of the situation, it became clear that a diachronic view was needed as aspects of change had occurred over time in relation to learning in the first year course ElectEng101. These changes became important in explaining why the current situation existed. To achieve this level of understanding, a lengthy time in the environment was required, to assure the situation was well enough understood (Bhattacherjee, 2012).

3.6. Research strategy and methods

The research activities are summarised in Table 3 on page 98. These are the result of a strategic approach that was planned to guide the research in the early and middle stages. It was evident at the beginning of the research that to reach the 800+ students in ElectEng101, some aspect of educational technology would be useful.

A strategy was developed based upon the design based research model for doctoral student work by Herrington, McKenney, Reeves and Oliver (2007). Their model was chosen from alternative design based research processes (Barab & Squire, 2004; Herrington et al., 2007; Laurillard et al., 2009; R. Phillips et al., 2012), as it fully expressed the need to capture the complex nature of the situation and was centred on a model of design based research that encouraged early engagement in iterative and reflective projects that could meet doctoral study timeframes. Figure 24 shows the research strategy centred on the four research questions.

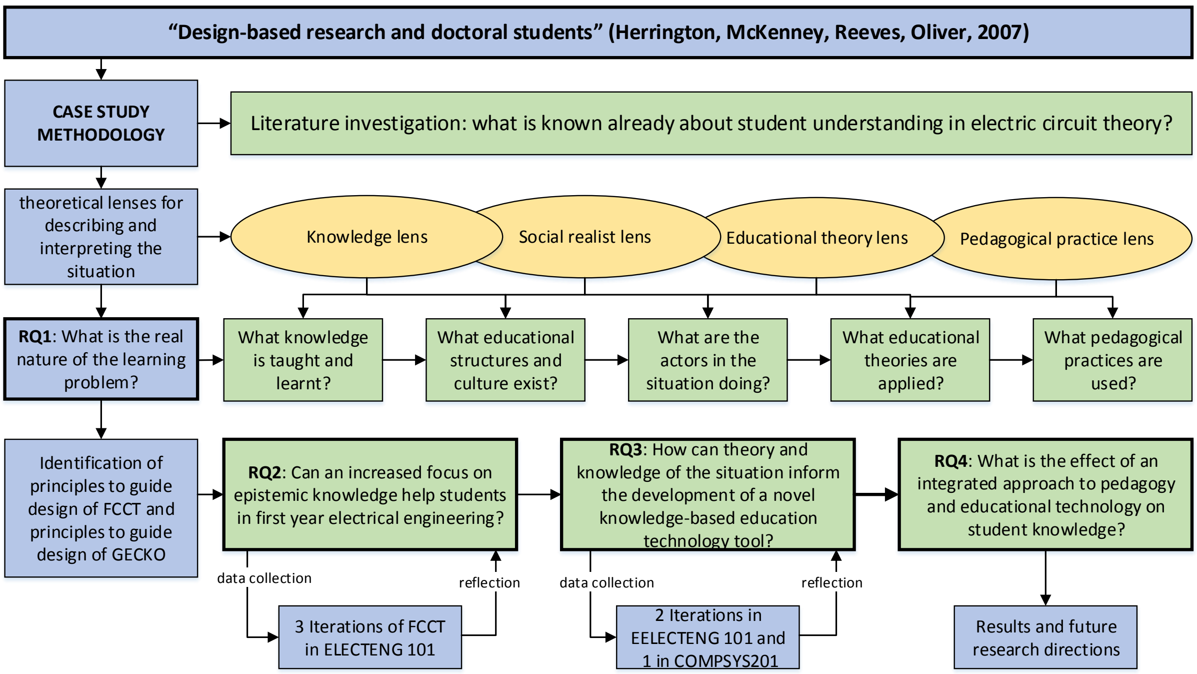


Figure 24: Design based research strategy, design based upon work by Herrington et al. (2007)

The ability to carry out the four parts of the case study developed due to a range of synergistic factors. These were: understandings from prior research in the department into student understandings (Smaill et al., 2008), prior research into the culture of learning within the faculty (Godfrey, 2003), the institutionalisation of the existing tool OASIS within learning (Bigdeli, Boys, Calverley, & Coghill, 2001), a personal background that included 40 years of in electrical engineering, teaching, and software development.

Design based research requires identification of principles to guide design and reflective iterations of testing (Herrington et al., 2007) to refine the principles and design. The iterations of the FCCTs were carried out over three successive years in ElectEng101. The novel educational technology tool GECKO was used for two of these iterations and also used with CompSys201.

The research was covered by multiple ethics applications; selected documents are in Appendix 8, including the interview protocol used with students.

3.7. RQ1: What is the real nature of the learning problem?

The aim of this question was to 'lay open' the teaching and learning situation to identify any hidden or 'real' aspects needed to inform understanding. A number of sub-questions were developed to guide this:

- What knowledge is being taught and learnt?
- What pedagogical practices are used?
- What educational structures and culture exist?
- What are the educators and students in the situation doing?
- What educational theories apply?

3.7.1. Data collection and analysis

Research data were collected using a variety of both qualitative and quantitative methods. This was to enable triangulation of the results between the various methods and to gauge agreement to increase trustworthiness.

Interviews were used to gain a breadth of perspectives. Semi-structured interviews were carried out with students within ElectEng101 and students within the ECE department who had taken the course previously. Interviews were also carried out with lecturers, teaching assistants and secondary school teachers to gain their perspectives on learning in electric circuit theory.

Recruitment for the interviews was through advertising to students in ElectEng101. Respondents were to be selected to represent the whole population in terms of their prior school and first semester GPA results. This criterion was chosen to ensure participants were not a homogenous group of high or low achievers. However, it was not possible to obtain the student data so subsequently all respondents were interviewed; this revealed that participants were not homogenous.

Characteristics of the participants included students in their first year of university, two adult students, two students that transferred from another faculty and one student who had come from another university. The group also included students from a diverse range of cultures and schooling backgrounds as well as different genders and gender identities.

In addition to interviews, the second source of data was observations carried out in four first and second year courses. To develop as rich a dataset as possible, all lectures, laboratories and tutorials were attended in ElectEng210, CompSys201, ElectEng101 and ElectEng209 in 2015. An observation instrument was developed for lectures, which was adapted from the Irving Student Evaluation of Accomplished Teaching Style (Hattie, 2012) and complemented with guidance about impacts from assessment (Harlen & Crick, 2002), see Appendix 1, Table 17. A second instrument based upon the SOLO Taxonomy was developed for use when observing laboratories and students' project work, see Appendix 1, Table 18. These instruments were developed to provide an increased level of objectivity in researcher judgements and reduce researcher bias linked to high-inference judgements (Slavin, 1984). High-inference judgements include criteria such as 'student engagement', and low-inference judgments are items such as student time on task. Even as an experienced educator (perhaps because of it) I needed to avoid the bias of pre-judging the situation by capturing only what I was looking for or wanting to find (Kawulich, 2005). After several uses in courses, the instruments were not directly used but used selectively to support reflections.

Documentary evidence is an important source of case study data (Hancock & Algozzine, 2006). Course related documents included: course notes, course assignments and practice questions within OASIS (the departments' online question tool), as well as course tests and examinations. One source of data, the learning outcomes for ElectEng101 is shown in Appendix 4. Data collection also involved monitoring (and partaking in) course online forums, working with students in tutorials and drop-in clinics, part of marking of tests and examinations and interview-based summative assessments of student project work. Interview and forum data were collated using NVivo and along with field notes from observations and assessments, became part of a thematic analysis to identify what was happening at the level of the 'real'.

3.7.2. Thematic analysis

Thematic analysis was used with all case study data to separate it into distinct categories and to search for patterns of meaning in order to develop specific and explanatory themes (Braun & Clarke, 2006; Hancock & Algozzine, 2006). Thematic analysis can suffer from anecodatalism; in order to address this risk a number of steps were taken.

The first step was to determine the level as either semantic or latent. A semantic level identifies surface or factual themes which directly relate to external forces that act upon the learner or situation. For instance, several lecturers complained that students' maths is not good enough. The latent level is aimed at identifying hidden themes by theorising social contexts and structures (Braun & Clarke, 2006). The complaint about students' maths was identified as a semantic theme; the latent theme would be to identify patterns in student or lecturer behaviour that would explain why the lecturer said it and what these patterns mean.

The second step related to determining whether to take an inductive bottom-up or deductive top-down approach. In an inductive approach, the themes come out of analysing the data, whereas in a deductive approach, themes in data are identified that link to existing theory (Braun & Clarke, 2006). This research was inductive as its aim was to build theory rather than start with a known theory. These two points raise issues related to credibility in terms of a researcher's pre-sensitisation to themes, either through reading of theory or their own bias. To avoid bias and increase credibility these themes were discussed as part of a member-checking process with participants as the research progressed.

The next step was to choose whether to analyse the full data set or focussing on a specific aspect of it. The approach when analysing the case study data was to view the full data set so as not to miss any important themes and to avoid researcher bias toward any one or group of specific themes (Braun & Clarke, 2006).

With regard to credibility of thematic analysis, it is important to consider how much data is sufficient to establish themes. This requires both a necessary level of evidence to support theme identification as well as congruence across the themes that builds a coherent understanding of the situation. Rather than working towards a minimum number of interviews or observations, a common practice with qualitative evidence is to work toward a plateau effect or saturation (O'Reilly & Parker, 2013), until no new information is discovered. The data included 46 interviews with staff, teachers and students from different year levels as well as observations and data from online forums. Powerful themes were identified early in data collection, so that effectively saturation took little time to reach, however ongoing collection revealed nuances about the themes.

The process for analysing the data thematically followed that by Braun and Clarke (2006):

1. Qualitative data from interviews, observations, online forum comments and student feedback forms were collected into a dataset using NVivo as part of the process of familiarisation with the data and coded into latent themes.
2. Coding using coloured post-it notes was undertaken using a scrum board, which was used to identify semantic level themes from the qualitative data and summary comments from quantitative data.
3. An inductive process was used to identify latent themes from the scrum board.
4. Ongoing collation of new data led to a continual review of and reorganisation around sematic and latent themes.

Figure 25: Thematic 'scrum' board

The highly visible nature of an agile approach, using a scrum board (Figure 25), allowed triangulation of results from the different data sources to constantly take place as new interview and observational data could be seen to fit (or negate) the developing themes. The results relating to the first research question are presented in Chapter 4.

3.8. RQ2: Can an increased focus on epistemic knowledge help students in first year electrical engineering?

In order to answer this research question, a short concept quiz and a set of fundamental circuit concept tutorials (FCCTs) were developed. The quiz was used in 2015. It was used to gain an indication of the various ways-of-knowing being used by students and to confirm that results from prior research carried out in the department (Smaill et al., 2008, 2012) had not changed. The FCCTs were used with students in ElectEng101 over three successive years. The design of these, and the results of using them, are discussed in Chapter 5.

The FCCTs were aimed to operate both at the level of the 'actual' or visible and the level of the 'real' or hidden. At the level of the actual, they engaged students with conceptual understandings about electric circuits identified in section 1.5. This produced positive results for students who engaged with the tutorials. At the level of the real, they were an extension of the first research question to gain more insight into agency. While a survey might attempt to capture a measure of student agency, more than one interview indicated the use of espoused theories at work in student actions. Argyris and Schon's theory of action (1974), describes reasoning around the contrasting difference between what we say we do and what we actually do. A survey therefore, might lead to an understanding of what students think they do, but not data about what they actually do. In 2015 the FCCTs were voluntary, i.e. worth no marks and in 2016 students were awarded course marks for doing them. By tracking when students accessed the FCCTs, these results revealed data about student agency. The pre-course concepts quiz and questionnaire are in Appendix 2 and the FCCTs are in Appendix 3 and online at www.xplainittome.com.

3.9. RQ3: How can theory and understanding of the situation inform the development of a novel knowledge-based educational technology tool?

Using perspectives underpinned by the social realist investigations of the first year of the research, a novel knowledge-based educational technology tool called GECKO was envisaged and developed (see Chapter 6) along with a framework for its use. GECKO was theorised to help students develop KT-inferring through engagement with circuit visualisations. The nature of teaching and learning was found to have a significant impact on the effectiveness of the FCCTs in research question 2 and would have an impact on use of GECKO as well. This led to the focus on an integrative approach to using GECKO within a course and co-development of the pedagogic framework.

3.9.1. Developing an educational technology intervention

The intervention-evaluation stages by McKenney and Reeves (2012) in Figure 26 were used to both analyse 'OASIS' (see section 4.6.3), and develop and implement GECKO and the pedagogic framework.

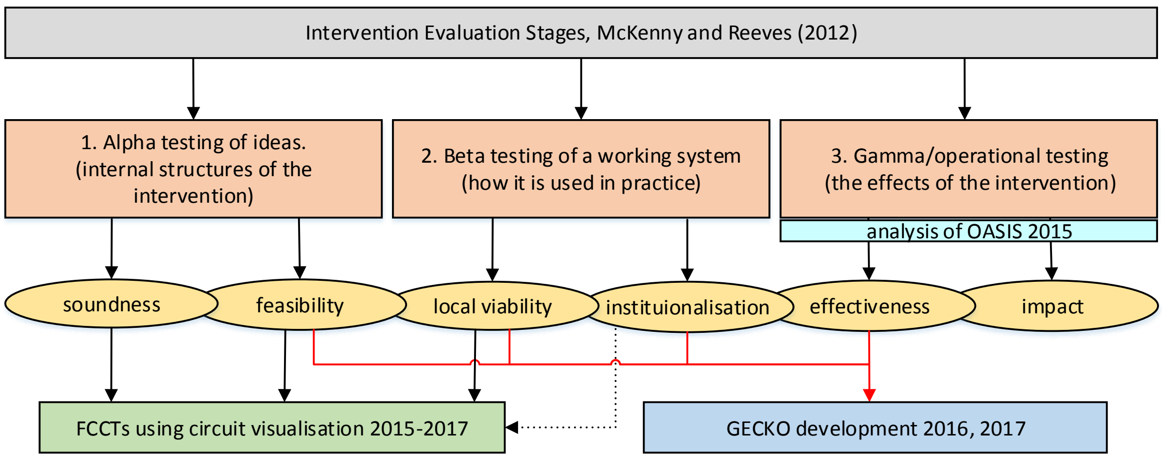


Figure 26: Intervention Evaluation Stages, diagram developed from theory by McKenney and Reeves (2012)

Alpha testing involves the testing of conceptual ideas and investigates soundness and feasibility. Soundness relates directly to theorising the intervention and it was used to consider how the relationship between KH-techniques and KT-inferring were influenced by educational technology. Feasibility relates to the identification of resources available – e.g. knowledge and time – and the practicalities of actually achieving a useful outcome.

Beta testing involves development of an intervention in a rudimentary but functional form and testing its basic features. This is tested in pilot trials and checks local viability and institutionalization. The local viability of an intervention's planned or anticipated outcomes do not become observable until this stage of testing. Intended and unintended effects, perceived value, and unknown pre-existing situational constraints are identified during this phase. Institutionalization requires developing an understanding of whether the tool could become part of the learning culture. This has less to do with the tools' feature set than with its perception of value within the organisation.

Gamma testing involves analysis of a more mature intervention. To make claims about the learning benefits of an intervention too early is not sound, as it can lead to false understandings. This is important within the context of learning in circuit theory as the long term results of ongoing research continue to reveal the significant difficulties involved. The strategies that form the gamma testing stage however, were applicable to identification of the effects of OASIS on courses, students and teachers. This stage involves analysing effectiveness and impact. Effectiveness relates to meeting the goals once implementation is complete and all supports to the intervention have been removed. Impact is the measure of how students' knowledge and practices have changed over time after the implementation. Analysing the impact of OASIS on students and courses turned out to be one of the most powerful factors in this research overall.

Figure 26 shows how the exiting tool OASIS was analysed for effectiveness and impact in 2015. Specifically circuit visualisation as a technique for helping students' conceptual understanding was tested for soundness, feasibility and local viability in

2015. During the local viability stage GECKO was conceptualised to leverage off the other two analyses. The opportunity to use GECKO allowed comprehensive local viability, institutionalisation and effectiveness testing. Evaluating GECKO's impact was not considered an option in the time available for the research, but forms part of a longer term analysis.

3.10. RQ4: What is the effect of an integrated approach to pedagogy and educational technology on student knowledge?

This question was addressed through redeveloping a unit of learning on microcontrollers in the second year course CompSys201 and testing this in 2017. One outcome of RQ3 was the novel educational technology tool GECKO. The implementation and results are discussed Chapter 7. While the research began with concerns about electric circuit theory, it had broadened into a fuller perspective on teaching and learning, knowledge, identity, agency and structure. This opportunity was seen as a valid direction for the research to take in further exploration of these areas.

Learning using educational technology encompasses a broader view than creating a new tool; this is described as TPCK and discussed in section 2.6.2. The pedagogic framework was designed using principles from TPCK to integrate GECKO with pedagogy. These understandings were complemented by those gained about the systemic relationships between knowledge, identity, agency, structure and culture within the situation. Both quantitative and qualitative data were collected to evaluate GECKO's effectiveness as part of operational (gamma) testing (McKenney & Reeves, 2012). Quantitative data were collected from the assignment students did using GECKO and from the final examination to identify trends and patterns in student knowledge and agency. Qualitative data were collected from observations and student surveys. To collect data about change in understanding and change in agency, observations were made using an instrument based upon the SOLO Taxonomy, see Appendix 1, Table 18. Observations took place in CompSys201 and the subsequent project-based design course, ElectEng209, to identify change in student knowledge and agency. The data from ElectEng209 was crucial as it is in the design course that students need to apply their epistemic knowledge and capability with KT-inferring, and cannot rely on KT-propositions and KH-techniques for success.

3.11. Summary

The data for the research was collected over an extended period of time from many sources to gain as full an understanding as possible of the nature of learning. The interviews carried out with undergraduate students proved highly valuable in understanding the way students approach learning and the learning structures that influence them. It was not possible to interview all students; however a wide range of values, opinions and knowledge capabilities were expressed and reinforced as themes by different students. Thematic analysis revealed many important aspects of the data and allowed comprehensive understanding to develop. As understandings were developed member-checking was carried out with experienced people in the department for their opinion.

Chapter 4. **The real nature of the learning problem**

Their maths is not good enough

I had heard this comment about students' mathematics ability a number of times from lecturers and teachers; and it is used to introduce the first research question: What is the real nature of the learning problem? A direct and immediate response to the statement about students' maths might be 'if their maths is not good enough, then give them more maths to do'. Case (2013) however, makes the point that such a surface view of an issue is unsatisfactory and we need to look beyond the discourse to identify the mechanisms at work at the level of the 'real' in the situation. This chapter reports on the intensive investigation undertaken to identify the mechanisms at work in four first and second year electrical engineering courses using the critical lenses from Chapter 2.

This chapter begins with a description of the structure of education within electrical engineering, followed by how the data for the investigation were collected. This data is used to develop an understanding of the situation. This starts with unpacking what is meant by 'maths' and 'not good enough' followed by an exploration of students' understandings from secondary school education. The nature of teaching and learning in the first two years of electrical engineering is explored and discussed, including the important transition that takes place during that time. One significant aspect of teaching during those years involves the use of an educational technology tool called OASIS, and data is used to discuss its soundness, effectiveness and impact on the situation.

4.1. Learning in electrical engineering at the University of Auckland

The Bachelor of Engineering (Honours) is a four year program offered by the Faculty of Engineering at the University of Auckland. It is the programme of choice for students to study engineering in Auckland and is large (1007 students in 2017). Entry is restricted and students must gain the New Zealand University Entrance standard and then their grades are given a rank score. If students meet the guaranteed entry score for engineering they are accepted into the program. As a part of this, it is stipulated that secondary school students must also have passes in Calculus and Physics in the external assessments of New Zealand's secondary school qualification or an equivalent. There are places for students in engineering who do not meet the guaranteed entry score under the university's Undergraduate Targeted Admission Scheme (UTAS) as long as these students have met the standard for university entrance. This includes Maori and Pasifika students, refugees, those with disabilities or others who schools are in low socio-economic areas.

Once into the program, all students take a set of seven prescribed courses in their first year. ElectEng101 is the Electrical and Digital Systems prescribed course. It has 12 weeks of lectures (4 x 50 minutes per week) and covers a range of topics: circuit theory; sensors and OpAmp conditioning circuits; digital number systems; combinational and sequential digital circuits; electro-magnetism and AC power. In 2015 there were two 2-hour laboratory sessions in the semester, the first a microphone with OpAmp circuit and the second a digital logic circuit employed to control a small wheeled vehicle by sensing two contact switches. In 2016 changes (described later) led to the first laboratory being removed from the course, leaving students with a single laboratory experience for the whole semester.

At the end of the first year, engineering students rank their five preferred choices of engineering specialisation. Specialisations have a cap on student numbers, and places are allocated based upon a student's choice and their end of year grade point average (GPA), with preference given to students with higher GPAs. More popular specialisations consequently fill with students with higher GPAs. The department of Electrical, Computer, and Software Engineering offers three specialisations: Electrical and Electronic Engineering (EEE), Computer Systems Engineering (CSE) and Software Engineering (SE). SE is one of the popular first choices for all engineering students so the GPA of students is high (see Figure 27), while EEE has been the least popular choice for students in the faculty for several years and does not reach its cap. Many students end up in EEE because their GPA was not high enough to get them into their first, second, third, fourth or even fifth choice (see Table 4) so the number of students with low GPA is significant (Figure 27).

Table 4: Engineering Specialisation Choice for Students at the end of 2016

Specialisation	1st Choice	2nd Choice	3rd Choice	4th Choice	5th Choice	Did not choose	Total
SE	87	1					88
CSE	26	33	7		1		67
EEE	39	13	5	1	3	1	62
							217

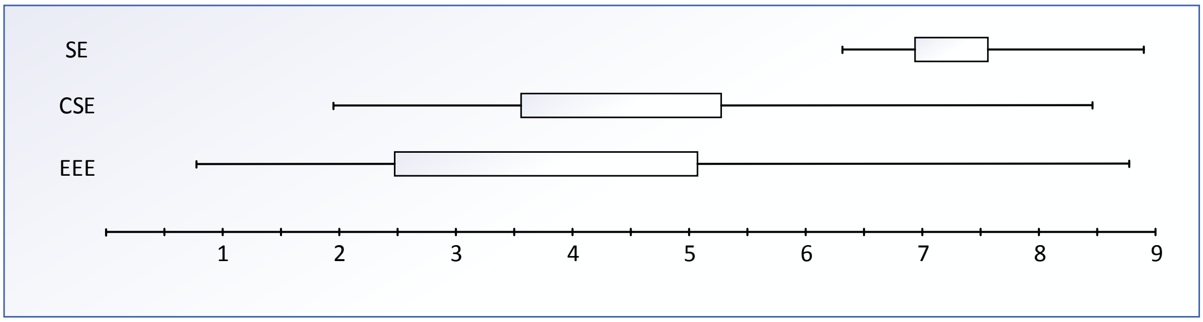


Figure 27: Student GPA by specialisation at the beginning of 2017

Once into EEE, the program of learning follows that of many engineering faculties with different types of courses that take students through a number of transitions in their learning (Case, 2013; Winberg et al., 2016) as per Figure 28. This begins with core scientific courses leading into engineering scientific courses. Core scientific courses develop scientific knowledge of principles and concepts and working with abstract representations of these using a range of mathematical models. Engineering-scientific courses involve principles and concepts that relate to the specific engineering discipline and their associated mathematical and other models. ElectEng101 includes elements of both core scientific physics knowledge and engineering-scientific knowledge of electric circuits.

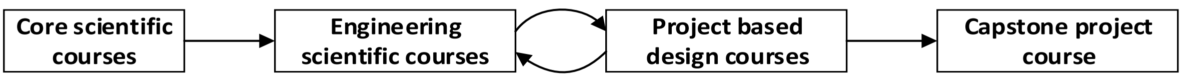


Figure 28: Engineering course stages and transitions

Once into EEE, engineering-scientific courses are interspersed with project-based design courses. Project-based design courses involve teams of students applying knowledge to develop a product or system; this includes using a variety of modelling techniques. For these projects, students need the ability to communicate, think and reason in the abstract using various models (mathematics is only one) and gain the ability to abstract pertinent aspects of reality including boundary conditions into these models for the purposes of problem solving around circuit and system behaviour. Through the degree these design courses become more complex and at each level student responsibility for the project increases as do the technical requirements. Lectures are replaced with project meetings and courses are allocated times in the laboratories for the project work which academic staff regularly attend. Several of these project-based courses centre on real world scenarios and some have industry representatives involved. In the final year, teams of two students develop a significant project with regular meetings with academic staff.

Table 5 describes the electrical engineering courses EEE students take during the first two years and when they are taken. It also indicates which specialisations the courses are required for.

Table 5: Students' First Two Years of Electrical Engineering

Faculty of Engineering Year 1 Common Courses		ECSE Department Year 2 Courses Includes EEE,CSE and SE specialisations	
Semester 1	Semester 2	Semester 3	Semester 4
	ElectEng101 (all engineering students)	CompSys201 (EEE, CSE, SE)	ElectEng209 (EEE, CSE)
		ElectEng210 (EEE, CSE)	ElectEng204 (EEE, CSE)
		ElectEng202 (EEE, CSE)	

This research investigated four of the six courses (those underlined). ElectEng101 has both core scientific and engineering-scientific aspects, CompSys201, and ElectEng210 are engineering scientific courses and ElectEng209 is a project-based design course.

As all students in engineering take ElectEng101, the course administration is complex. During discussions with staff, Figure 29 was developed to describe the learning and administrative structure. This chapter does not directly describe this diagram; it was developed to support the discussions that follow. Briefly the course coordinator is not a lecturer in the course, and the number of lecturers has changed over the period of the research from four to two. Responsibilities are indicated by bold lines, which indicate for instance, that the course coordinator is in contact with almost all areas of the course. This person also manages the OASIS tool and its question development, visits laboratory sessions and lectures to see they are running well, and also employs the TAs and GTAs. The lecturers are responsible for course notes, tests and the examination, and some of them will take an interest (dashed lines) in the online assignments or the laboratory. The head of department, course coordinator and lecturers are keenly aware that how students perceive learning in ElectEng101 reflects in student interest in taking the EEE specialisation.

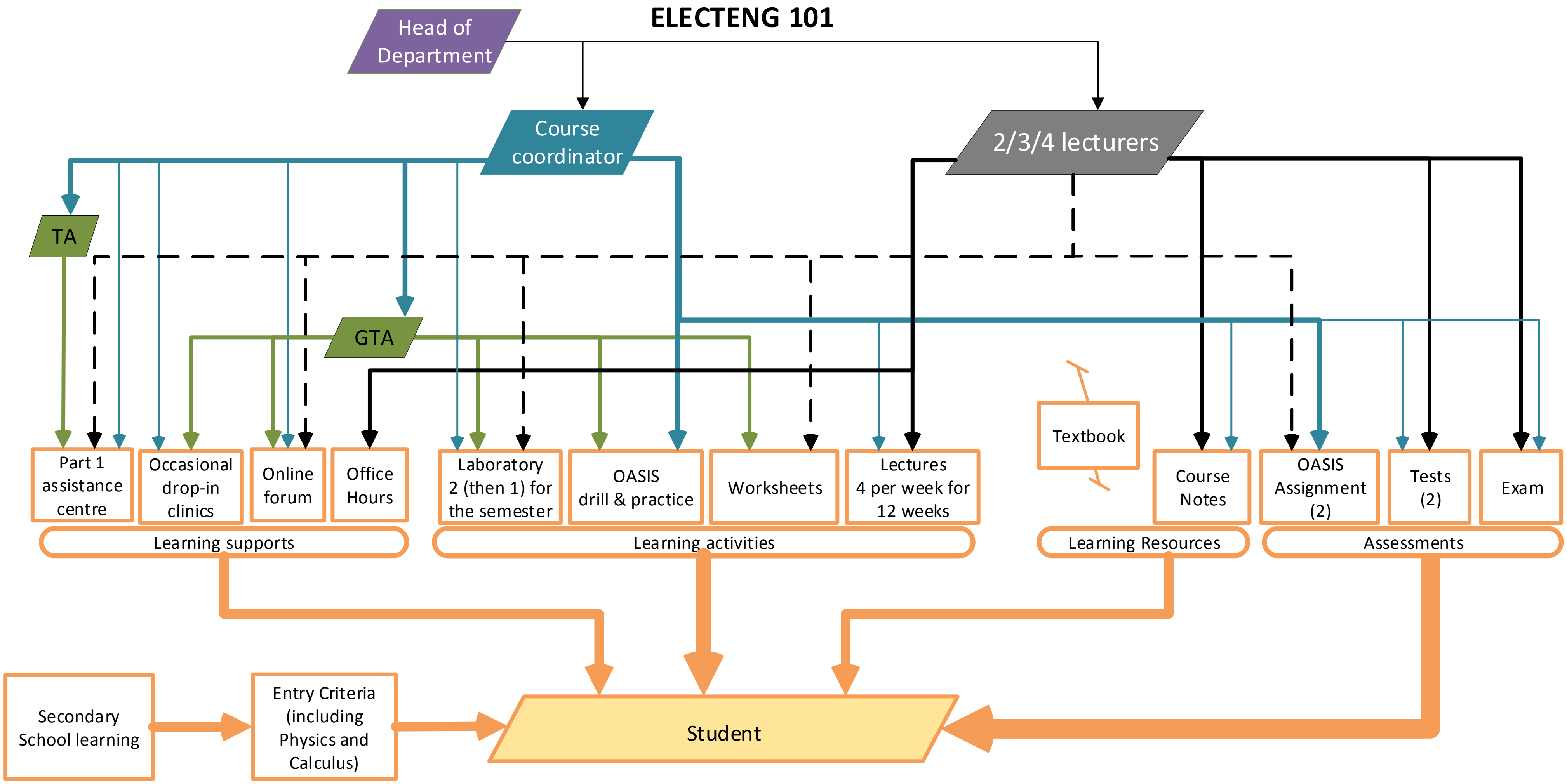


Figure 29: Learning and Administrative Structures in ElectEng101

4.2. Data collection

To gain a broad understanding of teaching and learning a prolonged period of data collection was undertaken from 2015 to 2017. Semi-structured interviews were conducted and recorded with 41 undergraduate students, 5 PhD candidates, 3 lecturers and 2 secondary school teachers. Observations were made in lectures, laboratories and tutorials, online surveys were carried out and a number of informal discussions with students, TAs, GTAs, technicians, lecturers and teachers informed the data as well. The methods used are described in section 3.7 and selected instruments can be found in Appendix 1 and Appendix 2; a description of the ethics process and selected documents are in Appendix 8. Data from documents were also collected; all of this data is presented in the next sections, interspersed with discussion to unpack the nature of the teaching and learning.

Table 6: Semi-structured interviews carried out for the case study

	Year 1	Year 2	Year 3	PhD	Lecturers	Teachers
2015	12		1	5	3	2
2016	20	1	1			
2017		6				

4.3. Unpacking the learning problem through the data

As the amount of data grew, the comment, "their maths is not good enough" began to take on an important significance. It became the first piece of data to be unpacked to inform a real perspective about teaching and learning. What did lecturers mean by 'maths' and what did they mean by 'not good enough'?

What is meant by 'maths'? In electric circuit theory mathematics refers to the ability to mathematically model electric circuit behaviour. Students were described by several lecturers as having a narrow formulaic perspective about the mathematics they do in electric circuit theory, as expressed by this lecturer:

> *It's just an equation for many of them and they might have this little circle and they've got I,R and V and that is kind of encouraging the equation view of things but many may or may not think of it as the model of representing a relationship between current and voltage through a device* [2]

The expression 'not good enough' relates to the discussion of literacy in section 2.5.2.2 where numeracy or mathematical literacy was described as the ability to apply techniques to problems and to apply mathematical modelling in unknown contexts. "Not good enough" was not found to relate to the ability to manipulate formulae, as students often showed prowess with complex algebraic methods when cut-and-dry application was required. It can be understood as the inability of students to use their capability with mathematics to solve problems.

This can be understood through relating a discussion with a GTA. He expressed frustration with students who had an incorrect answer to a problem because of a simple algebraic error and posted their working on the online forum without checking it first. When asked to describe the types of errors students presented in general, he described them as either conceptual problems related to not knowing fundamental concepts and how to apply them, or incorrect or blind use of techniques. He did not however, include mistakes with algebraic procedures as one of their problems. At this stage he concluded that students he had referred to originally, perhaps had so little confidence in their conceptual understanding that they did not know how to identify the mistake they had made. The issue was better described as more conceptual than algebraic, and not having the ability to recognise when thinking was faulty, students quickly resorted to the most reliable solution which was to post their working and ask for help.

4.4. New Zealand schooling and electric circuit knowledge

The first step in unpacking the nature of teaching and learning was to investigate students' understandings of electric circuits when they arrive into the faculty from secondary school learning. The powerful effects of summative assessment on learning

[2] (from Rata, Rowe, McPhail, Wang, & Collis, 2017)

have been discussed already (section 2.3.2); to understand what this means in this learning situation requires some context on the New Zealand secondary school qualification system, the National Certificate of Educational Achievement (NCEA). NCEA has a complex structure which is used to assess students over their final three years of secondary school, from Year 11 (NCEA level 1) to year 13 (NCEA level 3). Each subject is separated into a number of topics, and each topic is assessed individually by an Achievement Standard. Achievement Standards can be either for internal use within schools (e.g. via test, examination, assignment, report or project) or external (examination or portfolio) based assessment.

Year 11 Science is not a compulsory subject; whilst the cohort of students in Year 11 in 2017 was 60,122, less than half took Science achievement standard assessments. Those who take Science do a common course which includes multiple topics from Physics, Chemistry and Biology. In 2017, there were 34 assessable topics. Electricity, one of the internally assessed topics, was taken by 4304 students, whereas the Chemistry internal was taken by 27,579 students and the Genetics external was taken by 28,469 students. Of those students who took Science in Level 1 in 2017, approximately 15% took electricity as a topic. The practice of separating topics and making the topics optional for schools and students is described as weakening the epistemic knowledge in a domain (McPhail & Rata, 2015; Rata & Taylor, 2015). It also has consequences in terms of social justice principles relating to denying abstract domain knowledge which leads to learners not being able to have an equitable part in society (Rata & Taylor, 2015).

4.4.1. Entry criteria for the Faculty of Engineering at the University of Auckland

Faculty address the issue of fragmentation of knowledge described above, by requiring students to pass all three external Achievement Standards in NCEA Physics, before they can gain entry into engineering. These are: Waves, Mechanics and Electricity (Figure 30). One secondary school teacher described how this directly impacts secondary schools 'forcing' them to teach electricity, and stated that Level 3 students in Physics might not otherwise learn any electricity.

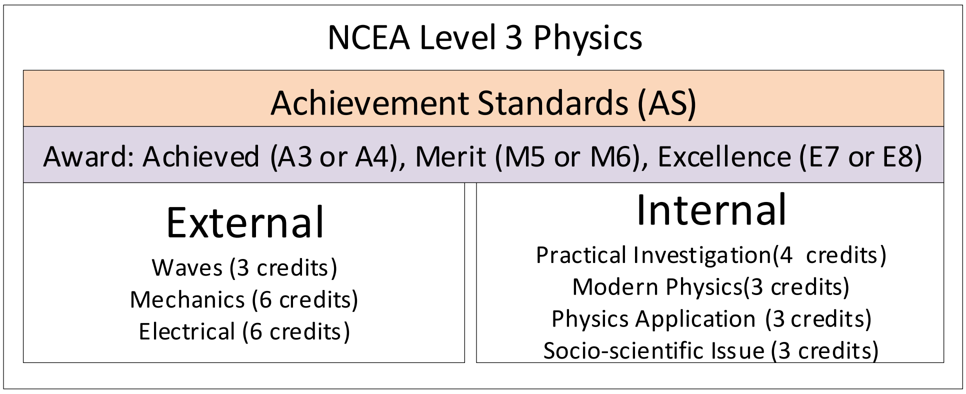


Figure 30: NCEA Level 3 Physics Achievement Standards structure

Requiring students to pass the electricity standard could lead to the assumption that students in first year engineering have the necessary foundational understanding when they enter Engineering. This however, is not the case as students' understandings of electric circuit theory have been tested on entry to ElectEng101 for many years and found to be quite deficient (Smaill et al., 2008). It was important to investigate what 'passing' the external Achievement Standard for Electricity (NZQA, 2017a) actually requires of students[3].

Achievement Standards are awarded as Achieved, Merit or Excellence and for externals these are refined further into grade-scores. In Figure 30 this is expressed as A3, A4, M5, etc. Investigating the examination paper and marking schedule for the Electricity Standard from 2017 (NZQA, 2017c) there are three questions for students to answer and each has multiple parts. The schedule reveals that each part of a question relates to achieved, merit or excellence criteria. Students can receive up to 12 achieved scores, 9 merits scores and 3 excellence scores from the three questions. The awarding of a final grade for the Achievement Standard is made in relation to the number and level of scores gained, as per Table 7. For example this reveals that students can get an A3 achieved (pass) if they scored 3 of the 12 achieved parts in the exam. Or they can get an excellence if they can answer 1 excellence level question (with its prerequisites).

[3] These descriptions relate to achievement data from 2017 rather than that from 2015 when the research began as some NZQA processes had changed during that time. These changes were not significant but it was determined that up to date information was most appropriate to present.

Table 7: Scores from 2017 for NCEA Level 3 External Achievement Standard 91526 – Demonstrate Understanding of Electrical Systems (NZQA, 2017c)

A3	A4	M5	M6	E7	E8
3a	4a or 2a + 1m	1a + 2m	2a+2m	2m+1e	1a+2m+1e

The requirement for A3 appears low; however NCEA should not be compared to a norm-referenced based system such as New Zealand's previous norm–reference assessment system where 50% of students had to pass and 50% had to fail. A system such as NCEA is promoted as fairer, as if students know the material, then they should get the grade, regardless of whether they are in or above the 50th percentile. This though requires still deeper understanding as NZQA still sets a norm for achievement; it is called a profile of expected performance (PEP) (NZQA, 2017d). Figure 31 has the PEP for electricity assessment from 2017, and it reveals the number of students who should get Not-Achieved (fail), Achieved, Merit or Excellence; i.e. 22% to 28% of students should fail. Examiners are not held to this PEP but have to make a case to work outside it. The PEP is therefore a firm guide to examiners in setting questions and marking criteria.

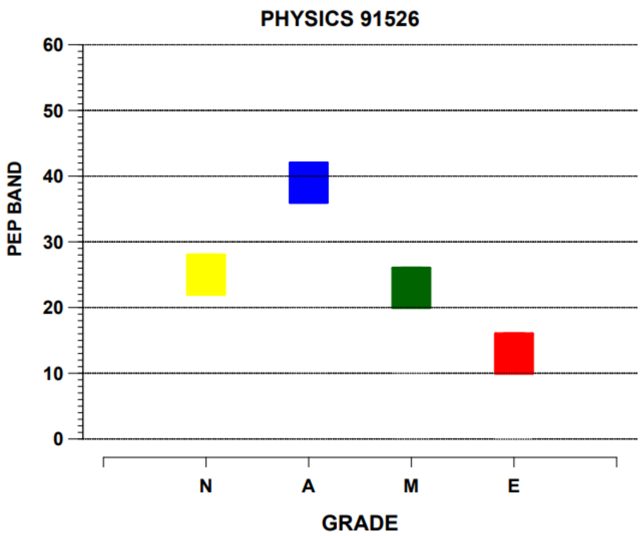


Figure 31: Profile of Expected Performance from 2017 for NCEA Level 3 External Achievement Standard 91526 – Demonstrate Understanding of Electrical Systems (NZQA, 2017d)

To make an informed statement about what students know when they enter university having passed Level 3 Physics, the actual nature of the 12 achieved level criteria need clarification. The Assessment Report (NZQA, 2017b) list these:

- used formulae to calculate basic values
- described and calculated time constant
- described how current changes as a capacitor charges
- calculated combined capacitance
- knew that a changing current creates a changing magnetic flux
- explained how an inductor induced an opposing EMF
- converted between RMS and peak voltage
- calculated the impedance of a LR circuit
- described the effect of increasing the dielectric constant for a capacitor on capacitance
- showed basic understanding of characteristics of LCR circuits.

These 10 criteria are all directly KT-propositions or KT-techniques related. This indicates that the minimum level of knowledge required for a student to pass Level 3 Physics in electricity is three aspects of KT-propositions or KH-techniques.

The excellence level criteria from the same report (NZQA, 2017b) are also informative; students needed to demonstrate one of these to gain excellence:

- demonstrated a good understanding of the three stages of charging a capacitor and explained the exponential shape of the sketched graph
- gave a thorough explanation of how an inductor affects the current and why a spark is produced when the switch is opened
- calculated the resonant frequency of an LCR circuit and explain why the current is maximum at resonance.

In terms of the ways-of-knowing framework, students require some epistemic knowledge and ability with KT-inferring to get an excellence; however a single demonstration is considered sufficient as per Table 7 excellence criteria.

While the specific criteria in the assessment change annually, students expressed their ability to get achieved or merit grades without difficulty, as this student expressed

> *my understanding was like none, … if I had graded my understanding I would have given myself a Not Achieved but I managed to get a Merit and how does that … reflect … my understanding (year 1 student)*

Some students attributed their excellence grades to luck in knowing the right thing being assessed that year. Students' actual abilities were investigated during interviews, and amongst most students, including the nine students who reported an excellence grade, there was a limited ability to handle electric circuit knowledge epistemically and to work inferentially. This was commonly dismissed as 'forgetting' by students.

> *There's a six month gap right, everyone forgets (Year 1 student)*

However in the interviews students were not asked questions that related to understandings with Level 3 NCEA material but Year 11 level fundamental understandings about epistemic knowledge of electric potential and charge and to make inferences using this knowledge.

4.4.2. The nature of teaching and learning in physics at secondary school

When describing their results several students related the ability to pass not to knowing but to doing.

> *I remember I learnt how to do the exams by doing the practice exams and then getting them wrong and then looking at the answers and learning what the answer was (Year 1 student)*

This was linked by some teachers and students in interviews as teaching being reduced to KT-propositions and KH-techniques

> *There's a lot of the stuff we do because it helps us get a reliable end, it gets us a correct result but often kids learn it as techniques rather than their*

> *understanding so they understand it instrumentally rather than relationally, which is often how we simplify teaching (secondary school teacher)*
>
> *So they still teach Ohm's law, basic power principles and also about inductors and how those work but people don't really seem to understand it. They [students] just rote learn, once they do that they forget about it. (PhD candidate)*

Not all teachers or students follow this practice; one teacher demonstrated a quite powerful approach to fundamental concepts:

> *I prefer potential difference to be used right from junior science … and stop using the term voltage. Like me saying I'll measure your 'centimeterage' rather than your height, come on I know it's a common term and people use it but part of our job is to get kids to use correct terminology and to use it correctly (secondary school teacher)*

Another factor that participants described for students' surface level capabilities was the lack of specialist teacher knowledge in physics at secondary schools:

> *[Schools] employ people who say they can do a bit of physics so they'll end up teaching the physics and then they don't necessarily do it very well. (Secondary school teacher)*
>
> *She herself was a chemistry teacher, didn't have the same grasp …it was fine for exams but whenever I asked a question why does that happen … it was a lot more difficult for her to answer. (Year 1 student)*

A very significant factor in schools related to poor quality learning seems to be the discourse around summative assessment. While NCEA is not unique in that summative assessments and examinations are known to be strong external motivators of student behaviour (Harlen & Crick, 2002), many interviewees, and my own experience of 18 years teaching, places the discourse in schools as overtly centred on 'credit farming' (section 2.3.1). NCEA is a criterion-referenced assessment system, however the prevailing discourse is not about the knowledge in the criteria but about the accounting of this knowledge. This discourse was pervasive in the school communities I taught and worked in as an educational facilitator:

I think sometimes I felt like they were teaching to teach to NCEA standards rather than teaching to teach the concept (Year 1 engineering student)

Just do whatever you can to get it into them before the test so they get the credits (deputy principal)

I only need 5 more credits to get my NCEA level 1 (secondary school student)

She only needs 2 more credits what can you do to help her get them? (parent)

The achievement standard we are doing is AS… it's worth …credits (secondary school teacher)

How many credits is this worth? (secondary school student)

I am not going to do that it's not worth any credits (secondary school student)

The nature of this discourse is an issue I felt compelled to address in my own classroom a number of years after NCEA had been introduced. I predominantly taught using a project-based pedagogy and developed a schema for obfuscating the credits within the project descriptions. For example, when students asked 'how many credits' a PCB design was worth, I would refer them to the diagram to identify the different assessments and which ones their PCB (not just its design) contributed toward. For most students, their project work became their focus and their discourse became centred on their projects and learning.

Another reason given in interviews for unsatisfactory learning processes was that the concepts involved were very difficult and the perceived benefit of knowing did not relate to the level of effort required. Two students related how their knowledgeable physics teachers made them concentrate on understanding; these students performed very well in the electric circuit questions in the interview

> *[The teachers] whole attitude about knowing where things come from and not simply using the formula. ... it was annoying but overall really good for my understanding*

Not all physics teachers seem to have the same level of epistemic knowledge of electricity

> *Yeah I quite vividly remember my physics teacher trying to tell me about voltage and I remember him getting confused and saying 'even I struggle with voltage' (Year 1 student)*

Some students described their teachers' pedagogical approach as contributing to surface level capabilities with knowledge

> *I felt in high school in physics class it was too, I don't know how to describe it, too classical the way we learnt electricity... They never related it; they never made that connection (PhD student)*

One physics teacher recognised this when discussing the role of context-of-use and described his own level of KA (acquaintance knowledge)

> *Why do we teach all that stuff in the level 3 external, I don't even know how it relates*

Another aspect of learning that was felt to contribute to surface level capabilities is the importance given to electrical knowledge. Both teachers and students indicated that the electricity and magnetism section of the Year 13 (final year) physics course is done at the end of the year, when there was limited time.

> *The electricity section is done when people tend to be tired of the year and so yeah it was most definitely done last. I remember missing a few classes and then not understanding the rest of it for most of the time because I was quite busy with lots of other kind of co-curricula's and all that kind of stuff especially in Year 13 (year 1 student)*

Another outcome of this is not just students' lack of preparation for learning in electric circuit theory, but a significant predisposition against it:

> *And so I … came into Uni doing engineering and… electrical hadn't really been my thing … I would prefer to do something else. And I was like that's fine. I just won't do anything in electrical (year 2 engineering student)*

4.4.3. The exam-taker identity

The purpose of the discussion relating to secondary school learning in Physics was to develop a critical awareness of students' knowledge in terms of the ways-of-knowing framework and to capture a perspective of student identity on entry to engineering. Identity as per Archer (1995), was defined in section 2.3.2 as personal projects - things people value and invest themselves in. This is informed by, but does not describe someone's sense-of-self, nor indeed is it all encompassing. All the students interviewed, however, demonstrated a powerful personal project aligned to passing. One student described this when referring to making choices about learning

> *All that kind of stuff is really interesting and exciting but as I say the issue is that when I apply to EngSci [the Engineering Science specialisation] they don't care how interested I am because they rank you on your GPA which is based purely off the exam and if this is an exam I need to get through it (year 1 student)*

In this research, the student identity that comes through most clearly when students enter university, is one that is expressed by the term exam-taker (section 2.3.2). The concept map in Figure 32 was developed to describe how the structural influences around learning in secondary schools encouraged students to adopt a personal project associated with assessment i.e. an exam-taker identity. This identity is then reflected in the limited KH-techniques and KT-propositions ways-of-knowing that students relied on to meet this personal project.

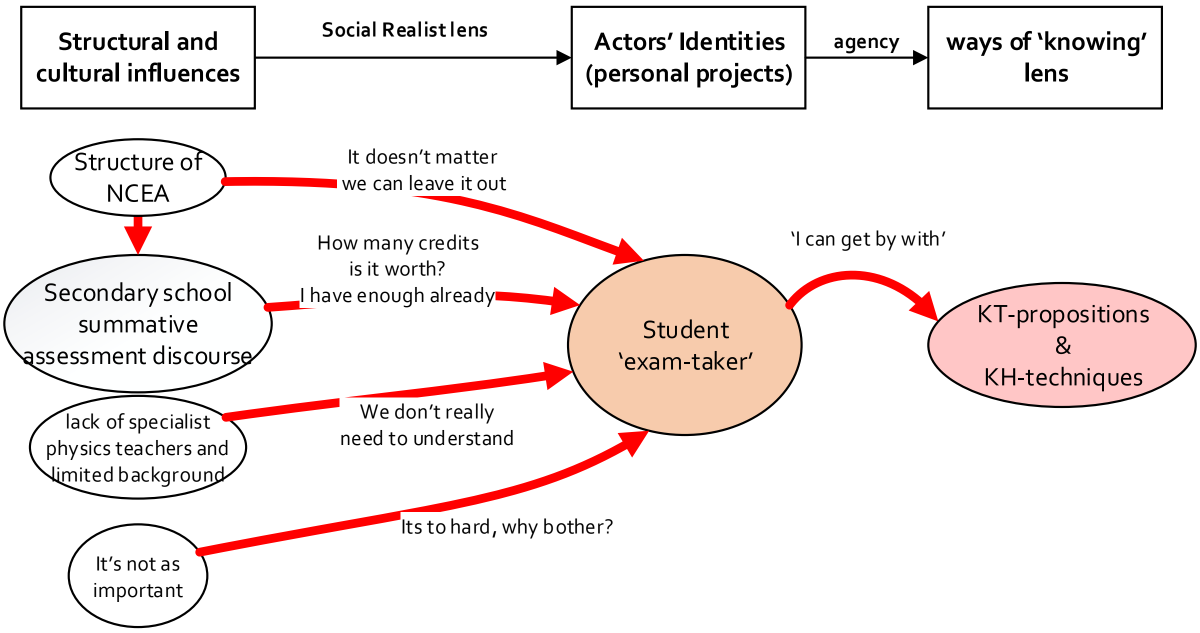


Figure 32: Student identity development and ways-of-knowing influences in secondary school physics

4.5. OASIS

A key factor in learning in the first two years of electrical engineering is the growth in student numbers to 1000+ by 2017. To manage the demands of such large numbers of students for practicing their circuit calculations, the department developed an in-house educational technology tool called OASIS. It is important to review OASIS and identify its impact on student ways-of-knowing. The evaluation model from McKenney and Reeves (2012) is for the development of new software, however its criteria (see Figure 26, page 109) reflect the importance of developing an understanding of a tool during its lifetime, not just at the beginning of it. The next sections present and discuss OASIS in relation to the criteria of institutionalisation, effectiveness and impact, then the criteria of soundness is used to make a reflective comment.

4.5.1. OASIS background

In the late 1990s lecturers became concerned about the increasing difficulty in providing the growing numbers of students in the course with the practice (and marking) of the questions students needed to build their familiarity with the techniques involved in circuit analysis (Bigdeli et al., 2001). A bespoke software application known as OASIS (Online Assessment System with Integrated Study) was developed in-house to meet this need. Questions are presented in a web browser as in Figure 33, where every time this question is presented the image remains the same but the values change.

Students have to calculate the correct answer and enter it in the textbox. Once submitted their answer is compared (to within 1% tolerance) with the matching answer in the dataset. A marked answer is shown in Figure 34.

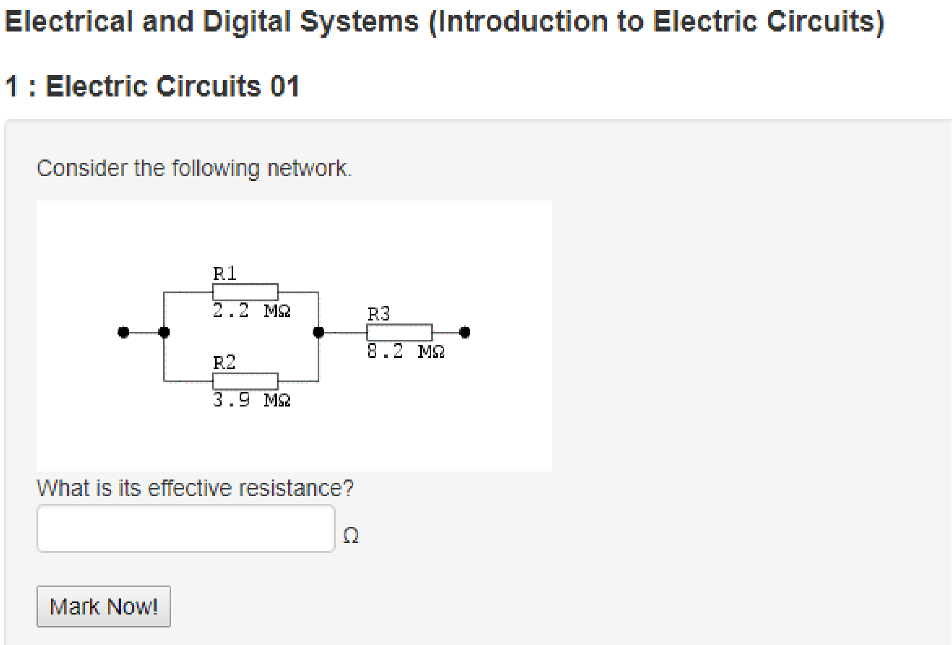


Figure 33: OASIS - web based question tool

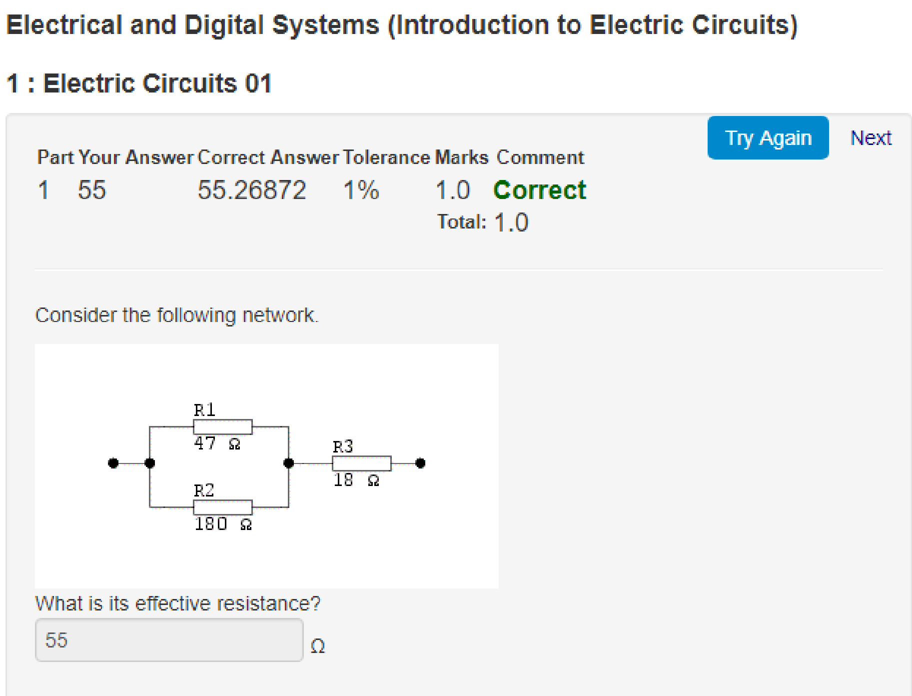


Figure 34: OASIS marked answer

4.5.2. OASIS institutionalisation

When OASIS was introduced, the changes to student learning were found to be so significant that OASIS quickly become institutionalised within first, second and some third year courses in the department. In ElectEng101 there are 74 questions spanning the topics of: electric circuits, power and digital electronics. With the growing numbers of students, OASIS easily provided quick results for students for practicing questions and for staff, the marking of large assessments became automatic.

The OASIS system has two modes of operation; a practice mode and an assignment mode. In practice mode, students are informed if an answer is in/correct and what the correct answers are, as in Figure 34. In assignment mode, students are given a fixed number of questions. Students are usually given from 6am until 10pm on the day of the assignment to start it and once begun must complete it within 60 minutes There are no restrictions on where students can do the assignment. In 2015 there were two assignments in the ElectEng101 course, each worth 4% of the final course grade. The same questions used in practice are reused in the assignments. While a number of comments were made about needing to develop more questions for courses this, however, did not take place (discussed later).

4.5.3. OASIS effectiveness

The benefits of OASIS have been reported in literature. Firstly that students benefit from the instant feedback and increased focus on accuracy of calculations; and secondly that staff benefit from reduced marking load, reduced supervision of students and reduced student contact hours (Hussmann & Smaill, 2003). Both students and staff confirmed these aspects of OASIS, and student's comments included:

> *'it helped pick up errors quickly'*

> *'they were a good resource'*

Staff remarks included:

It's fantastic isn't it; students absolutely love it as it gives them immediate feedback

I say to my students 'if you do all my problems in OASIS you will get an A+'

The way many students view the tool though, aligns with a focus centred on the drill and practice of KH-techniques; this comment from a paper published about OASIS captures this perspective.

Electrical circuits are the lexicon of electrical engineering as are the times tables for mathematics (Bigdeli et al., 2001, p. 58)

Some limits of OASIS's effectiveness were well understood by several of the students interviewed:

Good for rote learning not for understanding

I can practice what will be in the tests

One of the most powerful effects on learning relates to the quality and timeliness of feedback (Alton-Lee, 2003; Hattie & Timperley, 2007). The timeliness of feedback was one of the key drivers for OASIS development and one of its clear strengths. OASIS feedback, however, is limited to marking in/correctness and the margin of error. Some students commented about this.

There's no explanation whatsoever so I went to the tutoring at the hall to get them to explain what's wrong with my answers because I couldn't understand.

Staff also commented that for many students, OASIS was not fully meeting students' needs. This point was made in 2003 when it was indicated that diagnostic feedback would be a useful addition to OASIS (Hussmann & Smaill, 2003). This, along with more question development, did not take place.

4.5.4. OASIS - impact

Impacts of OASIS described in literature (Hussmann & Smaill, 2003) include: minimisation of plagiarism and cheating, that students become confident that they have improved their levels of skill, the assignments are meaningful and there are improved educational outcomes as it is a strong formative educational tool.

Discussions with students and the analysis of student data, however, indicate a different impact. Many students across years 1 to 4, TAs and GTAs spoke about the amount and type of cheating that occurred in OASIS assignments. This ranged from students passing around MATLAB scripts, Excel spreadsheets and formulae as well as sharing out questions for the assignment in groups and even having other students sit the assignment for them. One staff member indicated that this behaviour had actually been present since OASIS' early use.

Figure 35 shows graphs from OASIS of student activity levels; where the peaks reflect the way students generally use OASIS, in a just-in-time way to prepare for tests and the exam. The graphs indicate that this 'just-in-time' approach to learning behaviour is common in the course.

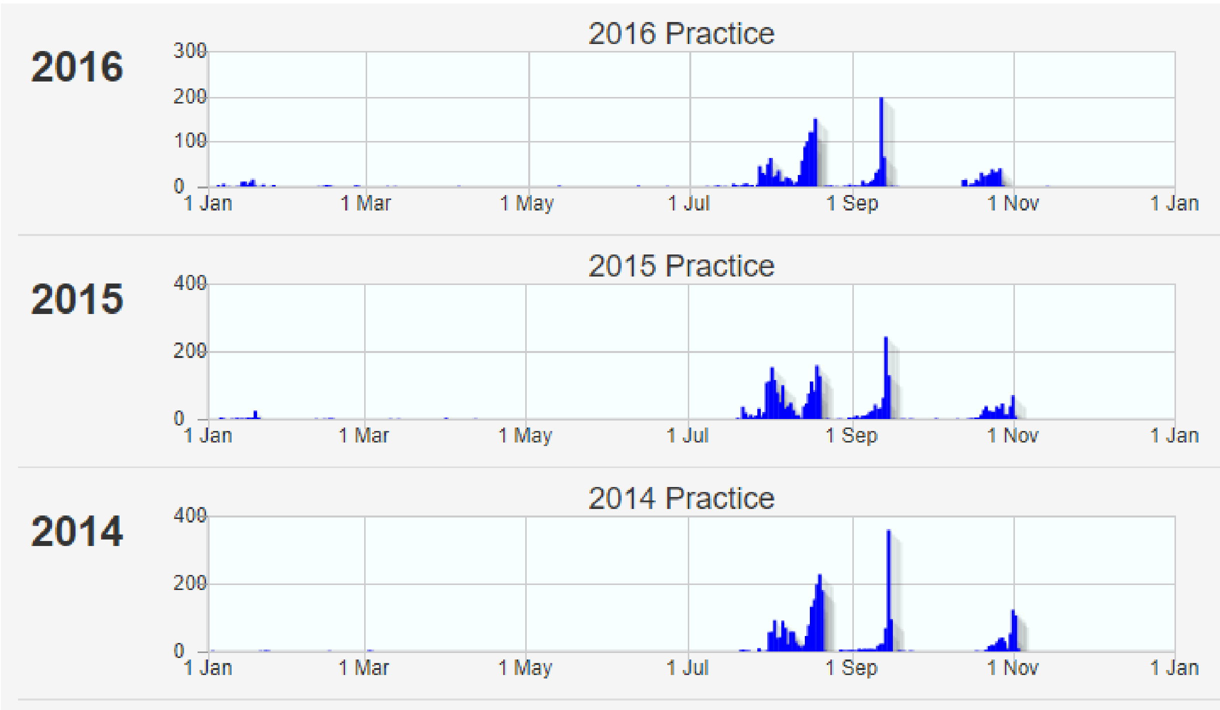


Figure 35: OASIS software activity graphs

The impact of student work in OASIS is indicated in Figure 36; the graph of students' results in the assignment against their examination grade. The data behind this graph reveals that out of 835 students 9 failed the OASIS assignment; however 120 students failed the exam. While it might not be unusual for students' assignment and examination results to not correlate as there might be different work involved, the assignment and examination both involve similar calculations on electric circuits. Interviewing students indicated they had become highly effective at 'gaming' the questions in the assignments. This can happen as small banks of questions are used for both practice and then reused in the assignment. Gaming of the assignment seemed to be encouraged as students were given significant detail about which practice questions were to be reused in an assignment; as in this announcement to students about the second OASIS assignment. There will be:

> *3 questions from the Electric Circuit Fundamentals (specifically Thevenin Circuit I – VIII); 5 questions from the Combinational Logic and Sequential Logic topics*

Also as this student remarked:

> *What I found really useful about this course is that there was going to be 13 number systems questions and there are 18 number systems question in OASIS.*

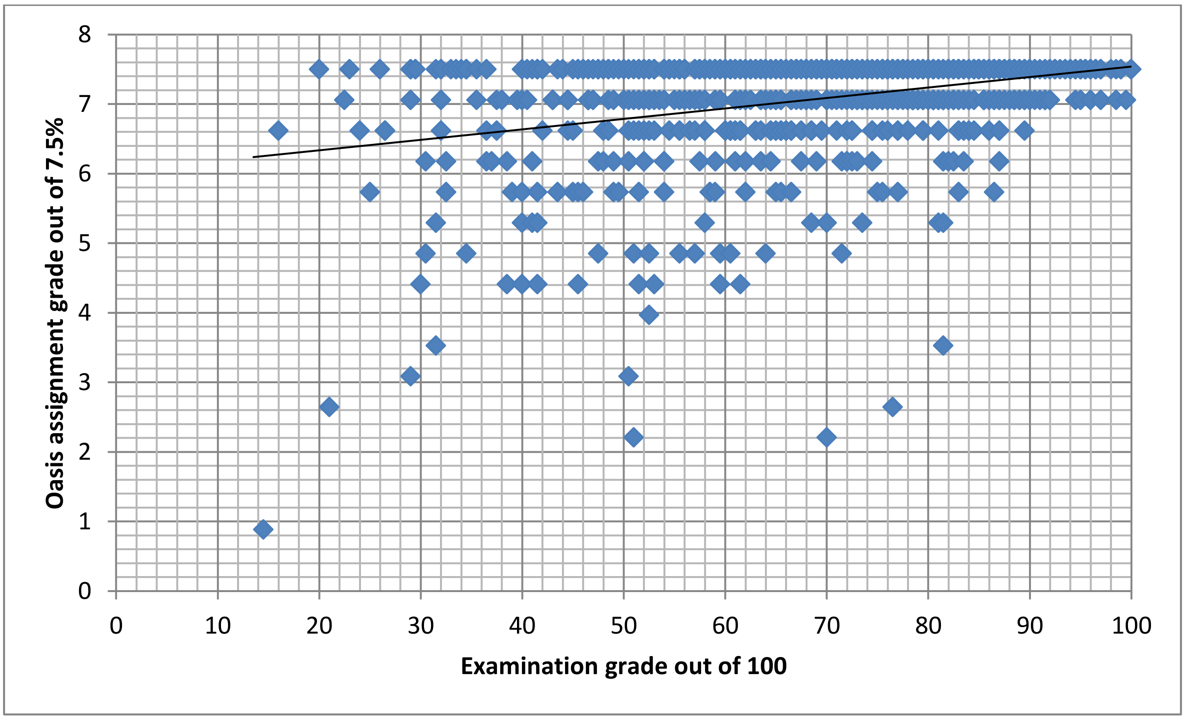


Figure 36: Second OASIS assignment correlation with examination mark (Pearson:0.30)

Some students recognised this approach as unsatisfactory.

> *More Oasis questions would be great and maybe if you turned the two quizzes into weekly assignments so I didn't just have to cram a day before but rather had to actually pay attention in class.*

While this student was aware enough to recognise the need for adequate pedagogy, the comment also indicates a high dependency upon someone else to manage learning, and an inadequate level of metacognitive behaviour. These results indicate that not only do students lose learning benefits by 'gaming' the system but that it may have a negative impact on learning behaviours.

4.5.5. Discussion of OASIS' soundness

While soundness is the first of the six stages of evaluation in the model by McKenney and Reeves (2012), it is used here as a reflective criterion about OASIS. Soundness investigates the underpinning ideas and how they were applied.

The first criteria of soundness relates to KH-techniques and epistemic knowledge. In the early stage of OASIS, development centred on getting students to practice questions, improving their accuracy and providing immediate marks. OASIS was recognised as being highly powerful for this purpose. One of the key pedagogical issues however, that a focus on KH-techniques (drill and practice) builds, is that learning goals become subverted by summative goals (Luik, 2007). This limitation of OASIS was not identified in the earlier research conducted about it and OASIS appears to be one of the key drivers that focus students' way-of-knowing on KH-techniques in the course.

The focus of learning on drill and practice is seen in the OASIS question in Figure 33 (page 131). This is a circuit fragment that is commonly found in textbooks, tests and assignments. The question requires students to practice calculations on the effective resistance of a network of three resistors. Being a circuit fragment, this question makes little if any contribution to the development of epistemic understandings or capability of KT-inferring. For the lecturer it is easy as the tool automatically assesses it and for the student it is easy to learn the process for getting it correct. In educational terms this is a behaviourist drill and practice question where the environment conditions the learning (see section 2.4). The question leaves the student none the wiser about their learning of the concept of *effective resistance* which is stated but not connected epistemically. It is seldom safe for an educator to leave the purpose of learning such as this for students to discover themselves (Clarke, 2001), as students do not guess what we have in mind but take the face value of the question as what they are supposed to know. Consequently students can end up at the epistemic dead-end that Sfard (1998) described - unable to function satisfactorily within a domain.

The term effective resistance is neither described in the recommended textbook for the course (Hambley, 2014) nor the course notes. Instead the term *equivalent resistance* is found in course notes and the textbook. In the course notes *equivalent* is described as working out how one resistor can replace two in series by adding the two values together e.g. $R_{eq} = R_1 + R_2$. It is explained in the textbook (Hambley, 2014) - which approximately 1% of students in ElectEng101 purchase - as there being no change in the relationship between the voltage and current. However Figure 33 (page 131) is a circuit fragment, where there is neither voltage nor current; so the question needs to be asked about the purpose of such a question. Using values centred in a pedagogical regulative discourse the question could be: What is the academic goal for students' abstract understanding from this question? The answer to this is not found in the question, the course notes or the text book. If the question has no link to an academic learning goal then it could be understood simply as 'busy work' which Monroe (1911) described as being of little intellectual significance.

The student needs this abstract knowledge and a way needs to be found for the student to make the link to it and to build an epistemic abstract thought-holder for the idea as described in section 2.3.1. The term *effective* has a clue in terms of seeking the abstract meaning for such a question. As an abstract thought-holder within the episteme, *effective* refers to how one thing has the same effect in the environment as another, or measuring the ability of how something meets the purpose it is used for. The question however, does not provide any explanation of this nor how to recognise *effectiveness* in the abstract nor lead into how to use it inferentially. Using the concept of *effectiveness* is perhaps the core underpinning idea of circuit analysis – how we replace complexity with sufficient simplicity for the purposes of modelling behaviour. Hambley's explanation of the relationship between voltage and current being the same stops before making this abstract KT-inferring goal; it would however make a satisfactory success criteria for student learning (section 2.5.3.1).

From a soundness point of view, OASIS was evaluated as having a very efficient 'more of the same' type impact on student knowledge around KH-techniques. This is reflected in Figure 37.

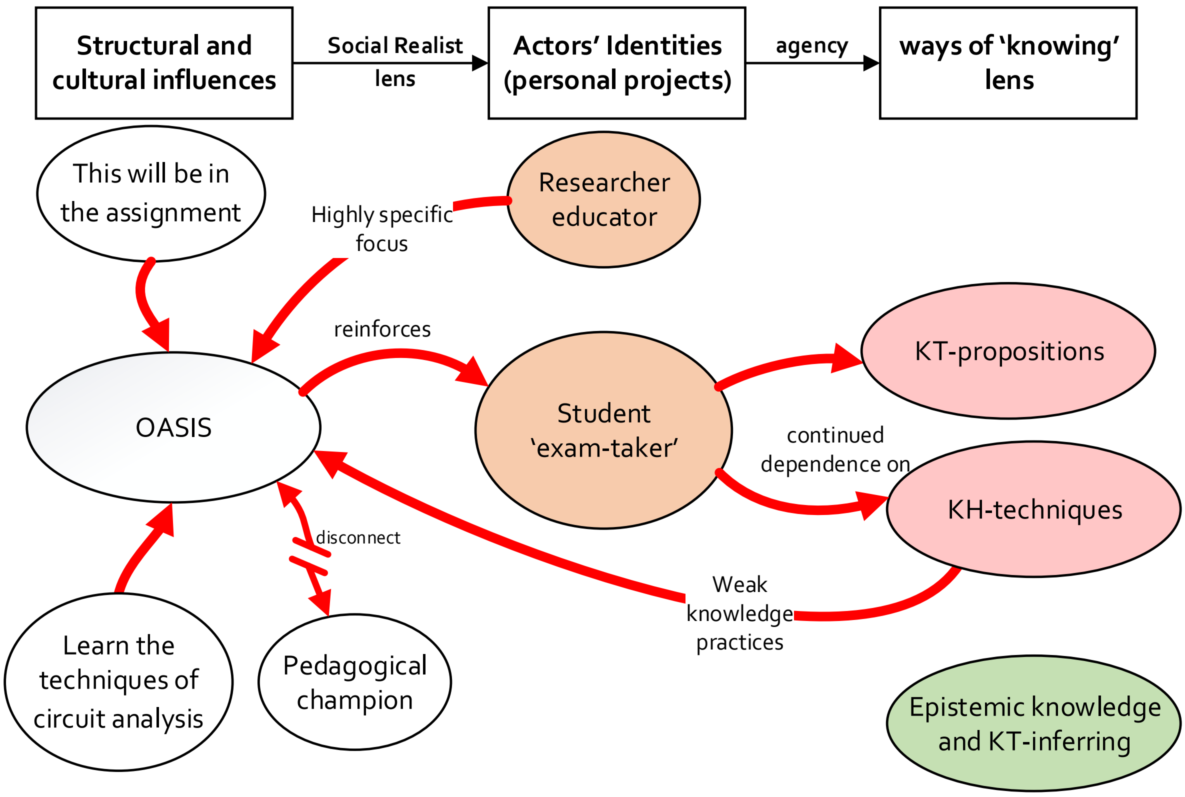


Figure 37: The impact of OASIS drill and practice tool on student identity and knowledge

The second reflection relates to comments made by staff and found in literature published about OASIS. These indicated that deficits had been known since OASIS' inception and development. Change to OASIS however had not taken place. Staff attributed this lack of change to OASIS being in-house bespoke software, and when work conditions changed for its developer, this left little time for ongoing development. Also IT support staff had moved from department to faculty level, and were only prepared to maintain OASIS at a subsistence level. These changes had resulted in a cloud of uncertainty about OASIS' future. These, however, were not recent developments and so did not explain why the situation had prevailed for such a long period of time, especially when the pedagogical deficits of this form of learning are so well known from literature. The lack of change was interpreted as an ongoing issue with instructional discourse and a lack of pedagogical championing around OASIS. This was identified not as a course level issue, but one linked to the nature of academic culture, where change must be led from the top (Godfrey, 2014). During the research, three universities in New Zealand and eight in Australia were visited, and two conferences on engineering education attended. During discussions with academic staff, the crucial importance of pedagogical championing at the level of professor was indicated if effective change was to take place.

4.6. Student learning in first year

In the first year of engineering, students take seven compulsory courses. ElectEng101 (Electrical and Digital Systems) is one of these and is in the second semester. This section discusses the data collected from interviews, course work and observations in laboratories, lectures and tutorials.

4.6.1. Ongoing student identity development

One student who ultimately went on to study a PhD in Electrical Engineering described vividly the nature of his exam-taker approach to learning in ElectEng101

> *I memorised procedures in that course, I put no effort into it as I wasn't interested in it and knew I wasn't going to do electrical, I have had to teach myself a lot of things since then that would have been good to learn. I minimised effort for maximising grade – I spent a large portion of my degree doing that, I did the same thing in high school, it's a skill I 'm really quite good at, you learn that from a really young age*

During interviews and conversations with students in ElectEng101 and later courses, an intensification of their personal projects around learning was noticed. The exam-taker identity for many students had become a 'get-through' identity. This related to the high level of assessed work in engineering. Godfrey (2003) describes the pressure on students and the culture of engineering underlying this as linked to a value that engineering should be 'hard' and students should develop the resilience to 'take it'. Students often spoke about the amount of assessment they were faced with and how as the work load increased, they became heavily focussed toward getting through it all.

> *Yeah I've got an electrical test today, a C test Thursday, ChemMat on Monday, I have to come up with a truss and I have to do lab work as well and in the meantime I don't want to get behind on lectures and things as well. So there is a lot of work.*

A number of students avoided lectures, preferring to watch them online at a higher than normal playback rate or just to read the course notes. Several described high workloads from assessment and working to a just-in-time routine where they became highly strategic about how much work they do on assignments.

> *We're talking crash courses, late nights that kind of stuff, memorisation all of which I know isn't real education but fortunately you can't directly test real education (Year 1 student)*

This played out in laboratory work as well, which is one of the few opportunities students encounter to handle electric circuits in the course. Laboratory staff described that students' discourse centred on completing the required tasks and not on understanding.

Once students have begun this focus on learning, it appeared to be highly behaviourist in an ongoing reinforcement cycle. Their lack of understanding led them to rely on learning as KH-techniques and KT-propositions. This further constrains their understanding, which further reinforces their exam-taker or even more parsimonious 'get-through' identity as in Figure 38.

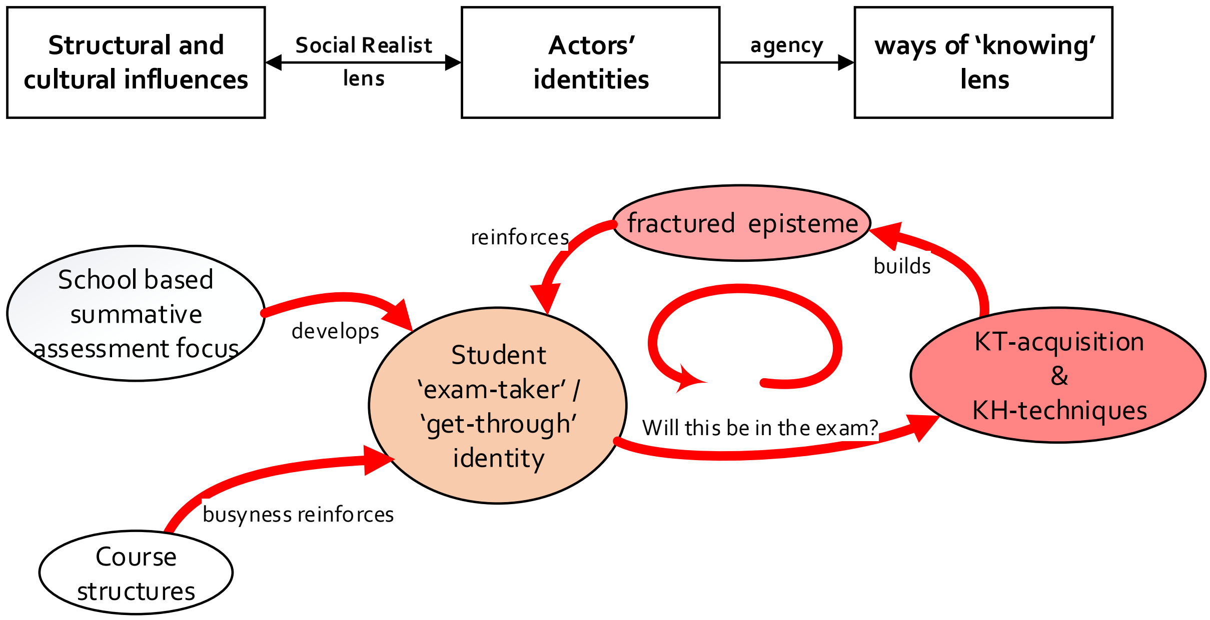


Figure 38: Self-reinforcing learning behaviour of the student with an exam-taker identity

4.6.2. Epistemic domain knowledge

The underpinning knowledge in electric circuits has taken a significant amount of effort by many researchers over several centuries to piece together into an epistemic framework. It is very complex, some of which is described in section 1.5.8. While these concepts are usually explained in lectures, when asked about conceptual (epistemic domain) knowledge students replies included:

> *I mean almost everyone if they see not examinable at the top will turn the page or scroll through very quickly (Year 1 student)*

> *But then my exam brain kicks in and says this isn't going to be in the exam and I can just scroll through (Year 1 student)*

On three occasions in ElectEng101 lectures, two groups of 50 students were observed over 15 minute time periods to gain an indication of their engagement with conceptual explanations. Each group was sampled while the lecturer was explaining conceptual material and while working examples. Students were generally highly attentive and quiet when the lecturer was working a problem; at other times engagement varied with up to 18 of the 50 students using their cell phones or having quiet discussions.

Several students indicated that an approach that excluded understanding was satisfactory:

> *A lot of the time without fully knowing, without understanding what was happening, you can still get a really good mark (Year 1 student).*

Literature however, describes how formulae, rules and calculations become a 'crutch' when there is no understanding (Van Heuvelen, 1991). This student comment from the forum about a question he could not solve suggests this is the case

> *I am having trouble calculating the current. What rule am I supposed to apply? (Year 1 student)*

This inability to work in a conceptual way was expressed by one student during an interview toward the end of the course who, when asked to describe a circuit where components had no values, replied he could not do so and after further encouragement still replied

> *No, no I can't, I'd have to use a formula (Year 1 student)*

A lack of epistemic domain knowledge, however, is a significant problem, because when a student needs to use KT-inferring (to reason) they were often found to struggle. This was demonstrated in student questions on the forum, such as this question for the circuit in Figure 39.

> *Can someone please explain how you go about solving this problem as I am unsure how to use current dividers with 3 resistors.*

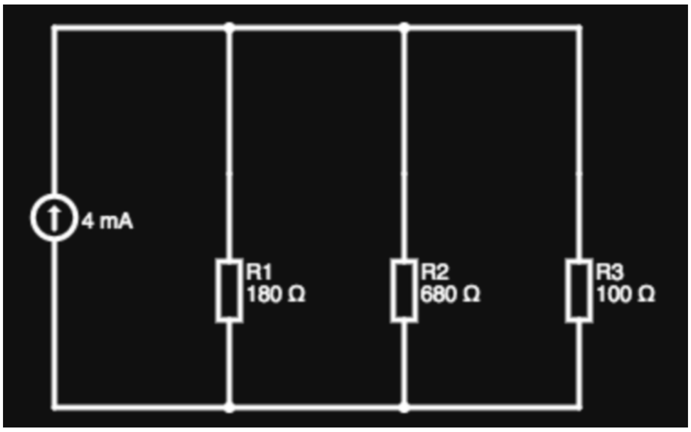


Figure 39: Three resistor problem demonstrating technique dependency

There is a formula for a current divider circuit using two resistors in the course notes, see Figure 40. This KH-technique approach however, may be the only knowledge many students will attend to, as many do not attend lectures or even watch the recordings or are inattentive when the circuit is explained in a lecture. So while students may develop KT-propositions about a circuit such as this, they are unfamiliar with epistemic domain knowledge underpinning it.

Current Divider

Current dividers occur when resistive components are connected in parallel, as shown below. Since the sum of the current through the resistors must equal the total current, the current through a single resistor is a fraction of the total current or can be seen as being the total current divided down by some factor. Hence the name: current divider.

$$i_1 = \frac{R_2}{R_1 + R_2} I$$

$$i_2 = \frac{R_1}{R_1 + R_2} I$$

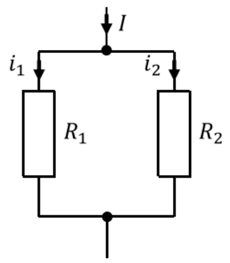


Figure 40: Current divider explanation from ElectEng101 course notes

One example of this is from a student who knew how to solve a problem for an ‘inverting summing amplifier’ but was confused when it was changed slightly:

> *Not really sure how to do this question, since we were never showed how to do a question for a* <u>*non*</u>*-inverting summing amplifier (Year 1 student)*

These comments suggest that many students have KH-techniques but are not able to use this knowledge outside its immediate context, since it has not become generalised or abstract. When considering the comment, ‘their maths is not good enough’, a picture of learning began to take form that for many students, learning seemed to be solely formulae and calculation related, and that their failure was one of epistemic knowledge and KT-inferring - to know where, when and why to use those techniques. This capability is underpinned by epistemic domain knowledge and not by KT-propositions or KH-techniques. As this student commented:

> *But like electricity & magnetism everything sort of connects. So if you don't understand the base then you're not going to understand the rest of it (Year 1 student)*

Perkins and Salomon (1992) describe this as a far transfer issue which requires both mindfulness of abstractions and a deliberate search for the ones to use. In contrast, near transfer is where problems are similar enough to not need the use of abstraction. This student may be expressing both of these points with this OpAmp problem he had trouble with.

> *I have worked this question out twice, one using node voltage analysis which gave me the correct answer, but I also tried working it out using current and gain and I can't get the right answer. Could someone please tell me where I am going wrong? (Year 1 student)*

The near transfer of the KH-technique of node voltage analysis for this student was successful. The problem the student had was with far transfer of abstract principles of the KT-propositions of an ideal OpAmp's properties and current. An inability with far transfer indicates one or both of two issues, epistemic knowledge (mindful abstractions) and capability with KT-inferring (deliberate search) of the right abstractions to use. It is evident that many of the students interviewed did not have the episteme of linked foundational abstractions needed in the first place, which indicates they may never been taught how to develop their capability with KT-inferring. In relation to the ways-of-knowing framework (Figure 5 on page 24), 'their maths is not good enough' began to be interpreted as a failure with abstract epistemic knowledge and not an issue with techniques. In these situations the epistemic fallacy is not to recognise this and instead to give students 'more maths to do'. As reflected in this comment by a secondary school teacher:

> *At Level 1 and 2 [NCEA] they don't really struggle with the concepts [in electricity], it's mostly the maths*

This is what Maton (2013, 2014b) describes as 'knowledge-blindness' (section 1.2). A view shared by this first year student who said:

I always thought the fundamentals would be the easiest and I was like, 'why do they keep talking on about it for so long?' And then I realised … it's actually really difficult to grasp.

The primacy of core principles however was identified as a key result of research undertaken around experienced engineer's knowledge (Winberg et al., 2016), where electrical engineers expressed the importance of fundamental or core knowledge as underpinning their ability to approach all practice and contexts they faced.

4.6.3. Students KT-inferring ability

During interviews, students were asked to reason about the concept of ground in an electric circuit. In the course notes it is expressed in a KT-proposition way as the 'common reference point' and in Hambley similarly it is described as 'the reference node'. Students' understanding of ground was investigated with the circuit in Figure 41 where students were asked to determine the electric potential and current around the circuit.

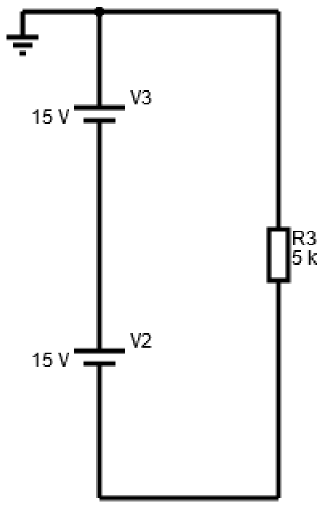


Figure 41: Interview question requiring KT-inferring (reasoning using epistemic domain knowledge) about ground

Of all 32 first year students interviewed none expressed a coherent understanding about ground. Two students demonstrated a KT-inferring ability to reason about it. These students came to accurate understandings without prompting, though their struggles were evident.

I'm sure, no I'm not sure, wait that doesn't make sense does it? Or does it? Yeah I think that's right, yes that's right

Three more reasoned about it with coaching. Most were quite confused by the circuit. As one student commented

You've got ground connected to the positive side is that physically possible?

While some students could reason, most could not. The students who could reason, even those with some coaching, had core principles in place to draw from. In contrast other students often expressed their inability to solve problems as forgetting:

Oh gosh this is a while ago. Oh my goodness, this is on Oasis, we did this on Oasis, we did heaps of those. I don't think I can tell you much about it (Year 1 student, several weeks after that part of the course – but still during the course)

Can someone explain how to find the output voltage? Completely forgotten over the holidays (Year 1 student after a two week mid-term break)

However it may be more appropriate to see this as not having understood what they did in the first place as the students who demonstrated KT-inferring had seemed to pass a point in their understanding where there is no going back and no forgetting, perhaps a threshold point. The idea of a liminal space may also have been observed; this is where understandings may be right or not and there is a lack of surety (section 2.5.3.4). Such as this student who correctly stated the concept of voltage but was not convinced he understood it:

It's like a weird kind of concept to me and I guess I'm not really clarified on it like it's the driving force that's getting electrons moving in the circuit (Year 1 student)

With such a large cohort, there is a likelihood that some students can reason using electrical concepts already; one of these students expressed his frustration quite bluntly about the amount of time taken up with fundamentals in the course.

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 (Year 1 student).

The number of students however, who have this level of understanding is not 90%, and instead is low, as expressed in the data from conceptual quizzes previously carried out in the department (Smaill et al., 2008). During interviews and observations, few students were identified with high levels of epistemic knowledge and KT-inferring, however many students were identified as having a subset of isolated KT-propositions.

4.6.4. KT-propositions

In interviews and in the online forum, many students demonstrated high levels of KT-propositions as opposed to epistemic understandings. The ElectEng101 forum has many examples: such as 'current across', voltage being 'used up', 'electrons decide', 'voltage moves'. Each revealing misconceptions or fragmented correct but disconnected concepts

How do you find V? I tried to find the voltage across the resistor between V and Vout by finding the <u>current across</u> that resistor but that doesn't work. Can you apply NVA at Vout? I'm so confused... (Year 1 student)

I'm struggling with this one. Since there's only one resistor in the circuit, shouldn't any <u>voltage get used</u> up before it reaches the intersection? (Year 1 student)

When <u>the voltage moves</u> the current moves (Year 1 student)

While these concepts have been presented in schools and in ElectEng101 there is a level of engagement that is needed for them to become part of an episteme. One lecturer made a frustrated comment about a problem that he felt students should have known

I told them that in a lecture

This is allied to another significant issue for students, the range of confusing terms to explain the same concept: electric potential, voltage drop and potential difference. The term voltage is perhaps one of the most poorly named concepts used; as one secondary school teacher said, it's

> *like me saying I'll measure your 'centimeterage'*

While issues with the words associated with 'voltage' were found to be common amongst students; the OpAmp is an electronic device that also has poorly worded definitions associated with it as well:

> *If we now diverge into talking about OpAmps. We talk about something that's called the virtual earth principle. Well I mentioned to a bunch of students this morning that I thought that whoever thought up the name virtual earth principle was a moron and should be shot, because actually the principle has nothing to do with earth. (Senior Lecturer)*

It was evident that 'telling' someone a KT-proposition or assuming these core principles is not enough for learning. Students need to use them and infer from them and have their understanding checked. This allies with the next issue.

4.6.5. The conflation of KH with KT

A number of students who were interviewed realised that being able to do calculations did not mean they understood.

> *A lot of the time without fully knowing, without understanding what was happening, you can still get a really good mark (Year 1 student).*

However, as proficiency with techniques increased, there was a tendency for students to express this ability in terms of understanding. Here the student expresses the conflation of proficiency of methods with concepts. During the interview his conceptual understanding was determined as quite low.

> *Oasis is really good in embedding the concepts, so because you did a question over and over again that method gets really solidified (Year 1 student)*

Case and Marshall (2004) in their analysis discuss the idea that perhaps proficiency can precursor understanding. As the next student did when asked about gaining understanding of circuits; he responded that his understanding came from proficiency.

> *I try to do those problems on my own without looking at the solution and then if I find I have done it and I compare my solution with the one that is in the notes, they are similar then I know I have understood. (Year 1 student)*

His understandings though were found to be shallow during the interview. As also were those of this student

> *So with me it's like you have to do a lot of problems to be able to get it, to figure out in your head why it works. (Year 1 student)*

Conversely students that did demonstrate understanding in interviews expressed its source in terms of teacher, parent or lecturers' explanations, or its association with personal work they had done making circuits.

4.6.6. KH-techniques, KT-propositions, epistemic knowledge and KT-inferring

When some students were asked to express what the term 'voltage' means they referred to their knowledge of formulae e.g. V= E/Q, and correctly stated that it is energy per unit charge. However when asked to make use of this knowledge in the context of a circuit they could not. These students knew the KT-propositions behind the formulae and knew the KH-techniques of using the formula, but did not have a KT-inferring capability with it. Their epistemic domain knowledge appeared lacking.

The most prominent occurrence of this occurred with Ohm's law. Almost all encounters with students were used to canvas their understanding of what Ohm's law was. All students expressed it as 'V = I times R', those who were asked to explain it could give little relevant, if any, explanation. The work that Georg Ohm did to establish this model is seldom treated by teachers in anything other than a cursory way (Jilek, 2010), and consequently the underlying concepts (epistemic understandings) are never given enough time to link properly together (Duit &

Treagust, 2012). When a formula is used to express the epistemic relationships of electric potential, charge flow and resistivity, such as V=IxR, there is no account given for cause (electric potential) or effect (charge flow). This algebraic form of Ohm's law, may be one reason students have such epistemic difficulty with it; as it can give the impression that electric current is the cause and electric potential is the effect. As this student said:

> *I think I've always been confused about voltage and current and what comes first between them. Is it correct to say voltage is caused by the flow of current?*

Understandings taught to students, are that charge separation in a source, such as a battery, causes an electric potential difference. When a circuit is closed then the electric potential difference across the circuit creates the movement of charge. The common expression of Ohm's law as V=IxR may account for some loss of Ohm's law's inferential meaning. If Ohm's law was expressed more often as I = V/R, the behaviour of circuits that the law expresses might not be so lost on students.

4.6.7. Teaching and graduate teaching assistants

Of particular interest when observing students engaging with graduate teaching assistants (GTAs) and teaching assistants (TAs) was whether the interaction developed a student focus on KH-techniques, KT-propositions, epistemic knowledge, KT-inferring or assessment. Maries and Singh (2016) describe TAs as not able to identify the common difficulties students have, which would indicate that TAs were not able to help students to work at the KT-inferring level. Several of the GTAs observed did this very well, generally linking the problem quickly to a student's lack of fundamental concepts. What was gained from this was the appreciation that the GTA had inherent within their role, one of the hallmarks of quality teaching, they were more responsive to student learning processes (Alton-Lee, 2003). One GTA related this to being closer in time to when they had resolved these problems with their own learning. This indicated that their understandings had not yet become tacit – the idea that the expert has forgotten that they know this knowledge and how difficult it once was to learn, as Polanyi said "we know more than we can tell" (2009, p. 4).

Figure 42 expresses the knowledge structures found when observing students with TAs and GTAs.

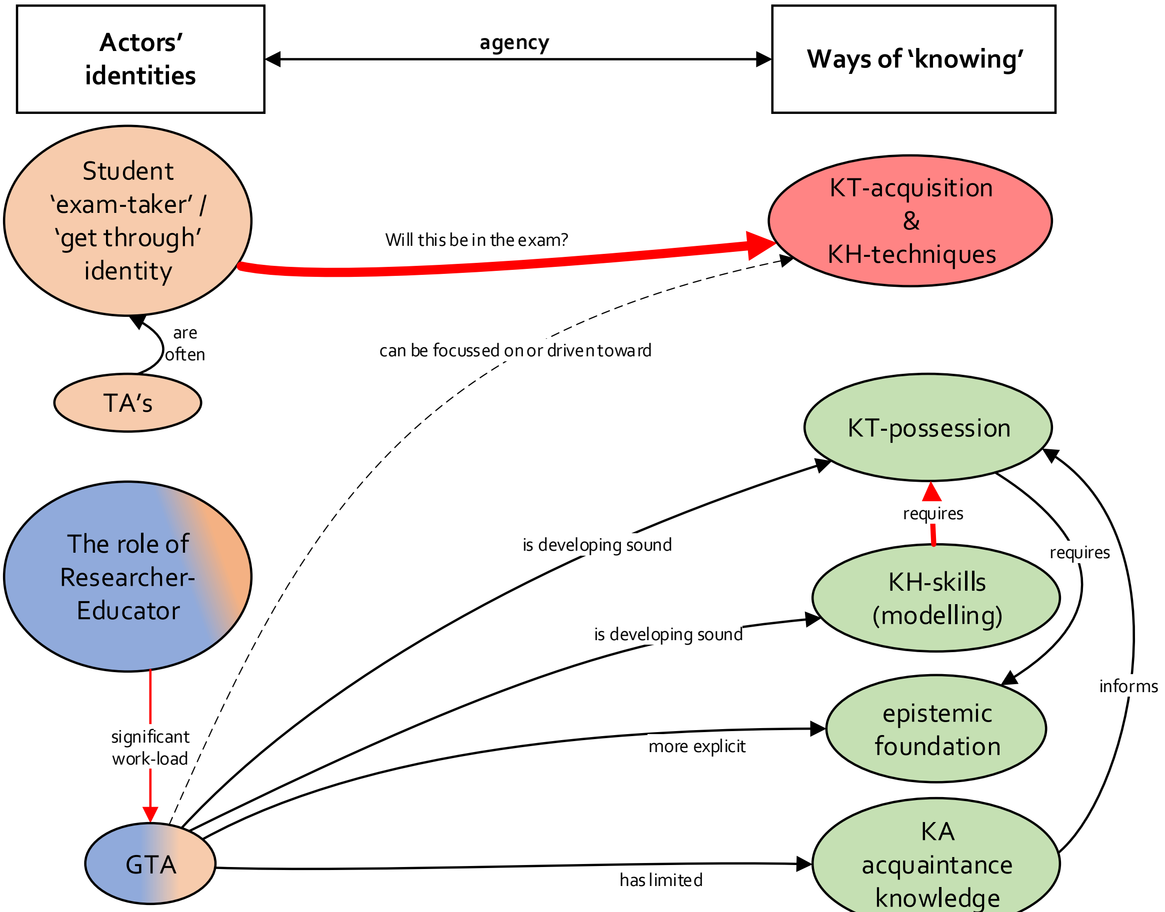


Figure 42: The GTA and TA in supporting students

The faculty have a drop-in centre for first year students. This centre is staffed by teaching assistants (TAs) who are in the second or third year of their engineering degree and doing well in their studies. The weakness of this structure is that the teaching assistants are mentoring students in subject material that they do not necessarily understand themselves. For instance, a student from Civil Engineering was observed assisting first year students with questions from ElectEng101. This had little benefit for the first year student apart from reinforcing their focus on KH-techniques and several students made comments about the inadequacy of this structure.

> *He couldn't help me understand what it was about*

> *Teaching assistants are good but lecturers are so much more better*

4.7. Reliance on KT-propositions and KH-techniques after first year

A reliance on KH-techniques without KT-inferring was observed in students in their third semester (first semester of their second year when they have entered their specialisation). This example of KH-techniques at the expense of KT-inferring is from a test in a second year course. Students were asked to draw the input and output characteristic curves for a bipolar junction transistor (BJT) and to identify the active, saturation and cut-off regions. 94% of students reproduced the graph accurately. Figure 43 is one student's correct answer.

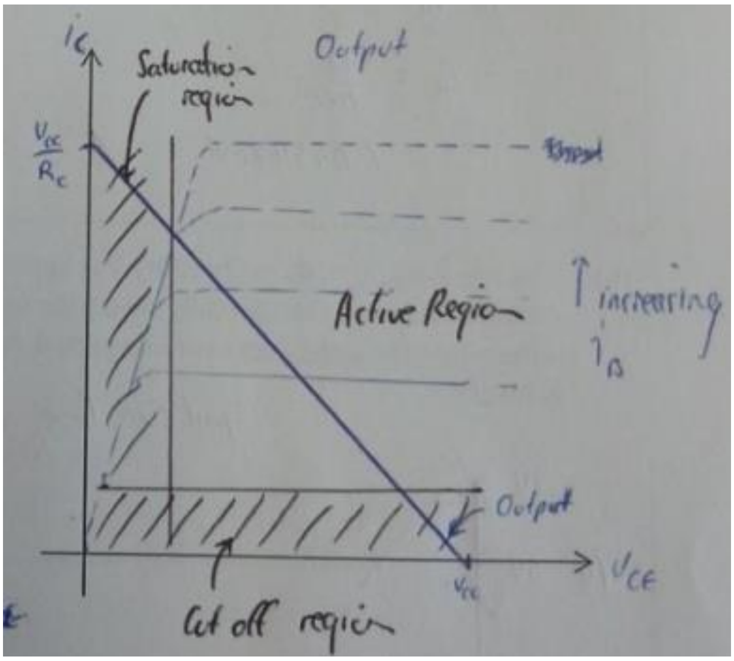


Figure 43: BJT Characteristic - student answer

In a later question in the test students were given the problem in Figure 44 which relies on the understandings expressed in Figure 43.

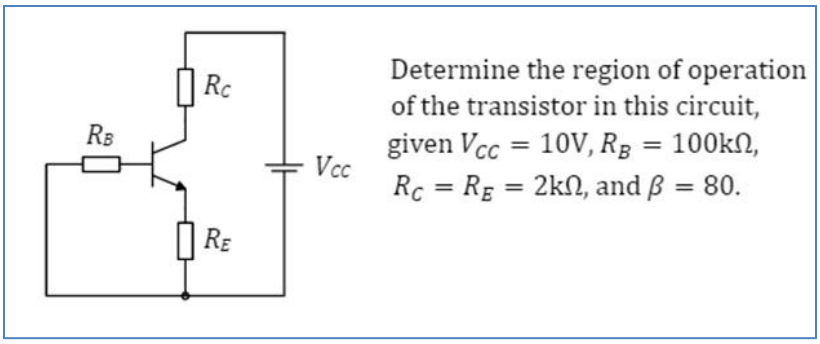


Figure 44: BJT KT-inferring question

Students had been taught a KH-techniques methodology based upon making an assumption about which of the three regions of operation a BJT is operating in and then using formulae to confirm or deny their assumption. If the first assumption fails mathematically, then another assumption is made and worked through. This parallels the understanding taught to students in ElectEng101 in circuit analysis, to first make an assumption and then trust the mathematics.

For those with epistemic domain understandings and capability with KT-inferring about BJTs, it is obvious from looking at Figure 44 which region the circuit is operating in, it is cut-off. The answer required a simple statement about there being no bias and it being cut-off, and 4% of the students gave the type of answer shown in Figure 45.

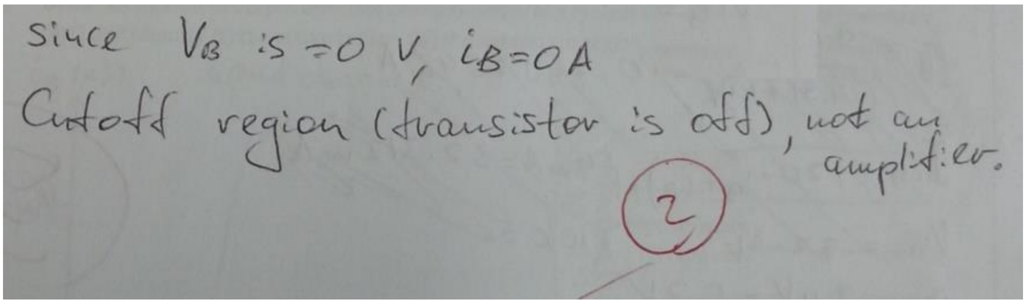
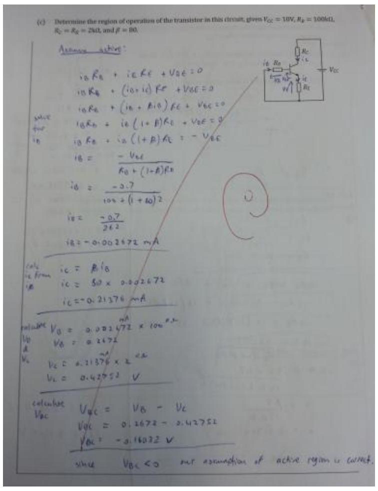
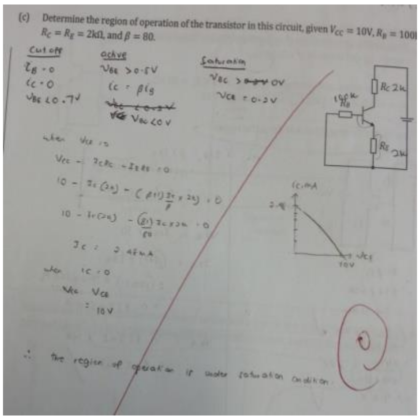
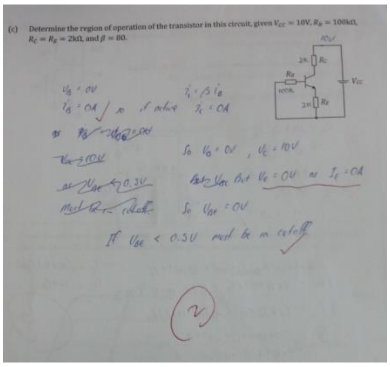


Figure 45: KT-inferring Type Answer to BJT Question

The rest of the students each followed the taught procedural methodology – KH-techniques – make an assumption followed by application of the formula to test the assumption. Student results were distributed as per Table 8 which also contains samples of student work.

Table 8: KH-Techniques Application to BJT Question

1 – Active (35%)	2 – Saturated (27%)	3 – Cutoff (34%)
<u>incorrect</u> application of KT-propositions, fragmented knowledge	<u>incorrect</u> application of KT-propositions, fragmented knowledge	<u>correct</u> KH-techniques carried through <u>or</u> KT-inferring evidenced?
		

In total 38% of students gave the correct answer (cutoff) to the question. It is unknown how many of the 34% of students who correctly followed procedure to get cutoff had the same level of KT-inferring as the 4% of students who stated the conceptual answer, as students may have thought it important to communicate their knowledge of the technique. One GTA expressed surprise at students even applying the rule in this situation, he stated it was obvious and was surprised students did not see it. Hower it is only obvious to someone with an episteme of understanding and the ability to apply KT-inferring.

While mathematical procedures were applied flawlessly in both incorrect answers in the table, students applied propositions in isolation as rules, and in doing so they negated the logical conections within the propositions. A proposition is a statement of truth or falsity, and a complex proposition includes logical connectives such as ‘and’, ‘or’, ‘when, and ‘if’. The first proposition is ‘there is 0.7V across the base-emitter *when* conducting’, however this has been replaced in the first incorrect answer with the proposition, ‘there is 0.7V across the base-emitter junction’; and the boundary of the proposition set by the connective ‘when’, that allows us to make inferences, is lost.

In the second incorrect answer, the same happened, the complex proposition 'there is 0.3V across the Collector-Emitter when saturated' is replaced by the unbounded 'there is 0.3V across the Collector-Emitter' and the capability to make correct inferences is lost.

In subsequent years, conceptually demanding questions of this nature were no longer used in the test. This may be evidence of reflexivity in action, as explained in section 2.3.2 where Merrow (2005) refers to the compromise or stand-off in expectations that exists between educators and students, which hinders them going outside the status quo.

It is not uncommon for a reliance on KH-techniques to continue through to the end of the degree, as a lecturer stated

> *I have a general concern that at part one they understand very little and that concern continues because I currently am working with students in part three design courses where electronics and therefore circuit theory plays a big part and my observation over quite a number of years, this year included, is that their fundamental understanding of electric circuits is very, very poor...My suspicion is that we graduate students who find themselves in that same situation. In other words their fundamental understanding of basic concepts is really, really shaky... You would expect a student who apparently has had a pretty thorough exposure to electric and electronic engineering to actually have good versatility and basic understanding of circuits and my view is that that just isn't the case.*

In this, and the previous section, KH-techniques were shown to be one of the primary ways-of-knowing relied on by students. When students struggle with mathematical techniques it does not seem illogical to infer that their 'maths is not good enough'. This deduction then only requires a small step to the logical consequence that educators need to 'give them more maths to do'. However the discussion so far has shown this to be the epistemic fallacy, that what we see is not what is actually happening. Instead students need a different approach to learning; this is further demonstrated by what takes place next in the learning sequence.

4.8. Transition to ElectEng209

The diagram in Figure 28 (page 115) shows the important transition to project-based learning in engineering, something which is different to most other faculties in universities (Godfrey, 2014). For students in the department of Electrical, Computer, and Software Engineering this happens in the second semester of the second year when they take the course ElectEng209. Up until then learning has centred on core scientific and theory/engineering scientific courses which have been in the familiar lecture and laboratory format.

Figure 46 describes the situation observed with regard to the ways-of-knowing framework for students on entry and over the first two years of the degree.

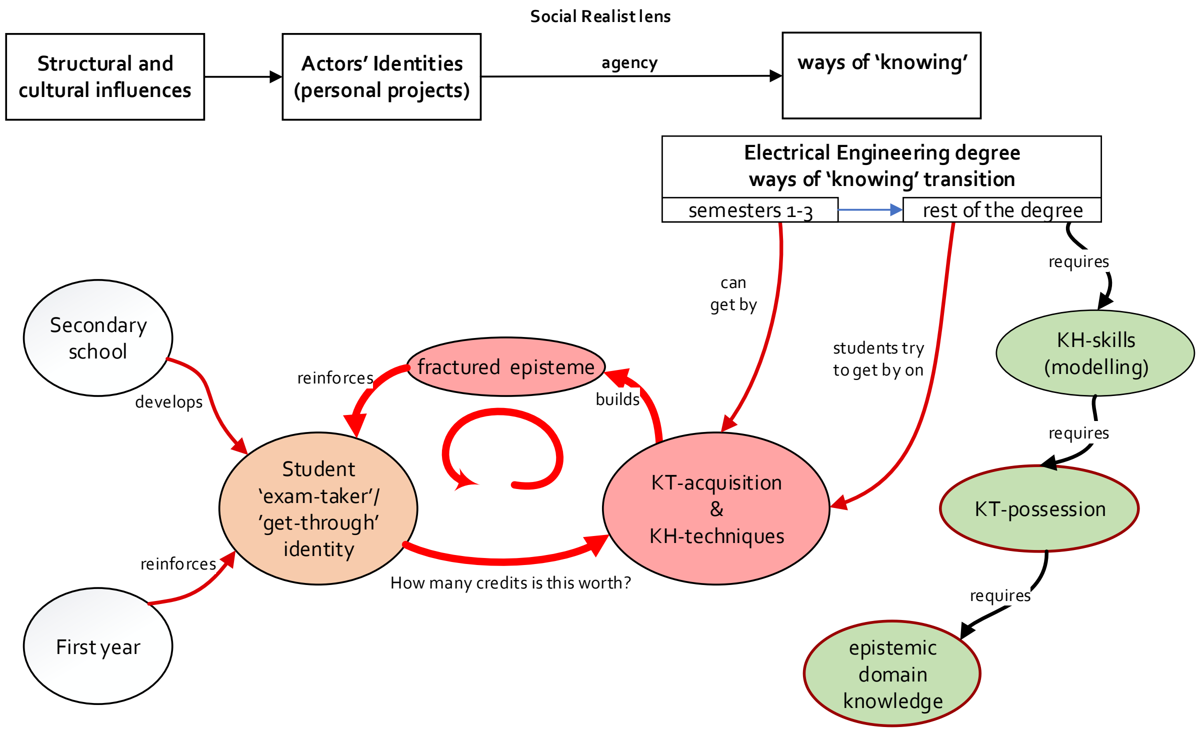


Figure 46: Ways-of-knowing transition in the fourth semester

During their first three semesters, students are able to 'get by' with the focus on KH-techniques and KT-propositions developed at secondary school. Interviews and observations indicate that students continue in this pattern of learning due to the relative ease in which this approach allows them to pass. Unfortunately this results in a fractured episteme of disconnected propositions. This pattern of behaviour has little consequence for many students, as described by one student in ElectEng101, he could *go straight to the question and get used to the style of questions and cram*

This approach is so engrained within some students that when teaching does not follow tests/examinations explicitly there is a view that the teaching is inadequate

I think he was quite erratic, like he'd do one thing one day and then sort of not really follow what the tests would be like (Year 1 student)

In ElectEng209 students are introduced to a real (mostly authentic) context which signals a significant change in the ways-of-knowing required. In groups of four, students design and prototype a product which involves the integration of OpAmp signal conditioning circuits, a microcontroller, a CPLD (complex programmable logic device) and Bluetooth transceivers as well as design a PCB and write in VHDL and C code. Students have no examination for the course, although there are practical and written tests and they are required to keep a design journal and make group presentations. It is during this course that a reliance on KT-propositions and KH-techniques and a subsequent deficit in KT-inferring begins to vividly present itself. GTAs and technical staff assist students in their project labs and indicate a number of frustrations around student lack of understanding, making strong comments about lecturing in the prior theory courses.

The transition this course requires is not easy for students as it signals the need for a significant shift in their identity and agency (learning behaviour). While a shift is indicated, students have varying responses to the transition. Discussions with laboratory staff who interact with students indicate that many students continue with inadequate learning behaviours. Others abdicate responsibility for what they perceive as more difficult aspects of the work to one person in the group. GTAs who have been through the course themselves promoted the idea of smaller project-based tasks in the prior theory courses as well to help students prepare for this transition. This had been trialled in the department previously, but was discontinued as insufficient resources were available to provide the adequate and timely feedback needed.

The time students need to invest in making the transition in ElectEng209 has impact on other courses. As students began spending a disproportionate amount of their time on the project, several lecturers in other courses raised concerns about the effect this has on course work and results in other courses; and that there was too much work in ElectEng209. In terms of the ways-of-knowing identified in this chapter, a more relevant question to raise about ElectEng209 is, are students well enough equipped for the course? The position of this research is that any concern about the work load in ElectEng209 is obfuscated by students' reliance on KH-techniques and KT-propositions and a lack of the required preparatory epistemic domain knowledge and confidence with KT-inferring. Rather than remove conceptual content from the course (i.e. remove the opportunity to engage with deep concepts – as was described about the BJT questions in the previous section) it would be better to focus on improving students' KT-inferring before they enter the course. In that way once students' understandings are better established, a more accurate assessment of the level of content in the course would be possible.

This is not to deny the place of mathematical capability, as electrical engineering has at its core the many methods and techniques of mathematics. While mathematics is crucial to the development of an electrical engineer's ability with circuit analysis, students often fail to recognise that engineering is about more than mathematics, and miss the point that mathematics supports their design decisions (Goris & Dyrenfurth, 2012).

4.9. Knowing and context

Meyer and Marx (2014) describe one reason for students' lack of understanding as the lack of real circuits being used because they are too complex for novices. This lack of use of real circuits was observed in secondary schools prior to this research and was also evident in the courses investigated. Students were only given circuit fragments which had an electrical function to perform, and these were seldom given purpose or a link to the world. This is not abstraction as it is not a description of what exists in the world (Laurillard, 2002), but some lesser level of decontextualisation. While circuit fragments such as two resistors in parallel or a transistor or OpAmp circuit fragment are abstractions or descriptions of reality, they describe fragments of isolated aspects of knowledge with no direct relevance to any purpose in the real world. Academic literature which describes the inadequacies of this approach describe the problem as being bound to its theory-first or deductive (top-down) teaching practices and portrays the alternative, the context-first or inductive (bottom-up) approach as preferred (Felder, 2012). Figure 18 (D) on page 66 describes the first and Figure 18 (E) describes the second, however neither produce satisfactory outcomes. It is important to place context accurately into the stages of the learning heuristic (section 2.5). It does not belong in the first stage that defines where learners need to go, but instead it belongs in the second stage of how learners are going. Learning should begin in the abstract but then needs to become deeply embedded in the real world so that the abstractions are seen for what they are, equivalent expressions of reality. Learning should then return to the abstract progressively building and reinforcing the generalisation; Maton's Semantic Wave model Figure 18 (A) is one powerful expression of this.

As part of the research, another lecturer and I took the opportunity to interview five PhD candidates, all of whom I had taught at school for four years in electronics. The other lecturer was important to reduce potential bias. Bias of course was still possible as I was part of the interview, however these students were candid about their opinions. Their most insightful observations related to understandings of electric circuits they gained from the project-based work they did.

> *Like now it seems kind of basic but it was a lot of understanding that we had*

Their learning process was described as

> *You teach us and then we have to go and make it on bread board.*

One stated this allowed them to

> *see what's happening in your mind as ... it's hard to visualise until you actually go make something*

Their reflection was that their physics teaching *never made the connection … that why it's so boring because we don't understand at that point what we're actually doing… [it was] too exam orientated*

One insight was how inferential thinking could be made in a practical situation using theory

So you just make a simple circuit and then you try to keep adding complexity to it but eventually your normal theory will be too difficult to use so then you'll be like oh here's a trick you can do KCL or KVL.

Importantly, these students recognised the congruence of KA, KH and KT being brought together at an early stage to build their understanding.

With the removal of the OpAmp laboratory from ElectEng101, students now have only a single introduction to this essential aspect of their development (one that uses a preassembled board rather than electronic components). This limitation of the course was commented on by several students, for example:

Having only one short lab session was disappointing. For a course where it would have been so easy to implement a practical component, having it be exclusively book work was a big let-down

The missing relationship between real circuits and theory in ElectEng101 and other courses was recognised by many of the students interviewed:

You've got maths and then you've got the practical but then you need to fully understand the applications of what you're building in terms of real life. … I felt understanding the application helped me understand why this device even exists (PhD candidate)

If you don't deal with it you won't have the practical experience to know how it operates realistically (Year 1 student)

The lack of physical interaction with the subject content is viewed as a significant factor that contributes to students' focus on KH-techniques, as they have little if any perception of what a component is, so a schematic may only be a drawing of geometric shapes and not a representation of components in circuits.

> *Sometimes the circuit on paper can just be so abstract from a real example, so I think if I saw it and it was like maybe like explained as well and that could help me to make a connection between the circuits I think it would be really, really valuable but because I sort of missed that like clear connection, yeah sort of just became something at the time was just like how can I get through this to get it right as opposed to yeah really understanding it. (Year 1 student)*

4.10. Physical circuits and systems modelling

Mathematical modelling is not the only abstract understanding that electrical engineers need to develop. Schematic symbols are models (behavioural representations) of real components and schematic diagrams are models of real circuits; and layout diagrams model components' foot-prints in the world. The ability to fluidly move between these modalities is a crucial aspect of learning that students need.

Students also need to work at the abstract level of systems which includes block diagrams and developing understanding of the input-process-output models of circuits. This is not an intuitive or easy understanding to develop, as evidenced by the many students in ElectEng101 who confused inputs and outputs. Most students did poorly in questions relating to subsystems that include: sensors, amplifiers and data monitoring devices. When asked to work out the input to one subsystem which is the output of the previous one, students often became very confused.

4.11. Researcher-educator identity and agency

The researcher-educator was described in section 2.3.4 as having two incompatible identities, where literature described the researcher identity as dominant (Godfrey, 2003) which led to either compromises (Table 1 quadrant 2) or elimination (Table 1 quadrant 4) of the educator identity. This section explores what this identity means within teaching and learning. This begins with Figure 47 where the dual colours of blue for researcher and brown for educator show the disproportion between the two identities.

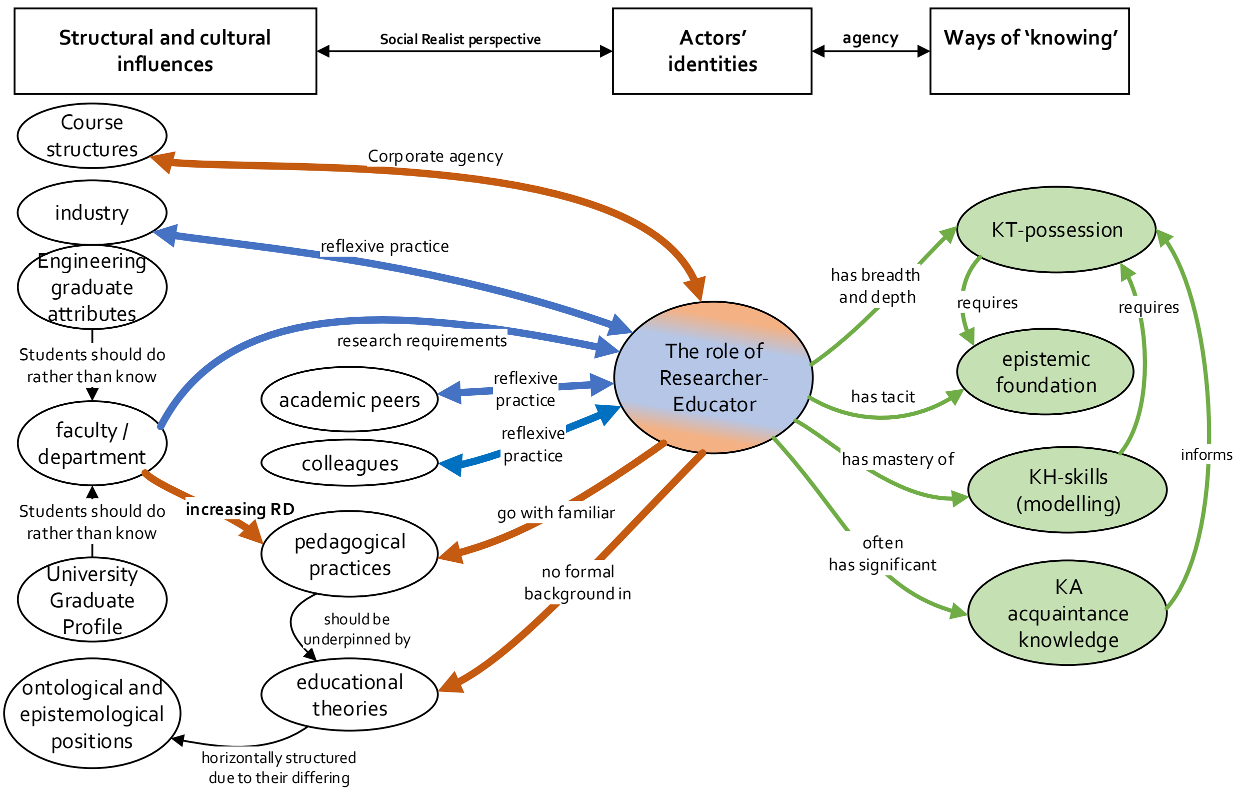


Figure 47: Lecturer identity/agency relationships

The researcher identity is strongly linked (blue) to industry, peers and research with a powerful domain knowledge base (green). The educator identity (brown) is not linked in the same theoretical way to the domain of educational theory; this is often the case in engineering education (Radcliffe & Jolly, 2003). This was recognised during observations and discussions as having an impact on course structure in recent years. In 2013 one of the two teaching staff in ElectEng101 retired; his role was that of a senior tutor; the tutor role is now known as a professional teaching fellow or PTF. At the University of Auckland a Tutor/PTF is employed in a non-research role which carries twice the teaching load of lecturers and no research responsibilities. Before becoming a tutor he had been a secondary school physics teacher. His retirement was seen as an opportunity by some academic staff to disestablish the PTF role which provided the funding to establish two new academic research positions.

The value attached to the educator identity was expressed by academic staff on two occasions. The first when talking with a programme leader about a course; in referring to the expert level of understanding of the staff, he stated that any of the staff could teach the material. No link was made however to why students in the course had not been doing well in it for quite some time. On another occasion a new candidate for a lecturer's position gave a presentation and listed an extensive range of content he was able to teach, however he made the comment that he had never actually taught, but had some tutoring experience. When asking another academic about this afterwards it seemed of little consequence because of the candidate's research capability.

The tutor who left had also held the role of course coordinator in ElectEng101 and the department appointed a separate academic staff member to manage the logistics of the large course. This and teaching changes brought total course staffing to four; only one of whom had been with the course previously. Along with this, one of the new teaching staff sub-contracted some of his teaching role to another researcher-educator. This took place at a time of growth in the faculty where the course grew in size from over 500 to over 1000 students. The course developed a complex set of roles and responsibilities as depicted in Figure 29 on page 118. Smooth course administration, one of the aspects of a non-pedagogically aligned instructional discourse (section 2.4.6), became central to learning. This was reflected when staff in two areas of the department felt that the course was not meeting the content needs of their subject. Resultant changes were made to course content with two of the three modules in the course book being rewritten with new topics added. Without an underpinning pedagogically-aligned regulative discourse, a significant amount of the material became overwhelming for students, several of whom made comments including:

> *Module … was so difficult; it was like you had to be a hobbyist already to understand it.*
>
> *I don't get any of this.*
>
> *We're not really taught.*

On the day before the final examination a student posted on the course forum

> *What is the most time efficient way to master module … when you didn't understand anything the lecturer said.*

The identity of researcher-educators had another noticeable impact on student learning; this relates to how southern hemisphere teaching cycles do not align with the summer conferences in the northern hemisphere. In 2016 one of the three staff left the course. This changed the distribution of course materials between the two remaining staff, one of whom was committed to an important disciplinary conference in the northern hemisphere. This resulted in changes to the course being made at short notice in terms of who taught what content and when. This impacted upon the epistemic flow of the learning material and consequently the timing for one of the two laboratories in the course no longer fitted with the material. Rather than rewrite the lab, it was consequently dropped from the course. Pedagogically, the removal of one of only two labs in a course is important in terms of student learning. The comments around it are perhaps more important. Several comments were made by staff about the relative importance of the conference in relation to teaching responsibilities, and that teaching should take priority. However, expecting a researcher to hold a pedagogical view seems incongruent with the values expected of them by a tertiary institution that rewards research and not education (Mills & Treagust, 2003). Just as Case and Marshall (2004) say about students we teach techniques to, why should we expect someone to deliver something other than that which is rewarded?

The lack of reward attached to an educator identity was indicated by other staff as well who had spent time focussing on their educator identity and also by other staff who commented on the risk it represented to academic careers to concentrate on teaching. While student learning has benefited from lecturers beginning to develop identities as educators, it seems the situational logic of the educator-researcher role is still one of contradiction. If a researcher-educator takes a position firmly in quadrant 4 of Table 1 of page 40 there must be a choice made between the two identities and as Archer (1995) describes, there must be both a winner and loser.

The compromise position of quadrant 2 in Table 1 seems attractive; however it is just that, a compromise, which no matter which option is chosen, the other suffers (Archer, 1995). One alternative to this situation was described by an academic as how some lecturers seemed to purposefully do such a bad job of teaching that their teaching duties were removed, perhaps as Archer (1995) describes, to get them 'off the hook' of having to deal with this difficult situation. The strategy where educators turn away from research also seems unsatisfactory, as they are the only ones who have had to adjust their beliefs. In some institutions, the contradiction has been removed through having dual pathways for career advancement. This is however a solution which also has an effect, as one academic said this is viewed as weakening the importance of the researcher.

Within this situation with researcher-educator identity sits the primary agents – the students and their learning. The concept map in Figure 48 represents the incongruence of the identity relationship in terms of its impact on student learning. Specifically, how decontextualised and fragmented useful-content, and a reliance on KH-techniques, reinforces student focus on passing examinations and getting through.

A significant aspect of this is the use of OASIS. The lack of theoretical underpinning of OASIS led to its development centred on KH-techniques. While this is an important realisation from this case study, more so is the lack of this awareness. The instructional discourse in the department related to a mix of pedagogical terms, such as: students engagement, student participation, active learning, modern learning, student-centred learning, student-led learning, experiential learning, changes to delivery and student experience. With a limited background in the epistemic knowledge of education, these terms become attractive amidst the powerful rhetoric of all that is 'wrong with lectures'.

Orchard and Winch (2015) describe that the identity of an expert educator is founded in deep engagement with educational theory. This is beginning to be recognised in engineering education. In a keynote speech at the 28th Australasian Association for Engineering Education Conference in December 2017, Brian Frank said that the most significant increase from their Improvement in Engineering project at Queens

University was the difference made by bringing in expert educators with relevant theoretical backgrounds in education (their team members have Masters and Bachelor degrees in Education). His comment reflects the critical role that a deep theoretical underpinning has in the identity of those necessary to bring about effective change in learning situations

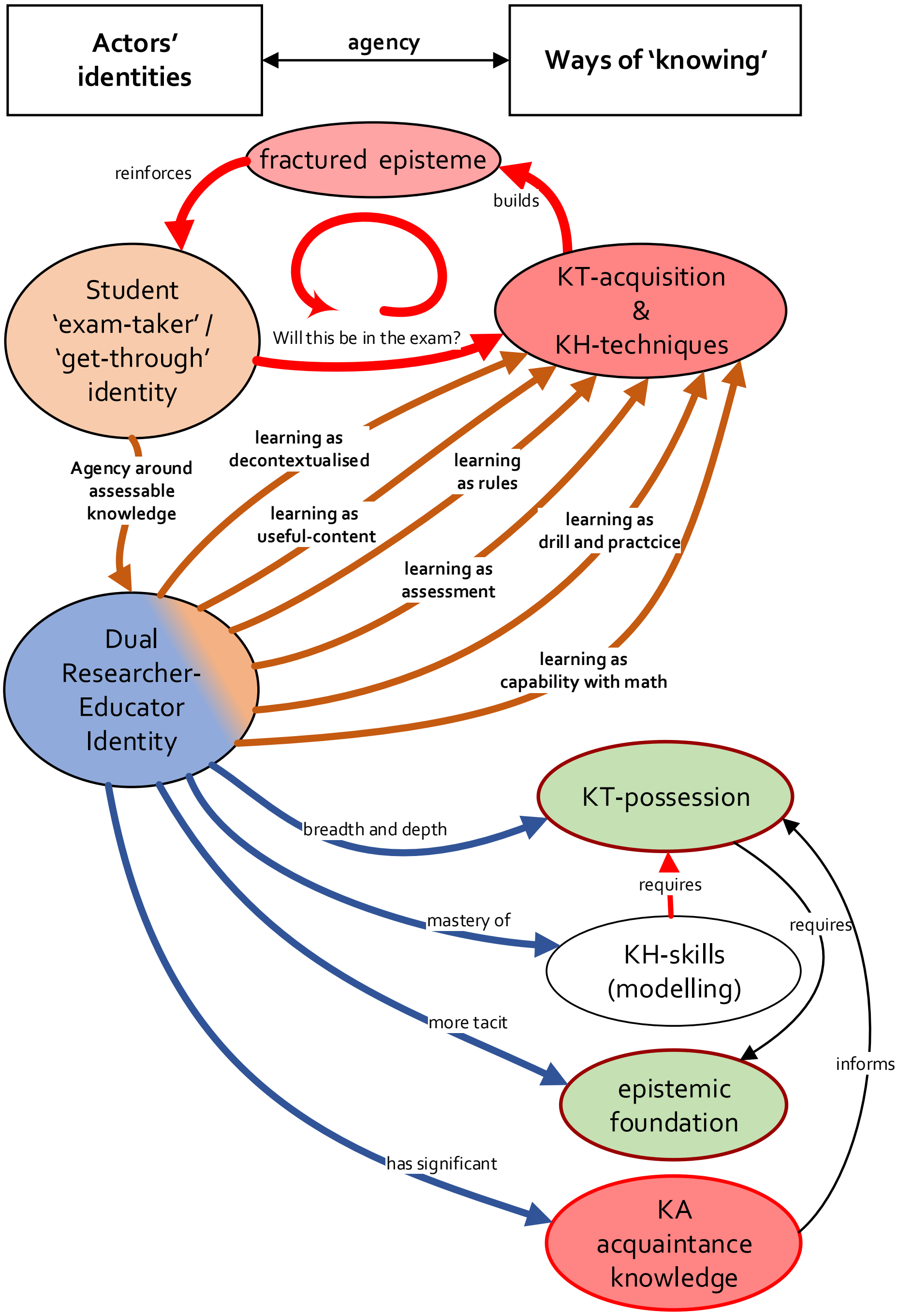


Figure 48: The dual identity of the researcher-educator

4.12. Conclusion

This chapter was aimed at answering the first research question 'what is the real nature of the learning problem?' A large set of data was collected over an extended period of time and analysed using a two level thematic analysis to identify the 'actual' (semantic) themes and the 'real' (latent) themes in the situation. Prior research in the department on electric circuit knowledge (Smaill et al., 2008) and on culture (Godfrey, 2003) were highly informative as the insights provided valuable underpinnings in developing the perspective. Analysis of the situation exposed the structures, culture and identities which influence agency and their impacts on learning. These were expressed in several concept maps through the chapter and are put together in a systemic overview in Figure 49. These influencers operate at the level of the 'real' in the situation; the outputs are students' limited ways-of-knowing, and are expressed using the concept of parsimony, which exposes an inappropriate definition of successful learning.

The result of this exploration was an understanding of the 'real' nature of teaching and learning taking place. The analysis began with an understanding of how student learning behaviour in the first years of electrical engineering had previously been established in secondary education through summative assessment strategies aligned to 'credit-farming' which led to many students being described as having an exam-taker identity. The researcher-educator identity was established as a powerful domain expert with responsibilities for creating epistemic domain knowledge, but one without corresponding epistemic knowledge of educational theory, and a split focus (hence the blended colour). This situation led to many students following a KH-techniques (can follow procedures) and KT-propositions (can remember isolated fragments of information) focus. In early stages of learning these students were not provided opportunities to develop the capability for KT-inferring (inferential use of concepts from the domains episteme). This was evident as a deficiency in students' KH-skill (competent follow through) of the key engineering practice of modelling (ability to create and understand symbolic inferential relationships) in their first project-based design course.

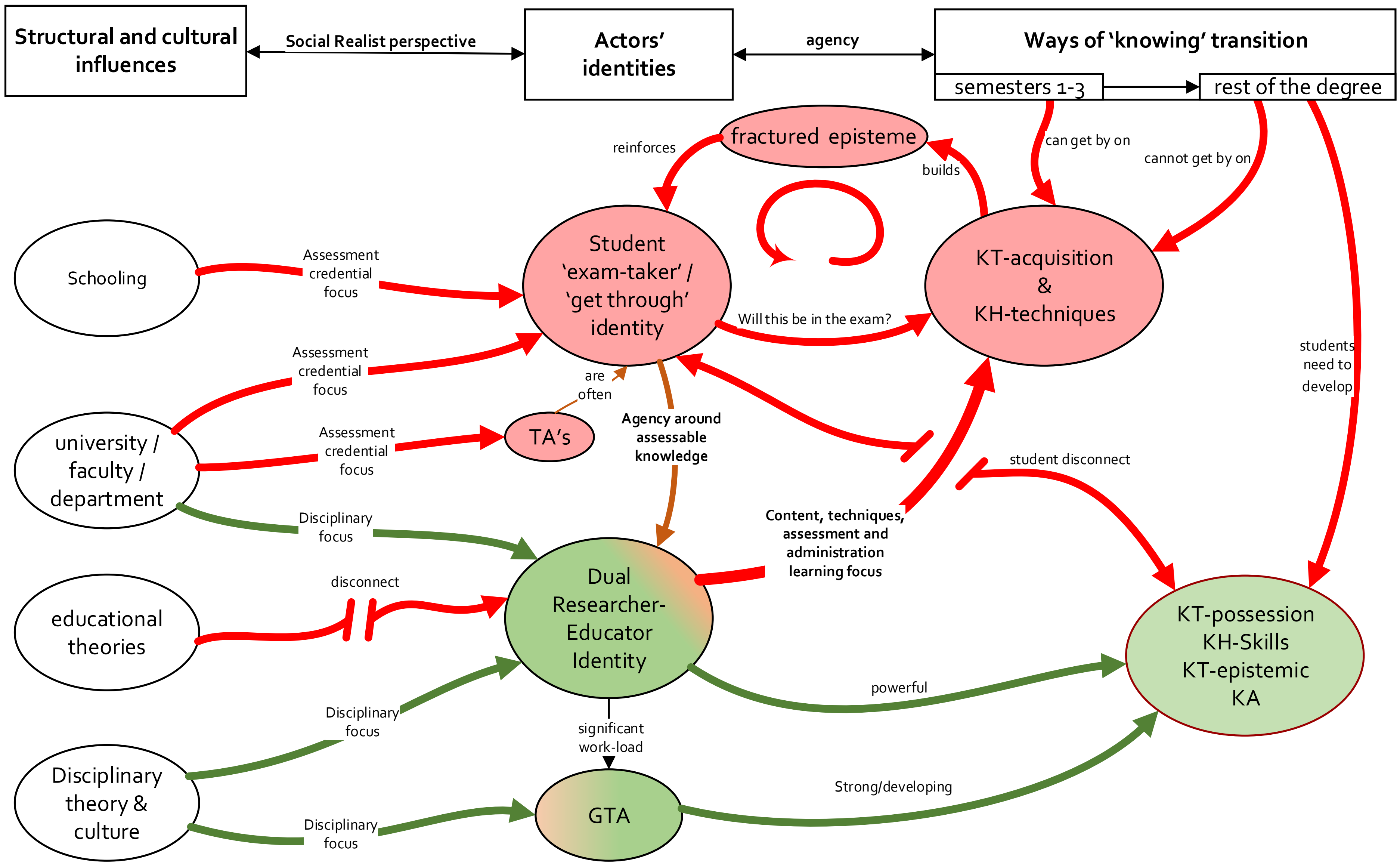


Figure 49: Concept map of teaching and learning in the first two years of electrical engineering education.

This situation was reinforced by the single laboratory opportunity in the first year course and the substantial reliance on the online learning tool OASIS, which engaged students only at the level of drill and practice, further encouraging the focus on KH-techniques.

A non-pedagogically-aligned instructional discourse was found to be taking place; one that focussed teaching around useful-content, rules and capability with maths as opposed to an epistemic underpinning of the domain via abstract learning goals. While this discourse was changing, without an episteme of educational theory to underpin the internal regulative discourse, it was viewed as drifting toward potentially unsuitable learning practices.

4.12.1. Parsimony

Student learning is demonstrated in agency that was seen to 'game' or parsimoniously circumvent learning due to an inappropriate definition of successful learning. This perpetuates a self-reinforcing situation where a fractured episteme causes students to further focus on this subset of learning, which in turn fails to build the epistemically structured understandings they need to leave the spiral. In Figure 49 the red colours represent parsimony at work and the green epistemic knowledge. About parsimony Ptolemy writes:

> *We consider it a good principle to explain the phenomena by the simplest hypotheses that can be established, provided this does not contradict the data in an important way (as cited in Townsend, Busemeyer, Vandekerckhove, Matzke, & Wagenmakers, 2015, p. 301)*

This idea is often expressed as Occam's Razor. The problem with parsimony in education is that the 'real' phenomena is most likely hidden beneath the surface or 'actual' level, and the agency of those involved leads to concentrating effort on the visible aspects of learning such as: assessment results, activity (busy work), useful-content and mathematical capability. Parsimony encourages taking the simplest path that does not contradict this data, so leading to doing more maths, learning more rules, practicing more problems, tightening procedures and having a useful-content approach. However what was identified in this chapter is the important deeper levels of the 'real' and the parsimonious approach to the 'actual' was not all that was happening. The theoretical lenses were essential in developing the necessary critical awareness about teaching and learning to expose the 'real' structure, culture, identities, agency and knowledge at work; and to see the crucial need for a sound grasp of educational theory to underpin teaching practice. To borrow a saying about parsimony that I had on my classroom wall for many years and used regularly with my students:

> There no shortcuts to any place worth going
>
> *Beverly Sills*

4.12.2. A closing analogy

When considering the overall situation of teaching and learning, an analogy came to mind that I felt aptly described the situation. It is used to express the relationships between structure, identity and knowledge. The analogy is that of a phase locked loop (PLL) in false lock, and this quote by Stensby (1997) describes it.

> *The false-lock problem can be very perplexing from an operational standpoint. The pull-in process halts when a false-lock is reached, and the PLL appears to lock at a frequency that is incorrect. Common lock detectors can indicate incorrectly that the loop is phase locked and operating properly. The false-lock state may be detected by observing a low-frequency periodic beat note in the phase detector output. However, the beat note may be hidden by noise, and this method may fail to detect the false-lock state. In fact, the false-lock state may go undetected until overall system failure is noted (Stensby, 1997, p. 157)*

To parallel the analogy with the situation: the false lock represents the many students whose learning is parsimoniously centred on fragments of knowledge and following techniques in order to pass. These are valuable but are only a subset of the knowledge necessary for the project-based design course.

The quote by Stensby describes false lock but not explicitly why it happens. A loop requires feedback from the output to inform itself; false lock occurs when the system latches on to the wrong signal in the feedback. The loop thinks it is seeing the real feedback signal, but it is not. In teaching and learning this is the epistemic fallacy, where the wrong signal is taken from the output. One example of this was 'their maths is not good enough', another that more useful-content is needed. While these are real signals, they are not the main signal but support it, as they are the signals on either side of it. The real learning need is epistemic domain knowledge and being able to reason using it.

An inability to discriminate the real signal from those on its periphery happens for several reasons; the right signal is obfuscated by the wrong signals or by noise, or the error detector is not good enough. In teaching and learning the two pedagogical practices aligned to KH-techniques and KT-propositions are dominant and drown out the real knowledge need. The noise is also loud; it is the constant pressure on students from high levels of assessment, the drive to reduce academic load through managing student contact, the administrative demands of the large cohort involved, and the pressure on lecturers for research output. Just as noise in circuits can be caused by inadequate grounding, noise in education can be caused by inadequate grounding in theory. Another reason for the wrong signal being selected from the feedback is due to the feedback controller not knowing what to look for. In teaching this requires a tuned ear to recognise, one that requires a theoretical background in eductaion. As Hattie writes, teachers need

> *to be the best error detectors in the business (Hattie, 2012, p. 163).*

The subtle error 'beat' described by Stensby is present in the situation; Niemann's description (Dadich, 2017) at the beginning of Chapter 2 describes this as the nagging feeling we have when we know there should be something better but we aren't quite sure how to grasp hold of it. This is due to the many complex factors to be taken into account in a feedback loop. In electrical engineering, special detection circuits such as the proportional–integral–derivative (PID) controller are used to take account for such complexities. In teaching and learning this equates to the ability to delve deeply into educational theory, to recognise the strengths that each theory has due to their different epistemological and ontological positions and then decide how best they should come together in the right proportion at the right time and at the right rate for learning to occur. There are simply no short cuts to this process, and it is difficult to get it to work and maintain it.

When a loop is in false-lock, it is fragile, susceptible to small even innocuous changes in the feedback or its discrimination. In education this is called pedagogic frailty (Kinchin et al., 2016), it is only semi-stable and also susceptible to naïve changes. As changes to the situation took place, this error-beat became more pronounced, but this led to an incorrect assumption being made about the problem and consequently how to fix it. More resource was then brought to bear on re-establishing the prior situation, the false-lock, through more administrative oversight. Now that the subtle error-beat had been heard, an instructional discourse began to develop around what to do about it. This discourse however needs a pedagogically aligned regulative discourse that can help tune the system onto the best mix of practices, and when, how and why to use which ones and for what purpose.

It seems from this chapter that the inputs –the students - and outputs – the learning - of the system are not entirely satisfactory. This hints at the real nature of the learning problem; learning is at the level of the actual or the visible. The real problem is usually hidden, it is within the system. It may be that the real nature of the learning problem is that it is seen as a learning problem; and not as a teaching problem that needs theory to engage with a systemic processing and feedback problem. This requires unpacking and exposing epistemic knowledge, and finding ways not just to make it comprehensible for students, but to make students link it together so as to be able to reason using it.

This chapter has focussed on describing the situation with the complexity it deserves; it now needs options that do justice to this complexity and those involved. The research question at the centre of the next chapter is part of beginning to explore these options.

Chapter 5. **Fundamental circuit concepts tutorials**

This chapter investigates the second research question: 'Can an increased focus on epistemic knowledge help students in first year electrical engineering?' This involved the development of a pre-course quiz and a set of fundamental circuit concept tutorials (FCCTs) for students in ElectEng101. While the research question involves seeking an improvement in student epistemic knowledge, the results from Chapter 4 indicate that the structure and culture of learning have significant effects on student identity and agency around learning. A significant aspect of developing the quiz and FCCTs was to gain further understanding of the magnitude and nature of this phenomenon. This understanding would be useful in informing subsequent decisions about the nature and approach to be taken in future work.

5.1. Pre-course quiz design.

Prior research in the department investigating students' understandings had revealed that many students did not have conceptual understandings / epistemic knowledge of electric circuits on entry to ElectEng101 (Smaill et al., 2008, 2012). A short quiz was prepared; firstly to identify students' knowledge in terms of the various ways-of-knowing, and secondly as a form of 'wake-up call' as described by Smaill, Rowe and Godfrey (2008) to encourage students to engage with FCCTs.

The quiz was used in the first year of the research in 2015 and the FCCTs were used over three consecutive years. In 2015 and 2017, the FCCTs were worth no marks and in 2016 they were worth 4% of the course grade. The purpose of making both the quiz and FCCTs worth no marks in 2015 was to gain a measure of the scale of student agency. If students could decide for themselves to take the quiz and FCCTs, then the numbers of students voluntarily choosing to do them could be used as an indication of the strength of the exam-taker identity identified in Chapter 4 and an indication of student agency around unassessed work that was promoted as beneficial for them.

5.1.1. Pre-course quiz question development

The quiz incorporated questions across the range of KH-techniques, KT-propositions, epistemic knowledge and ability with KT-inferring. Usually concept inventories preclude remembering and calculating type questions to focus only on identifying conceptual understanding (Scott et al., 2014). The quiz however, included questions of all types in order to identify the relative strength of each of the ways-of-knowing.

The epistemic knowledge and capability with KT-inferring questions were chosen after reviewing existing concept inventories and research which had used them (Engelhardt & Beichner, 2003; Flores & Fabela, 2002; O'Dwyer, 2013; Ogunfunmi & Rahman, 2010; Simoni et al., 2004). For instance, Question 4(h) in Appendix 2 is a question similar to several concept inventory questions that use lightbulbs to capture students' abilities to reason. The KH-technique and KT-propositions questions were developed from reviewing physics and electronics engineering textbooks. Research into student reasoning in computer science (Krone, Hollingsworth, Sitaraman, & Hallstrom, 2010) and the limits of some concept inventories around multi-faceted problems (Steif, 2003) was used to inform the ideas for the questions involving KT-inferring. These questions sought to engage students' manipulation of ideas without being easy to replace the ideas with mathematical techniques.

5.1.2. Pre-course quiz results

The summary of the results from the quiz are in Table 9 and full details are in Appendix 2. In total the course had 845 students; 477 began the quiz and 468 completed it. The table is ordered by the number of students whose first attempt at a question was correct to indicate students' relative capabilities with different ways-of-knowing.

Table 9: Pre-course quiz, knowledge types and results from 2015

Question	About	Knowledge type	Correct on first attempt
Qu 4(f)	Using a formula for KCL	KH-techniques	86%
Qu 4(c)	The nature of charge	KT-propositions	67%
Qu 4(a)	EMF and PD	KT-propositions	66%
Qu 1	General electrical information about charge, energy	KT-propositions	63%
Qu 4(b)	Batteries	KT-propositions	50%
Qu 2	Series and parallel	Epistemic knowledge	31.5%
Qu 3	Series and parallel	KT-inferring	30%
Qu 4(d)	Causal relationship of voltage and Current	Epistemic knowledge	30%
Qu 4(g)	Topology and electric potential	KT-inferring	21%
Qu 4(e)	Does current weaken	Epistemic knowledge	12%
Qu 4(h)	The nature of charge flow	KT-inferring	7%

These results indicate that students had significantly stronger KH-techniques and KT-propositions than epistemic knowledge and capability with KT-inferring. The result for epistemic knowledge was consistent with conceptual quizzes used previously (Smaill et al., 2008) which had been as low as 11% for a difficult conceptual question.

5.2. FCCTs design

The FCCTs drew from understandings about what is known about specific conceptual or epistemic learning issues in electric circuit theory in section 1.5. This knowledge is often treated in school and engineering course work as fragmented KT-propositions or as KH-techniques with mathematical formulae. The first step in the development of the FCCTs was to accurately theorize them as epistemic knowledge. There are 16 tutorials and they target the electric circuit knowledge of: charge, charge flow, electric potential, topology and the fundamental relationships of KVL, KCL and Ohm's law. After initial trials with the same seven students who trialled the pre-course quiz, three iterations of the FCCTs were carried out in ElectEng101 from 2015 to 2017. The next sections of the chapter discuss how theories about: recontextualisation, student agency, ways-of-knowing, development of mental models, Variation Theory and the three pedagogical question heuristic, were used to inform the development of the FCCTs. The FCCTs are shown in Appendix 3 and can also be accessed online[4].

5.2.1. Recontextualisation

Recontextualisation is described in section 2.5.2.1. It involves deciding which knowledge from the episteme was necessary and in what order it should be taught. The literature in section 1.5 revealed a range of issues, particularly that current often precedes voltage in teaching, and that the voltage concept is particularly difficult - as this teacher described:

> *Voltage! It's got to be the most significant learning challenge for student understanding*

The order of the tutorials was linked to the purpose of electric circuits: the manipulation, transfer and storage of electrical energy. The sequence chosen began with electrical energy coming from the separation of charge, and then moved to the causal relationship of electrical energy with charge flow and then the epistemic relationships between electric potential, charge flow, components and topology.

5.2.2. Student agency

In addition to providing students with an opportunity to develop epistemic knowledge through the FCCTs, the FCCTs were developed to further investigate student identity and agency. The lecture environment was not seen as an applicable place to investigate identity and agency as not all students attend lectures. Online tutorials

[4] In their most recent form the FCCTs are available at www.xplainittome.com. A simple online registration with the University of Auckland is required to access this site.

were chosen as they have already been shown to be an effective means of reaching large cohorts who vary in readiness (Scott, Balsom, Round, Peter, & Harlow, 2013; Smaill, 2005). Students would need to do more than do each tutorial; they would have to actively engage with the knowledge. Active learning was one of the terms being used within instructional discourse in the faculty; and the work on the different levels of engagement: viewing, responding, changing, constructing and presenting (Naps et al., 2002) as discussed in section 2.6.3, was seen as a way to bring meaning to the term. Each iteration of the FCCT from 2015 to 2017 used the same engagement criteria of responding and changing.

One way to encourage students to engage with the FCCTs was through the pre-course quiz as described in section 5.1. If students did poorly in the quiz then it was hoped they would go on to do the FCCTs. Encouraging student agency around the FCCTs also involved making the FCCTs seem worthwhile to students. To do this, each FCCT provided feedback to students with what they might have wrong and feed-forward to encourage students to think about what they should take away from the question. Each question also has individual analytics, so that students can see how many times they have attempted a question and how many times they got it correct. The front page of the FCCTs also has a full analytic that provides an overview to students of their progress, as shown in Figure 101, page 288.

5.2.3. Ways-of-knowing

The next consideration was to seek to improve students' epistemic understandings and not to reinforce a focus on KH-techniques or KT-propositions. The FCCTs were theorised to develop epistemic knowledge about the hidden properties of electric potential, charge flow and their interrelationships as expressed by Kirchhoff's and Ohm's laws. They were also designed to reveal inferential reasoning about electric circuits such as in FCCT 10 in Appendix 3, which is "Identify causes and consequences of short circuits" where I describe a real fault that was fixed and how I reasoned through it to resolve it. The FCCTs also had to be aimed at the lowest levels of student understanding as the majority of students exhibited conceptual problems with most fundamental concepts.

5.2.4. Mental models

Development of students' mental models was an important consideration in targeting epistemic understandings. Theories that align with knowledge development such as psychological constructivism and cognitivism are powerful as they have shown benefits for students' development of mental models. Previous experience with using circuit simulators with students at secondary school indicated that simulation could be helpful in developing students' epistemic knowledge. One issue identified was the complexity of some simulators, so that any simulator would have to be sufficiently simple to make it accessible to novices and not just meaningful to experts (Donzellini & Ponta, 2007). One of the simulators that had previously been used with school students was the open-source electric circuit simulator by Paul Falstad (2016). When using it students had commented that it was useful in conceptualising or 'picturing' what happened in a circuit. While it is open source, the author was contacted to seek his agreement with using the simulator in the research.

The circuit simulator presents a rich representation of an electric circuit which is one of the main requirements for accurate model development (Rosengrant et al., 2009). However the term 'rich representation' requires definition, and the criteria developed by Mayer (1989) about mental model development were used to make explicit decisions about what a 'rich representation' meant in practice. Mayer's criteria are: completeness, conciseness, coherency, concreteness, conceptual, considerate and correctness. The first of Mayer's criteria chosen was that any intervention had to be conceptual. Electric circuits are dynamic and the schematics students are presented with in textbooks, lectures and even circuit simulators are static and lack the conceptual hidden epistemic nature of electric circuits. More than this though, students need to see how co-varying aspects such as electric potential and charge flow interrelate (Jonassen & Easter, 2013; Marton & Pang, 2007). This was important, as students ideas about Ohm's law are linked to KH-techniques and not to an understanding of electric potential as the driving force in a circuit, with charge flow as its consequence. Completeness was important as the common practice of teaching circuit analysis relies predominantly on KH-techniques using fragments of circuits. Also a fragmented 'useful-content approach has been linked to how students incorrectly use sequential reasoning (Smaill et al., 2012). Correctness is another important characteristic as students often use terms incorrectly such as those associated with voltage (at, across, between, drop, dropped, loss, lost). The term voltage was consequently replaced by electric potential and one tutorial was developed to target the correct use of language. The coherency characteristic relates to the use of circuit fragments and the importance of engaging with KT-inferring about epistemic knowledge in contexts-of-their-use (Amin et al., 2014). Consideration was taken to refer to recognition of students' previous, often negative, experience of learning about electric circuits. This was important as students needed to know that it was possible to understand electric circuit properties, in contrast to their prior school learning that students stated did not generally encourage understanding but rather having sufficient knowledge to pass.

5.2.5. Variation theory

The development of students' mental models of electric circuits was encouraged by having students engage with the visualisations through answering questions or modifying the simulator while engaging with the now visible properties of electric potential and charge flow. While seeking to increase engagement, this is also a well-used term in instructional discourse; one which requires a theoretical underpinning to reveal how it can become part of meaningful pedagogy. The Variation Framework (Marton & Pang, 2007) was discussed in section 2.4.4.2 and in Figure 50 it is used to specifically engage students with the epistemic properties of electric circuits (in this case topology, electric potential and energy transfer). Students are required to fix the open circuits to make all the LEDs glow the letters LOL (acronym for laugh-out-loud). The circles filled with red represent glowing LEDs, with these indicating energy is being transferred and converted to light. The levels of electric potential around the circuit are represented by the colours green (positive) and grey (0V). They indicate that there is electric potential but not energy transfer because of the open and short circuits. As students fix the open circuits in the simulator, energy transfer takes place. Through explanation and the facility of the simulator, the co-varying nature of electric potential and topology are exposed to students.

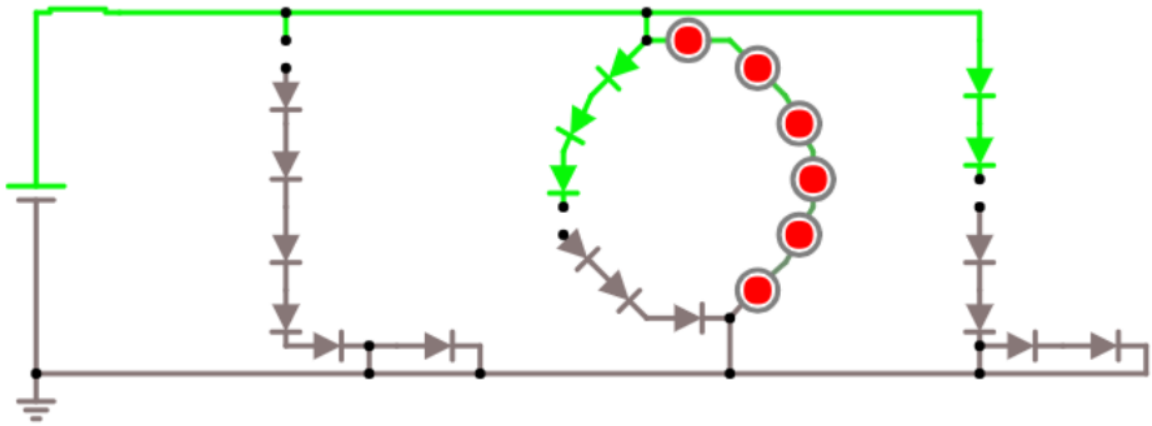


Figure 50: FCCT Question 7: Identify co-varying circuit aspects of electric potential, topology and energy transfer

Ohm's law is seldom viewed by students as anything other than a formula which they quote as V=IxR. Changing student's awareness of this was encouraged through a tutorial that included the schematic in Figure 51. Students are required to modify resistors in the circuit to change the current in the LEDs to acceptable levels, with one change effected through changing the 1Ω series resistor and the other by changing the 10MΩ parallel resistor.

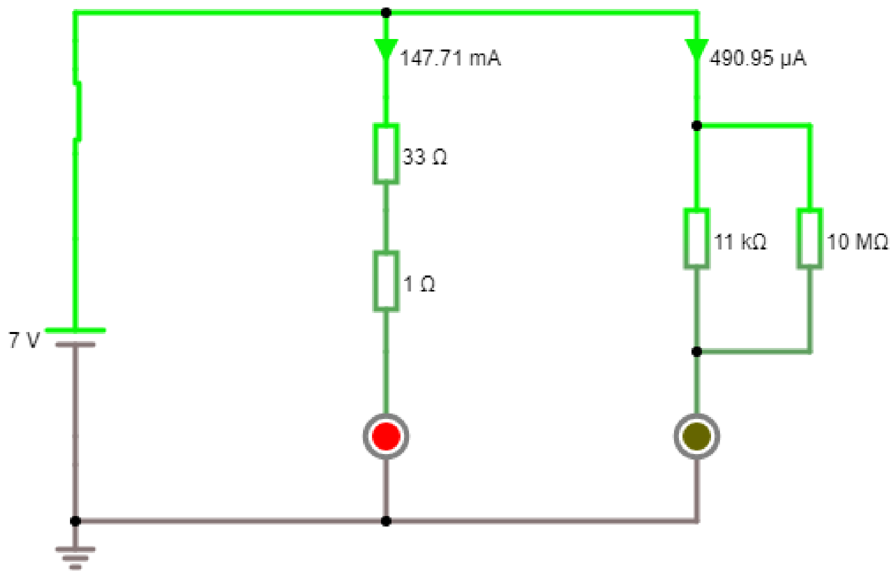


Figure 51: FCCT Question 12: Turning Ohm's law into epistemic understanding and an opportunity for KT-inferring

As students adjust the resistor values in the simulator, they can see the effects of Ohm's law and the instructions are used to describe how charge flow changes in response to change in resistance. In this case the co-varying properties of resistance and charge flow are observable while electric potential is held constant.

5.2.6. The three pedagogical questions heuristic

Designing the intervention then turned toward the three pedagogical questions espoused by Hattie and Timperley (2007), the first of which is to explicitly inform students about the goal of learning. The FCCTs were presented to students as per Figure 52.

> For many years we have measured students understandings of fundamental electrical concepts as they begin ELECTENG101, and while they have great grades from school, each year we find 80-90% of students will have incorrect electrical concepts that this course relies upon. To help you we have developed these tutorials to assist with the concepts at the core of electric circuit theory giving you a firm foundation for the course.
>
> The primary goal of these tutorials is for students to see **an electric circuit as an energy conversion, storage and transfer process** - after all that is why engineers design and make circuits!
>
> Students who have previously engaged with the tutorials have said positive things about them and do better in the course and end of course exam. So spend some time thinking about them and not rushing through them.

Figure 52: Introduction to the FCCTs

This was written as part of investigating student agency, by being explicit about the FCCT's target of developing understanding and not techniques. It focusses on students' narrow range of ways-of-knowing, that grades do not indicate knowledge, that the FCCT improved examination scores (this was added after the first iteration), and that they were foundational to the work they would do going forward.

The second question from the learning heuristic is 'how am I going?' The FCCTs were developed to incorporate immediate formative feedback for students and for them to retry until they got the answers correct. Design around the third of the pedagogical questions - where to next – involved strategizing about developing students' metacognitive behaviour. The FCCTs made explicit use of academic learning outcomes and success criteria as these are key aspects of developing students metacognition (Clarke, 2008; Hattie, 2014); in contrast to the contextualised learning outcomes ElectEng101 students are familiar with such as in Appendix 4. Figure 53 shows the header section for question one of the FCCTs. Each FCCT refers to the abstract learning goal, the keywords that need to be drawn to the student's attention and the title or success criteria for the question, to reinforce these to the students.

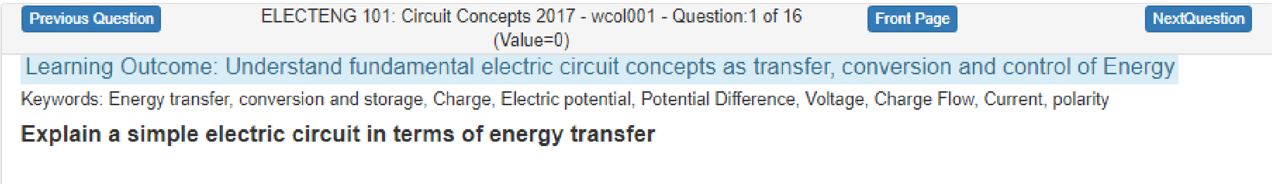


Figure 53: FCCT abstract learning outcome and success criteria

To promote metacognitive awareness, the FCCTs also included feed-forward to encourage students to reflect on what they have learnt and what might be important next steps for their knowledge.

5.3. The 16 FCCTs

The FCCTs were developed to align with the known student misconceptions described in academic literature as discussed in section 1.5. The literature on measuring understanding using concept inventories was influential with its focus on avoiding the use of calculators. The FCCTs were informed by others' work which used non-calculation type conceptual materials such as: Ashby (2012), Hewitt(2014) and McDermott and Shaffer (2002). Questions were integrated with the text and the visualiser to make students attend to the important aspects covered in each tutorial. A mix of cloze (fill in the gap) and multiple choice questions were used to provide students with immediate feedback. The FCCTs are in Appendix 3, and the topics are:

1. Explain a simple electric circuit in terms of energy transfer
2. Describe charge in terms of atomic particles
3. Describe how separation of charge creates electric potential
4. Explain charge flows in an electric circuit
5. Explain the different types of models used in electric circuits and the purpose of each
6. Describe circuit topologies: closed, open, short
7. Identify levels of electric potential around a circuit
8. Identify levels of electric potential with respect to ground in a circuit
9. Create sources with both positive and negative values with reference to ground
10. Identify causes and consequences of short circuits
11. Explain how energy sources are actually drawn in electric circuits

12. Describe Ohm's law as a model for circuit behaviour
13. Replace simple series or parallel combinations with an equivalent resistance.
14. Explain electric circuits in terms of energy conservation using KVL
15. Explain electric circuits in terms of conservation of energy using KCL
16. Applying correct conversion between metric prefixes

The 16th tutorial is slightly different to the others in that it targets students' abilities with conversions between metric prefixes, something that a lecturer indicated many students had problems with, and which was confirmed in the pre-course quiz and through the use of the FCCTs.

5.4. Methodology

In 2015, links to the optional pre-course quiz (Appendix 2) and the optional FCCTs (Appendix 3) were sent via email to students in ElectEng101 before their course began. The quiz was promoted as allowing students to self-assess their understandings and the FCCTs to refresh their understandings of secondary school electric circuit theory. In 2015 the FCCTs were voluntary, and in 2016 students were given the incentive to complete the FCCTs by allocating 4% of the course grade to them. In 2017 students were again offered the FCCTs as voluntary learning in the course, however without the quiz. The purpose behind having the FCCTs voluntary in 2015 and then worth grades in 2016, was to gain a perspective on the nature of students' agency. While the discussion in section 4.6 reported that many students in interviews identified with an exam-taker identity, this however gave no indication of the scale or strength of this identity. It was expected that when worth no grades, student's participation or non-participation would reflect their agency.

In all three instances of using the FCCTs, students were allowed as many attempts at questions as they wished and could repeat the questions as many times as they wanted, and at any time during the course. Each time a question in the FCCTs was accessed, results were collected allowing a comprehensive data set for analysis. In order to gain student voice concerning the tutorials, students were asked to leave feedback using two seven point Likert scales and two comment fields. Semi-structured interviews and informal discussions were also carried out to collect further data from students. To collect individualised data from the FCCTs, they were hosted within the university so that students had to login to access them. For the first iteration, the University of Auckland tool CourseBuilder was used. This was selected after considering a number of alternative educational technology tools in the university: OASIS, CourseBuilder, CECIL (the previous LMS), PeerWise (peerwise.cs.auckland.ac.nz) and Best Choice (bestchoice.net.nz). CourseBuilder was chosen as it had the flexibility to add the circuit simulator and user data was accessible. For the second and third iterations the FCCTs were moved to GECKO (see Chapter 6), as having developed it, I could manage and streamline the collection and analysis of data.

5.4.1. Quiz and FCCTs credibility and dependability

Case study methodology was described in terms of credibility and dependability in section 3.5. This section discusses how the quiz and FCCTs, and the data from them were collected to establish the credibility and dependability of the research. In the design stage, peer review and member-checking (Guba & Lincoln, 1989) were used. For peer review, the quiz and FCCTs were checked by a colleague who is a physics teacher. For member-checking, both the quiz and FCCTs were trialled with a group of seven students; I had taught five of these students at secondary school and I knew they would be comfortable providing critical feedback. After these processes, KH-techniques questions about electric potential and power were removed from the quiz, and multiple clarifications and corrections were made.

Several steps were taken to monitor credibility and dependability during the data collection and analysis stages. The data collected from the quiz were compared to that collected previously in the department (Smaill et al., 2008) to seek consistency between the results from conceptual questions. Also having three iterations of the FCCTs over three years meant that the data had a level of dependability as similar results were produced. Lastly, during the middle stages of this research I became involved with another research project with my primary supervisor, and the data collected for this research was used and reviewed as part of that project as well (Rata, Rowe, McPhail, Wang, & Collis, 2017).

5.5. Results from the FCCTs

5.5.1. Participation

The following tables show the participation rates of students in the optional pre-course quiz and the FCCTs in 2015 to 2017.

Table 10: Student Participation in the Not-For-Credit Pre-Course Quiz and FCCTs in 2015

Students who completed the course (2015)	no Quiz			Quiz		
	No FCCTs	1-8 FCCTs	9+ FCCTs	No FCCTs	0 to 8 FCCTs	9+ FCCTs
844	323(38%)	26(3%)	26(3%)	227(27%)	96(11%)	146(17%)

Table 11: Student Participation in the 4% FCCTs 2016

Students who completed the course (2016)	No FCCTs completed	1-8 FCCTs completed	9 or more FCCTs completed
867	33 (4%)	28 (3%)	806 (93%)

Table 12: Student Participation in the Not-For-Credit FCCTs in 2017

Students who completed the course (2017)	No FCCTs completed	1 to 8 FCCTs completed	8+ FCCTs completed
979	672 (69%)	132 (13%)	175 (18%)

In 2015 (Table 10) 20% of students did 9 or more FCCTs (3% no quiz and 17% quiz). In 2017 (Table 12) 31% of students did some or all of the FCCTs. In 2016 (Table 11) when given 4% of the course grade 93% of students did all the FCCTs. Comparing the difference between these results seems to indicate a strong external motivation of students towards grades.

5.5.2. Not for credit FCCT results

An interesting feature of the 2015 data is that of the 469 students who did the quiz 227 students did not go on to do the FCCTs that were promoted as helping their understanding. This data is presented in more detail in Table 13. The data is divided into those who did well in the quiz (got 10 or more correct out of 26) and those who did not.

Table 13: Student participation in the FCCTs in 2015 as a function of quiz result

<table>
<tr><th>Students taking the quiz
N=469</th><th>no FCCTs
N=227</th><th>1-8 FCCTs[5]
N=96</th><th>9+ FCCTs
N=146</th></tr>
<tr><td rowspan="2">Did not do well in the quiz (fewer than 10 correct) N=381</td><td>193 (51%)</td><td>77 (20%)</td><td>111 (29%)</td></tr>
<tr><td colspan="2">71%</td><td></td></tr>
<tr><td rowspan="2">Did well in the quiz (10 or more correct) N=88</td><td>34 (40%)</td><td>19 (21%)</td><td>35 (39%)</td></tr>
<tr><td></td><td colspan="2">60%</td></tr>
</table>

The data shows that 71% of the 381 students who did poorly in the quiz did none or few of the FCCTs that had been specifically designed to help their understanding. This effect was less noticeable for students who did well in the quiz (N=88) as 60% of them went on to do some of all the FCCTs, when they had less need of them.

[5] Note: the 1-8 and 9+ cut-offs were chosen as they were found to demonstrate a noticeable difference in examination score means

5.5.3. Not for credit FCCTs and examination results

Examination results were normalised to a range of 0 to 20 for display purposes and the graphs for 2015 and 2017, when the FCCTs were optional, are shown in Figure 54 and Figure 55.

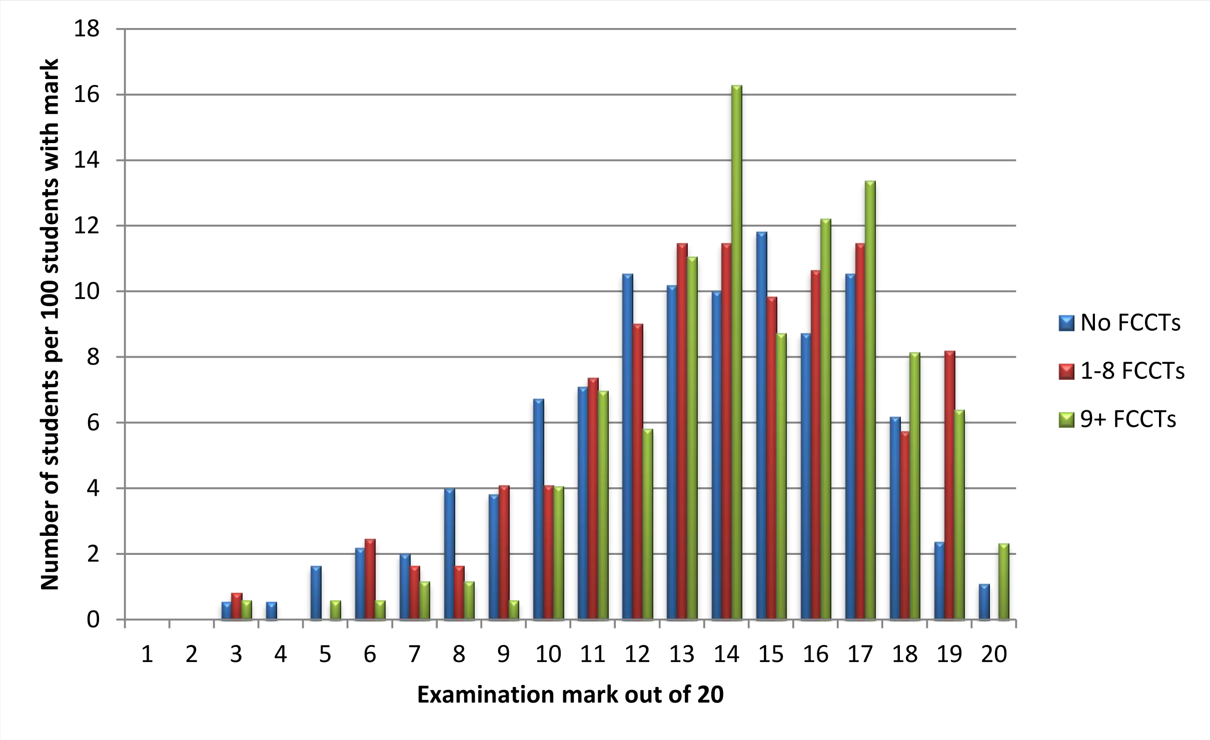


Figure 54: Normalised results for examination mark distribution in 2015

In 2015 there was no significant difference in the exam mark between students who did not do the FCCTs and students who did 1-8 FCCTs. There was a significant difference of 6.7% in mean examination results between those who did 9 or more FCCTs and those who did none. A one-way ANOVA was conducted to compare the effect on examination scores of those students who did the FCCTs in 2015. An analysis of variance suggests that the effect of doing nine or more FCCTs on the examination results was significant $F(2, 841) = 10.98$, $p < .0001$.

In 2017 there was no significant difference in the exam mark between students who did not do the FCCTs and students who did 1-8 FCCTs. There was a significant difference of 6.3% in mean examination results between those who did 9 or more FCCTs and those who did none. A one-way ANOVA was conducted to compare the effect on examination scores of those students who did the FCCTs in 2017. An analysis of variance suggests that the effect of doing 9 or more FCCTs on the examination results was significant $F(2, 976) = 18.44$, $p < .0001$.

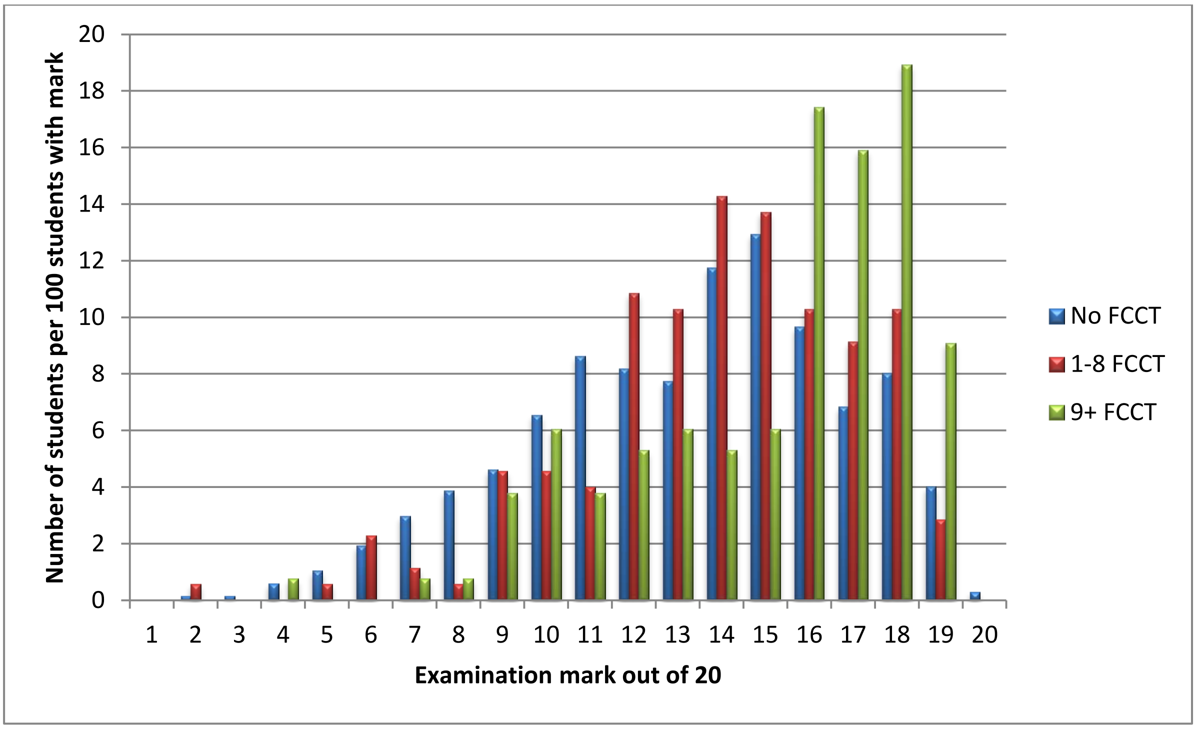


Figure 55: Normalised results of examination mark distribution in 2017

5.5.4. The FCCTs when worth credit

In 2016 the FCCTs were worth 4% of the course grade. Figure 56 is the distribution of when students did their first question in the FCCTs in 2016.

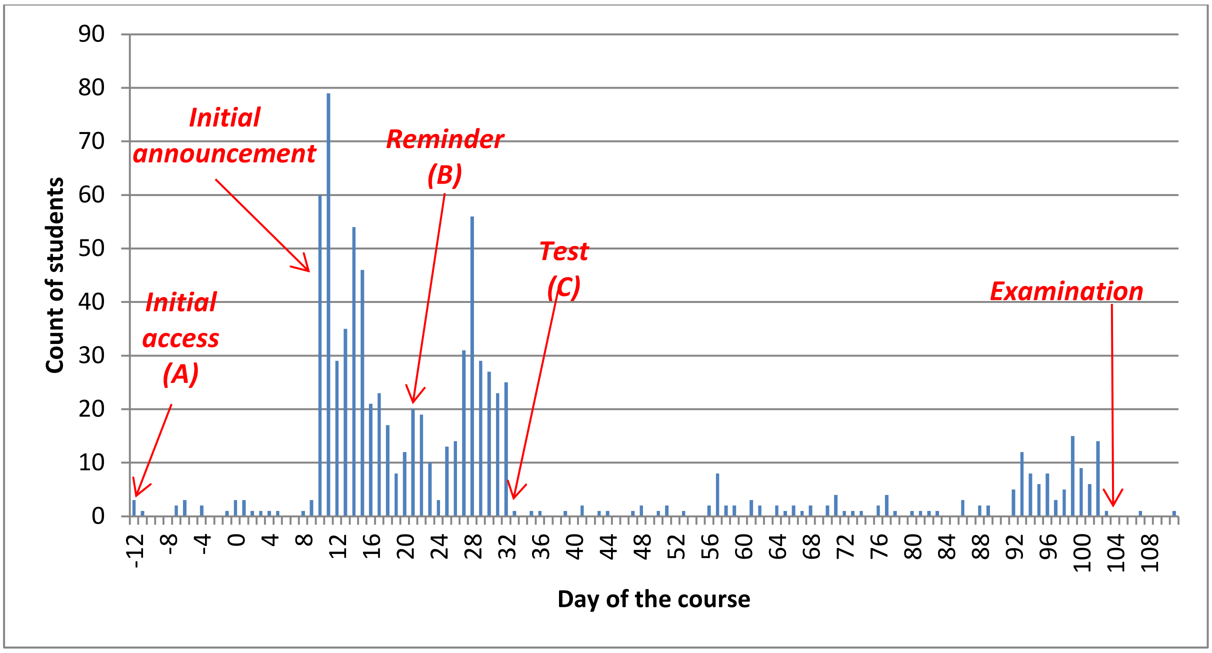


Figure 56: Day when students did their first question in the FCCTs in 2016

Using the graph the data were broken up into 4 time periods as in Table 14.

Table 14: Grade Distribution by Time when Students began the FCCTs (2016)

Group	A	B	C	D
Day of the course	-12 to 21	22 to 32	> 32	Did not attempt
Student count N= 867	430 (50%)	250(29%)	162(19%)	25(3%)
Examination mean	66.7%	57.0%	50.9%	38.3%

Students received an email and an in-class invitation on day 10 of the course encouraging them to work through the FCCTs, and this is when the main activity in the graph began. The activity prior to day 10 is from students who found the link to the FCCTs while exploring the course on the LMS. There are three apparent groupings in the data: students who did the FCCTs close to when they were given them (day -12 to 21), students who did them after being sent a reminder that they would benefit by doing them before the first test (day 22 to 32) and students who did them later or on completion of the course (day > 32). Table 14 shows the numbers of students in each group and their examination scores.

A one-way ANOVA was conducted to compare the effect on examination scores of when the FCCTs were done by students. An analysis of variance showed that the effect of the FCCTs timing on the examination results was significant $F(3, 865) = 47.82$, $p<.0001$. Post hoc comparisons using the Tukey HSD test were carried out to compare each condition as in Table 15.

Table 15: Tukey HSD post hoc comparisons for the FCCTs results for the four groups in 2016

From	To	Significance
A	B	P<0.01
B	C	Not significant
C	D	P<0.01

The only grouping that was not significant was from B to C. From these results it appears that doing the FCCTs early was the best condition, while doing them later was not as good, but still better than not doing them at all.

The graph in Figure 57 is a distribution of the examination scores for students who began the FCCTs early (Group A) and the other three groups combined. These groups were combined as there was not a significant difference between groups B and C and group D was small. The results are not normalised as each group is approximately 50% of the population.

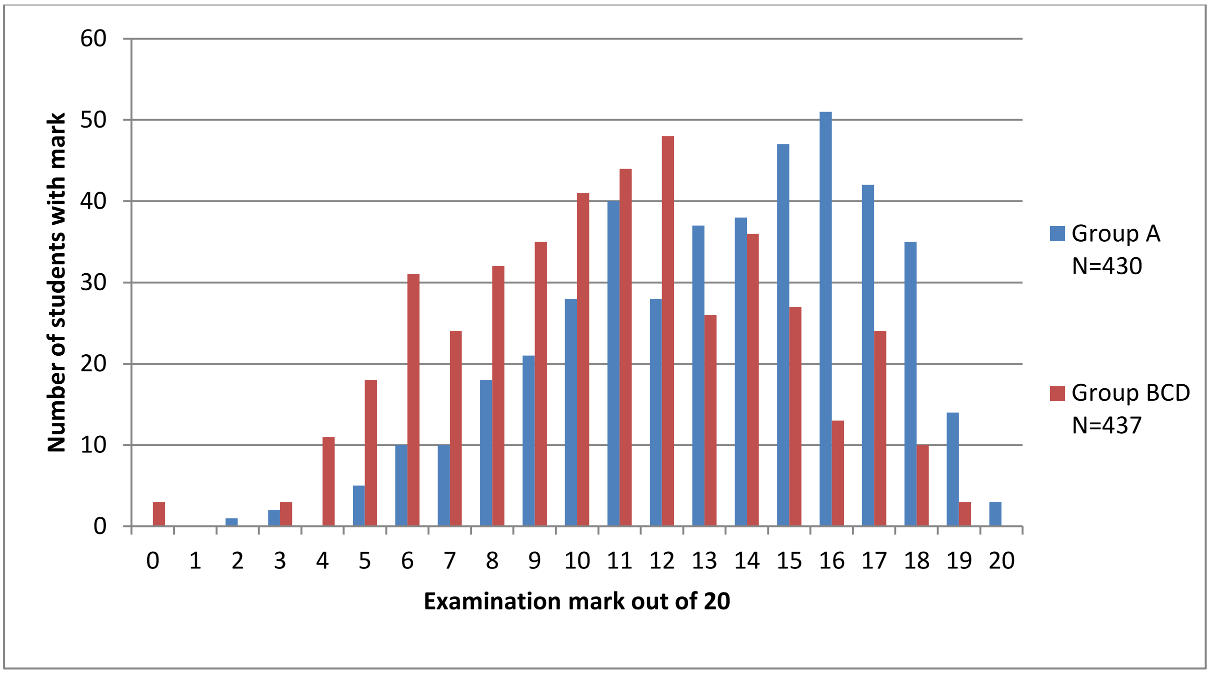


Figure 57: Examination mark distribution 2016

The spread of the distributions of the graphs for each year (Figure 54, Figure 55 and Figure 57) along with the statistical significance found in each year suggest that early use of the FCCTs is preferred, and may positively impact examination results.

5.5.5. Relationship between the FCCTs and examination scores

While relationships appear to exist between doing the FCCTs and examination mark for each year from 2015 to 2017; this does not necessarily indicate the cause of the relationship. When considering any causal relationship, other unknown factors and limitations of the data need consideration. One of factors could be that students who did the FCCTs already had better knowledge. There may be other factors at work in the data such as ethnicity or school background. One of the factors that has bearing on these is whether the FCCTs actually represented epistemic knowledge and were beneficial to student knowledge.

5.5.6. Are the FCCTs epistemic electric circuit knowledge?

The FCCTs were developed to increase students' epistemic knowledge around electric circuits and encourage KT-inferring. To understand if the FCCTS had an effect epistemically, student comments were invited via interviews and online surveys in 2015 and 2016. Each tutorial had a feedback area for students to enter a Likert scale rating for the tutorial and a place for written comments. In order not to bias students, while the feedback asked them to comment on changed understandings, it did not ask about any particular aspect of circuit knowledge.

In 2016 when the results were worth 4% of the course grade, students left 1,082 Likert scale ratings, and Figure 58 is a graph of these. In 12.8% of the responses students reported that a tutorial had a transformative effect on their understanding. Of the responses, 73% were that the tutorial provided useful (4) through to transformative (7) impacts. 10.7% of the ratings indicated that for those students the tutorial or visualisation provided no benefit to their existing understanding

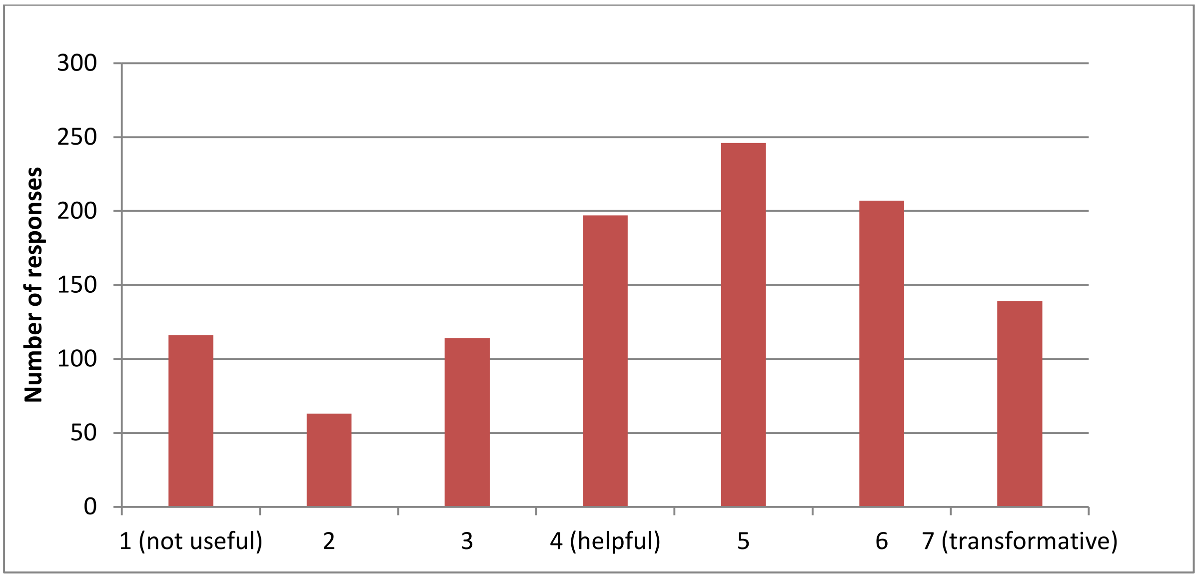


Figure 58: Student Likert scale response to FCCT 2016, N= 1,082

In 2016, 205 students left 607 written comments about the FCCTs. Of these, 50% were positive, 34% related to content that students felt needed change or clarification, 8% were negative and 8% were that the tutorials provided nothing more than students already knew. Of the positive comments, 159 were specific responses and were categorised using known issues with understandings in electric circuits from section 1.5.

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

In high school I think it might be really good if they could embed the idea how current flows as opposed to voltage

I found that I learnt a lot from them [the FCCTs], with those diagrams and the animated currents, I actually understood voltage

Students left 31 comments highlighting visualisation as essential to their clarifications of voltage and current, for example

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

Ten comments related to clarification of terminology around voltage, for example

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, for example

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 FCCTs, for example

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

Seeing like applications you'd see in real life it make things cool

Students left 16 comments about increased conceptual understanding of topology, for example

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.

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

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

One student commented positively about the non-formulaic nature of the FCCTs:

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.

During later interviews students were asked to reason about the circuit in Figure 59, first when the switch was open and then when it was closed. All students showed good understanding of the two conditions of the circuit. Students also had sound understanding about the voltage across the switch, and all students used the terms 'across' or 'at' correctly with regard to voltage.

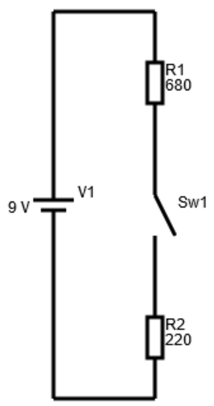


Figure 59: Example of question used in interviews to determine understanding of electric potential

When asked to account for their knowledge, students gave one of three replies: they had been taught it at school, or had learned it during the course, or as these students indicated, they learnt it from the FCCTs

> *I learnt that from the online tutorials, I think personally they were a real turning point in my understanding of circuits because at first understanding electric potential in the first part of the course was a bit difficult for me but after looking at the tutorials and consolidating them I found that actually my understanding had improved tenfold.'*

> *I found that I learnt a lot from them. With those diagrams and the animated currents, I actually understood them, I actually learnt a lot from these compared to the lecture part of the circuits.*

During interviews students also directly indicated benefits from engaging with the circuit simulator and there were positive comments about its use, for example

> *Very good at showing exactly what happens*

> *The simulation is pretty neat maybe if we had that in high school, electricity wouldn't of been that bad*

Students also made comments about their increased engagement with the material and the course, for example

> *It was fun to use*

> *I actually had to do stuff in them, that was cool*

> *I liked the stories as it made the course real and helped me want to take electrical*

Student responses suggest that the FCCTs did indeed address known conceptual difficulties and resulted in an increased focus on epistemic knowledge. One student expressed this as:

> *I definitely learnt things from here that I didn't from the lectures or the book*

5.6. Conclusion

The research question was: Can an increased focus on epistemic knowledge help students in first year electrical engineering? The purpose of this chapter was to put the FCCTs into the context of the structure and agency explored in Chapter 4 to determine the efficacy of the FCCTs in supporting the development of epistemic knowledge. The student comments, and the corresponding correlation between FCCT use and examination performance, suggest there was a significant benefit to students epistemic knowledge.

These findings raise a number of questions. The first of which has been discussed, that the FCCTs represent epistemic knowledge and that students did learn epistemic knowledge rather than KT-propositions or KH-techniques. The second question is how student agency – the personal projects that student invest their energies in – should be recognised within the data. A third question is identifying how the structures in the situation exert influence over students' approaches to learning epistemic knowledge, and also the development of new pedagogy.

5.6.1. Student identity and agency

While epistemically beneficial to students, the FCCTs could only be of benefit if students engaged with them. The data from ElectEng101 in 2015 and 2017 showed that 29% to 32% of students were willing to do unassessed conceptual tutorials to support their understanding. The examination results from those years reveal that for the students who engaged with the FCCTs their average grades were respectively 6.7% and 6.3% higher than those who did not do the FCCTs. This indicates a strong relationship between examination results and being willing to do unassessed work that is promoted as helping understanding. This result appears to indicate that 29 to 32% of students either do not have identities that might be described as exam-takers or are willing to employ agency to move past an exam-taker identity to access beneficial learning. With regard to the voluntary nature of the tutorials in 2015 a student comment revealed that the link between agency and knowledge should not be left up to students to decide:

You do need to understand the theory... why aren't these compulsory?

This finding is supported by students in 2016 when the FCCTs were given 4% of the course grade. Several students comments indicated that being 'made' to do the FCCTs was important to them.

The online tutorials were quite good. I think because you had to do them for a percent and so when you're forced to do that for a percent you learn, Yeah I'll do it for a percent, for a 4% because there's obviously a reason they want you ... to learn it

Because you prioritise what is worth marks at the end of the day and when they force you to get it because otherwise you're going to miss out on a mark you're forced to fit it into your schedule no matter what and then you end up reviewing things, yeah I quite like that.

Students found benefits to their understanding in terms of their course work as one student remarked:

If you understand something you really like going through like practice questions because you know that you are getting it right

However even with grades attached to the FCCTs not all students appear to have the facility to put aside their identity, as one student remarked about the FCCTs

...I rushed through them to get the marks

One aspect of the data from 2015 is the interaction between the pre-course quiz and the FCCTs as shown in Table 13 (page 186) where 71% of the students who did poorly in the quiz did no or few FCCTs. This data reveals a clarification of what seems to be a dichotomy identified in two articles published by staff in the department. Two statements have previously been made about students, firstly students are unconcerned about non-examinable results and do nothing about them (Smaill et al., 2007) and conversely students are concerned about non-examinable results and viewed these as 'wake-up call' which lead to behavioural change (Smaill et al., 2008). While these two views contrast, they both appear to be at work in the agency of students as shown in Table 13 (page 186). The data however suggests that the 'unconcerned about poor results' effect may be more powerful than the' wake-up call' effect, for students who are doing less well.

This expression of agency by students who are doing less well could reflect the comment by Case (2013) that students have a commitment to an identity, one which is not easily changed. Psychologists call a commitment to a negative course of action, an escalation situation, where we continue to persist in spite of the likelihood of it producing a negative outcome (Whyte & Saks, 2007; Whyte, Saks, & Hook, 1997). This commitment to a negative course of action could describe the situation in 2015 where 50% of students who did badly did not take the opportunity provided with the FCCTs to help their understanding. It could also describe the self-reinforcing behaviour presented in the previous chapter in Figure 38 (page 141), where students do poorly and are committed to maintaining an emphasis on rote and formulaic learning, further weakening their knowledge which further commits them to their negative course of action. As one student said about his identity and how this impacted upon his choice for not choosing the electrical engineering specialisation:

> *The thing is you don't want to seem stupid … people usually avoid subjects that make them vulnerable.*

Of the students who did well in the quiz, 60% went on to do some or all of the FCCTs. This could indicate a similar commitment to a personal identity, one which is to continue to do well. This may indicate that these students have personal identities as learners. Comparing these two results, the data indicates that agency aligned to doing less well may be stronger than agency aligned to doing well.

Another aspect of identity should be considered, that of students' get-through identity. This seems to explain the data from 2016 in Table 14 which showed 29% of students delayed doing the FCCTs until reminded they would be helpful for the test. Also 19% of students left the FCCTs until the last stages of the course - perhaps because they forgot to do them or they left them until they recognised that having the 4% contribution could be useful in helping their personal project of passing or gaining some particular grade in the course. For 3% of students the allocation of 4% of the course grade to the FCCTs did not appear to be significant enough for them to even access and look at the FCCTs. It seems positive that only 33 out of 844 students viewed the understandings that could be gained from helpful tutorials in this way.

Archer (1995) makes the comment about agency that structures are not all powerful, but are more aligned to good reasons for actions; and that anyone with their 'wits' about them would choose to evaluate their situation and make any necessary changes required of them. It seems, however, that there are significant numbers of students in the first year of electrical engineering that do need to be provided with much more than good reasons to do the work that will help them. It also appears that this is not just something that first year students need. A lecturer commented that even in fourth year, students needed guidance on managing their project time. This is the duty of the course and where teaching becomes so important, not only as Winch (2017) describes in terms of meeting students' epistemic knowledge needs but just as much for the development of their identity. This leads into what the FCCTs indicated about the teaching and learning structures of courses.

5.6.2. Structure and agency

One student in 2015 made a comment about courses in general:

> *Something I do find really annoying is if I do focus on a lot of understanding stuff, a lot of working it out, doing all the kind of proper work, even if I know it will help me in the exam, that kind of stuff I still find it really annoying if I do that and then I get to the test and it's really easy -it's kind of annoying*

The student identity of learner is not always rewarded, just as the identity of the lecturer as educator is not always rewarded. Identity as a learner is not easy to hold onto within courses that do not value change in epistemic knowledge and the ability for KT-inferring; but instead reward the development of KH-techniques; as this student commented:

> *I prefer to learn over a longer period of time and like remember the knowledge and ideally I love to read before a lecture and recap afterwards but I feel the way*

the whole degree is set out there's always something to do that there's not really much time to review.

During the research, the influence of course structures in the form of smooth administration was encountered in regards to the FCCTs. In section 2.3.4 the identity of researcher-educators was identified as being worked out through an instructional discourse and agency centred on teaching useful-content, administration and summative assessment. This was noticeable in the interpretation of the results and feedback from using the FCCTs in 2016. While the Likert scale results and 50% of the 607 written feedback responses were positive, there had also been many comments left by students relating to improvements being needed to clarify questions, layout and usability. There were also negative comments from students, such as this comment where the student questioned the value of the FCCTs:

This course as a whole was utterly pointless, it failed to teach me anything I relied entirely on guess and check. I did not understand most of the exercises.

In very large courses, the structure of smooth administration is a critical factor for stability; and there can be a point where lack of administration gives way to chaos. A single student complaint may be the "tip of an iceberg" as one lecturer commented and therefore urgent action is required. Within a non-pedagogically aligned instructional discourse there is a direct association between negative student feedback and course administration; when courses run smoothly student ratings are high and courses avoid becoming 'red-flagged'. Negative student feedback relating to the FCCTs was viewed as more important than their pedagogical benefits. This concern was reflected in discussions about whether the FCCTs would be used at all, and led to the 10 day delay in 2016, which is visible in the graph in Figure 56 on page 189. In 2017 these administrative concerns also meant that FCCTs reverted to being voluntary which consequently required changes to the research design. A lack of pedagogical championing was described in section 4.5.5 around the ongoing use of OASIS and this was the case for the FCCTs as well, as it was only through the intervention of one senior academic that the FCCTs were used.

5.6.3. Summary

The understandings from this discussion recognise that it is possible to engage students with epistemic knowledge and many students will learn when given the incentive to do so. While that incentive is highly linked to grades, this need not be seen as negative, but as a tool to help motivate change to students' identity from a personal project attached to summative assessment to one attached to knowledge. It does involve moving pedagogy toward epistemic knowledge and using grades to incentivise students to learn to infer and reason with that knowledge. Grades, however, must never become the focus of the discourse to avoid the issues that plague NCEA. Long term change also requires commitment to a level of uncertainty and some negative responses from students if there is to be change to something as important and difficult as epistemic knowledge. As one lecturer at another university commented to me:

> *Student survey results hinder any hope of change*

One critical aspect of the situation is to find ways to engage students in such large cohorts (Graham, 2018). Many of these students are absent from the lecture either physically or cognitively while epistemic knowledge is being exposed and explained; yet these students must engage with epistemic knowledge in meaningful ways for their capability with KT-inferring to develop. With the size of the cohort involved and the ready access to computers and the internet, it seemed that an educational technology intervention would be a valid direction for the research. The next phase of the research was the development and initial testing of an educational technology intervention aimed at exposing epistemic knowledge and making students engage with it inferentially.

Chapter 6. **GECKO – theoretically grounding a novel educational technology tool**

This chapter addresses research question 3: How can theory and understanding of the situation inform the development of a novel knowledge-based educational technology tool? GECKO is an acronym for Growing Epistemic Circuit Knowledge Outcomes[6]. The idea for designing GECKO and the decision to develop it was made after the first iteration of the FCCTs in 2015, where many students had found the circuit visualisations powerful, but many more had not engaged with them. What was needed was a way to engage large numbers of undergraduate electrical engineering students, many of whom did not attend lectures, at a deep level with visualisation in order to develop their epistemic knowledge and provide opportunities for them to develop capabilities with KT-inferring.

The issues uncovered were not isolated to the problems with electric circuit theory that triggered the research. Firstly, they covered teaching and learning across the first two years of electrical engineering, which included both digital and microcontroller electronics. Secondly, they were integral with student identity and the structure and culture of teaching and learning uncovered in Chapter 4. Also Chapter 5 had revealed that use of educational technology needed to be highly informed by theory to be powerful. Consequently at the same time as GECKO development took place, ideas for pedagogy assisted by GECKO were also taking form. The concerns in literature about the undertheorized nature of educational technology (Gunn & Steel, 2012; Howard & Maton, 2011) were taken to include all of the theory and understandings gained to date. This led to the deployment of all the pedagogical lenses in Chapter 2 during the development of the pedagogic framework and GECKO.

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[6] GECKO was used to write and present various questions and assignments for students in a number of courses, a number of these are accessible online at www.xplainittome.com. A simple online registration with the University of Auckland is required to access this site. Once registered the support website I am developing for GECKO can also be reached at https://www.coursebuilder.cad.auckland.ac.nz/flexicourses/4305/publish/1/index.html

6.1. GECKO's conceptual underpinning

The underpinning design goal for GECKO was that students would engage with epistemic knowledge within simulations and through questions use this knowledge inferentially to solve problems. Specific ideas for GECKO came from thinking about what the epistemic knowledge needs of students were and how many tools were not equipped to meet those needs. Two distinct types of tools were found to exist; the first were the real ones such as those in Figure 8, Figure 9 and Figure 10 on page 36. These tools attempt to be conceptual through demonstration of the dynamic nature of circuits; however they operate at the level of the real and not in the abstract where epistemic knowledge exists. These tools often leave learning up to students to make the conceptual connections to the abstract or, as described in section 2.4.5.2, at an epistemic dead-end. The second type of tool includes OASIS as shown in Figure 33 on page 131 and others that were investigated, such as: Web-Tutor (Rodanski, 2006), Circuit Tutor (Deken & Cowen, 2011), Java applets (Canesin, Goncalves, & Sampaio, 2010), KIRCHHOFF (de Coulon, Forte, & Rivera, 1993), and SEQUEL (Raju & Karnik, 2009). These tools use circuit diagrams that operate at the abstract level that students need, however they do not conceptually expose the properties of electric potential and charge flow or their interactions. With these tools, epistemic knowledge remains hidden and conceptual connections are not sufficiently encouraged.

The circuit simulator on its own was found to be both conceptual and abstract; however it did not have the features to manage student engagement with epistemic knowledge and its use. A new idea for engaging students was needed, one not found in the other tools investigated. The central idea for GECKO became one of writing questions where the visualiser was under programmable control. Question writers would write scripts, sequences of programmable commands, that generate random parameters for circuits and control the circuit being simulated. These would allow questions not just to be presented with different characteristics and requirements for each student, but provide the ability to read data back from the simulator once a student had submitted an answer. The initial random parameters generated for each student would then be used to test their solution.

To achieve these engagement goals for GECKO, the circuit simulator required extensive modifications and additions, many of these changes are explained in Appendix 5. Because GECKO would work across the first two years of electrical engineering education, work that had previously been undertaken on simulation with microcontroller based embedded systems (Collis, 2013) was fully redeveloped and extended to become part of GECKO as well. GECKO developed into a suite of educational technology tools; these included both circuit and microcontroller simulators with automated feedback features, feed-forward and usage analytics to provide students and educators with critical information to evaluate their performance.

6.2. Regulative discourse and a pedagogic framework

Just as the development of educational technology needs to be supported by a discourse centred on theory (Gunn & Steel, 2012), an educator's instructional discourse about the use of educational technology needs to be centred on a regulative discourse focussed on values and philosophy (Bernstein, 2000). At the same time as GECKO was being developed, ideas around its use within a course were formulated. These centred on using GECKO in ways to develop students' epistemic knowledge and their capability with KT-inferring. This had become highly relevant as by 2017 GECKO had become viewed as a replacement for OASIS (section 4.5). The original developer of OASIS had left the university and IT staff stated that OASIS would have to be removed sometime in the future as it was not possible to maintain it. The discourse around the use of GECKO became an instructional discourse centred on a replacement for OASIS to maintain smooth course administration, the ongoing reliance on practicing KH-techniques and for its use in summative assessment. This led to GECKO being used to replace the existing OASIS platform on a direct question by question basis in several courses. At that time it became possible to influence the development of epistemic knowledge in some questions. For example, the question about effective resistance in Figure 33 (page 131) was replaced by that in Figure 63 (page 211). None-the-less the instructional discourse around assessment led to questioning the value of visualisation, for example through these comments by senior academics in the department:

That's not what students would see in a test.

Questions can be presented using other tools that exist within Canvas [the university's new learning management systems]

Even though the data collected from the FCCTs indicated significant effects from students' engagement with epistemic knowledge using visualisation, GECKO was viewed in terms of its value for KH-techniques, smooth course administration and summative assessment. Kinchin et al. comment on exactly this sort of situation with regard to new technology:

The adoption of innovative technologies … into such a restrictive model means that any transformative potential is corrupted to perform utilitarian tasks, maintaining the status quo of non-learning (2016, p. 3)

The nature of the instructional discourse encountered, reinforced the need for developing a clear process for leveraging off the epistemic knowledge and KT-inferring benefits of GECKO. This led to the parallel development of the pedagogic framework in Figure 60 that embedded GECKO within a regulative discourse of pedagogical values. This framework does not reduce education to a simplistic binary comparison of teacher versus student centeredness. Insteads it positions an educator's abstract knowledge and pedagogic identity as the key drivers of teaching within a framework of direct instruction that leverages off educational technology.

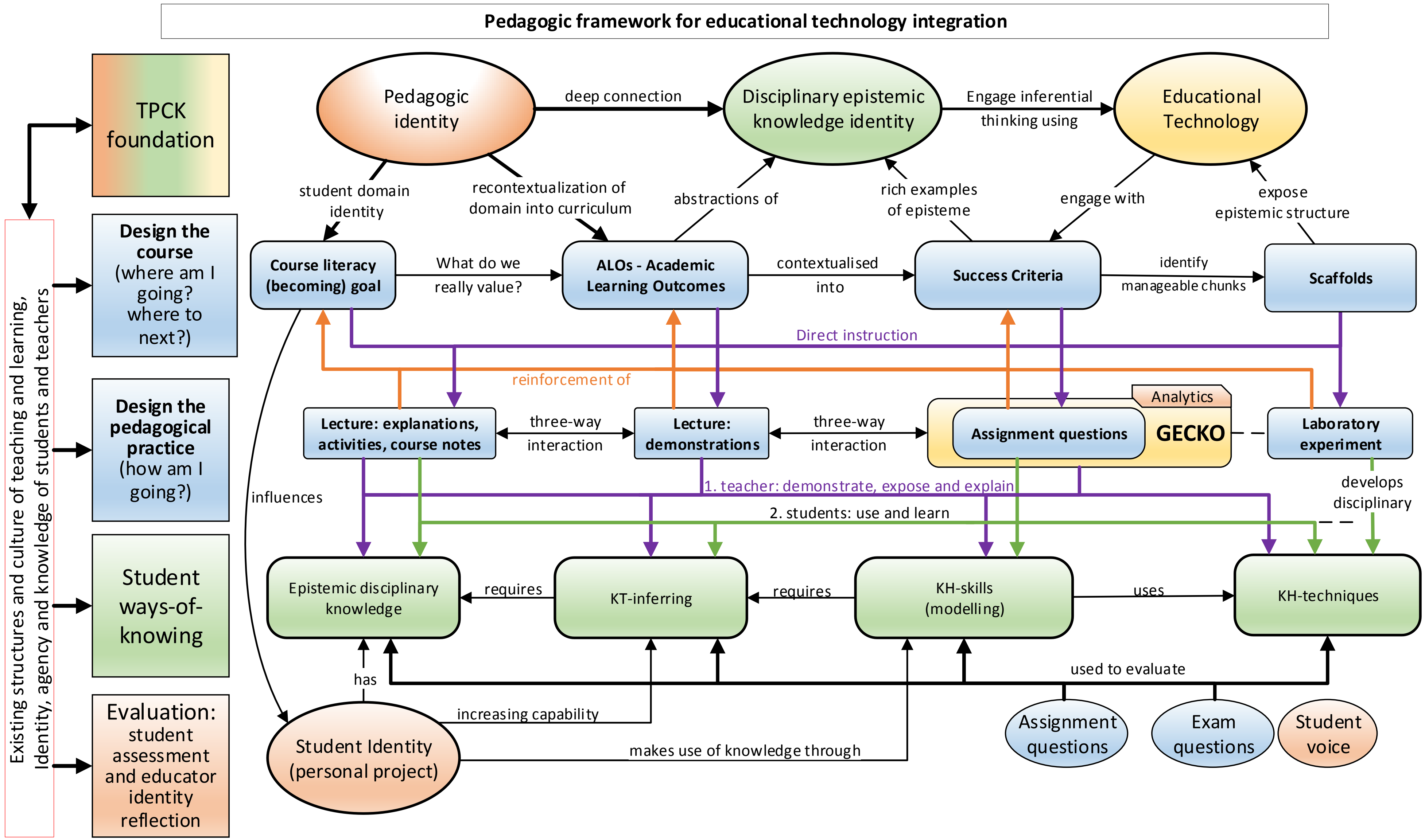


Figure 60: Pedagogic framework for knowledge centred education using GECKO and direct instruction

At the top of the diagram is the course foundation. This equates with TPCK, Technological Pedagogical Content Knowledge, as described in section 2.6.2. These are the understandings of the relationships between epistemic knowledge, pedagogic identity and educational technology – which together make student comprehension possible (Mishra & Koehler, 2006). The emphasis behind the term pedagogic identity is the importance of educative practice being underpinned by educational theory and understandings of pedagogical practices. The emphasis of disciplinary epistemic knowledge identity is the important place of an educator's deep connection with the knowledge in their domain and its epistemic nature. However, more than this, the emphasis is on moving away from the expression of an educator's deep knowledge merely in terms of its useful-content or value in terms of being easily assessable. The role of educational technology in this process is to view it as a tool for expressing epistemic knowledge and having students engage with this knowledge in ways that promote capability with KT-inferring to develop.

On the left edge of the diagram are aspects of the situation that require reflection prior to planning. The course is situated within the goals and type of learning (theoretical or project-based) determined by the department. There are practical structures as well, such as: number of learning opportunities, where and when these will take place (lecture rooms and laboratories) and other available resources. This also needs to include an awareness of the culture of learning, and the identity, agency and knowledge practices of students, which are apparent through their learning behaviour. This is not so that a course could be planned to align with these, but to inform course change. A change where epistemic knowledge and capability with KT-inferring, become compatible and necessary with the teaching and learning situation, as described by the morphogenetic framework of Archer (1995), in section 2.3.3.

The next stage to consider is the design of the course; this is focussed using the first and last pedagogical questions described in section 2.5.1 - as if the student were asking: Where am I going? Then once that is learnt, where should I go next? This begins with identification of an overarching goal for developing students' gaze – the way they see the subject within the world and who they are to become (Bernstein, 2000). Following this is the identification of a set of Academic Learning Outcomes (section 2.5.2.3). These express the abstractions, key ideas or abstract thought-holders at the core of the episteme.

Designing pedagogical practice is next and encompasses the second pedagogical question: How am I going? This is the development of success criteria, where concrete knowledge and practices for learning are established that will engage students with disciplinary knowledge (section 2.5.3.1). Through success criteria both educators and students can monitor and evaluate learning progress. Making learning explicit allows students to develop metacognitively, and ultimately to be able to frame their own learning needs e.g.: *I can (success criteria) and when I am proficient at it, I will be one step closer to (ALO), which is moving me toward seeing the world the way an engineer does and becoming an engineer*.

This process requires breaking success criteria into a manageable progression of chunks that take students from the already known to the required level. These became the basis for selecting learning opportunities, such as: the explanations, activities, demonstrations and useful-content for course notes and laboratories. Every learning opportunity therefore, is part of a cohesive framework that focusses on developing the KH-techniques, epistemic knowledge and KT-inferring that underpins the development of KH-skill. When there is cohesion, each learning opportunity is useful in reinforcing the success criteria, ALOs and the course goals; also they support evaluating the efficacy of the teaching as well.

From the links in the diagram, it can be seen that GECKO was developed not only as an assignment tool, but as a central part of bringing about this cohesion for a large cohort of students. It supports conceptual explanations and student engagement with the hidden epistemic properties of a circuit or microcontroller based embedded system. This was to reflect the positioning of the research within the third period of research into student understandings (Amin et al., 2014) as described in section 1.5.12, where language and propositions, visualisations and demonstration of context-of-use become synthesized together to reinforce the development of epistemic knowledge.

The pedagogic framework also places evaluation of student progress as more than demonstration of techniques but as opportunities to demonstrate skill – taking the known into the unknown. Analytics and a survey question option within GECKO allow student voice to be collected so that an educator can get feedback as part of their continuous improvement cycle. The next sections describe how these aspects of pedagogy were integrated within GECKO.

6.3. GECKO and academic learning outcomes

To develop a pedagogically sound question involves making the abstract learning outcomes and success criteria explicit and visible to students. These are the central ideas of the first and second pedagogical questions from Hattie and Timperley (2007) described in section 2.5.1. Learning outcomes or objectives are not well used with staff in the faculty; more often they were commented on as being a burden rather than recognised in terms of potential benefit to students. The use of success criteria is not something that lecturers were found to be familiar with either. When developing ideas for the question editor within GECKO, learning outcomes were placed at the top of the first (Main Options) section of the question editor as in Figure 61.

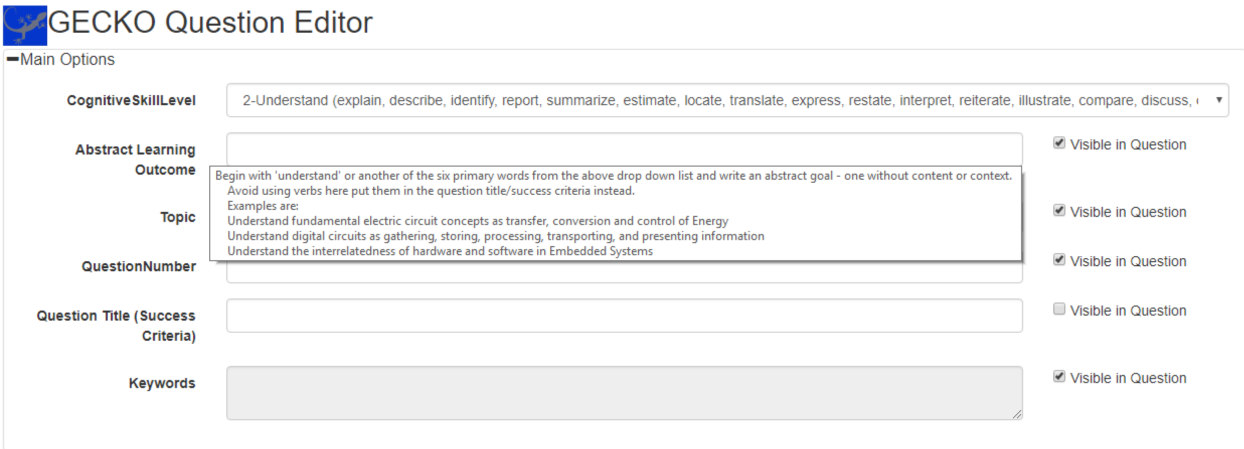


Figure 61: GECKO main option block

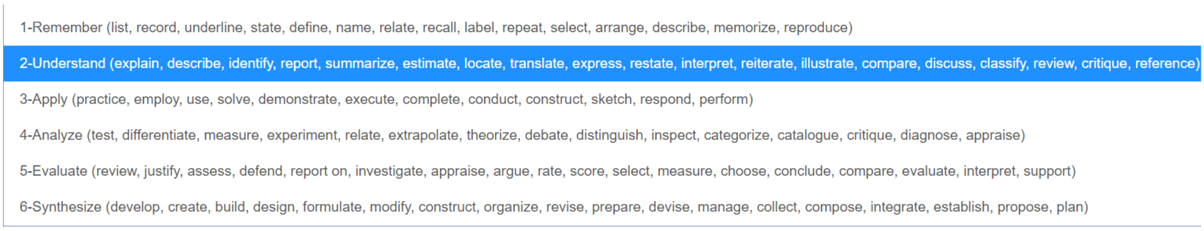


Figure 62: GECKO learning outcome dropdown

In Figure 61, the Abstract Learning Outcome field shows the tool tip to help question writers. The drop down for the cognitive skill levels from the Bloom's Taxonomy (remember, understand, apply, analyse, evaluate, synthesize) is in Figure 62. Verbs associated with each were written into the dropdown to scaffold the writing of success criteria. The term success criteria was used synonymously with Question Title in the editor to help anyone writing questions become familiar with it.

6.4. Increasing the epistemic value of circuit questions

The next aspect of soundness used in developing GECKO was that it needed to have the capability for the development of questions about epistemic knowledge. The first aspect of this is using simulation. This requires a question writer bringing fragmented knowledge together into a system of meaning of 'know-that' knowledge as described in section 2.2.1. Figure 63 is a question written in GECKO to replace the OASIS effective resistance question in Figure 33 on page 131 to make it focussed on epistemic knowledge. To answer the question, students are required to modify the simulator so that the right hand circuit would have the same effect as the circuit on the left. This was written so that students could see the concept of *effectiveness* at work. Figure 64 is the view students get if their answer is incorrect. In this view, the simulator is active, the voltage is the same but the current in the two circuits is different, i.e. the circuits do not behave the same. It is anticipated that students would then see that R4 is not *effectively* the same. The goal is to raise the question level in terms of the SOLO Taxonomy as presented in section 2.5.3.3. Originally it was a multi-structural level, see Figure 33 on page 131, centring on KH-techniques of series and parallel resistance calculations. At the relational level of the SOLO Taxonomy, epistemic knowledge about electric potential and charge flow are used to expose the concept of *effectiveness*.

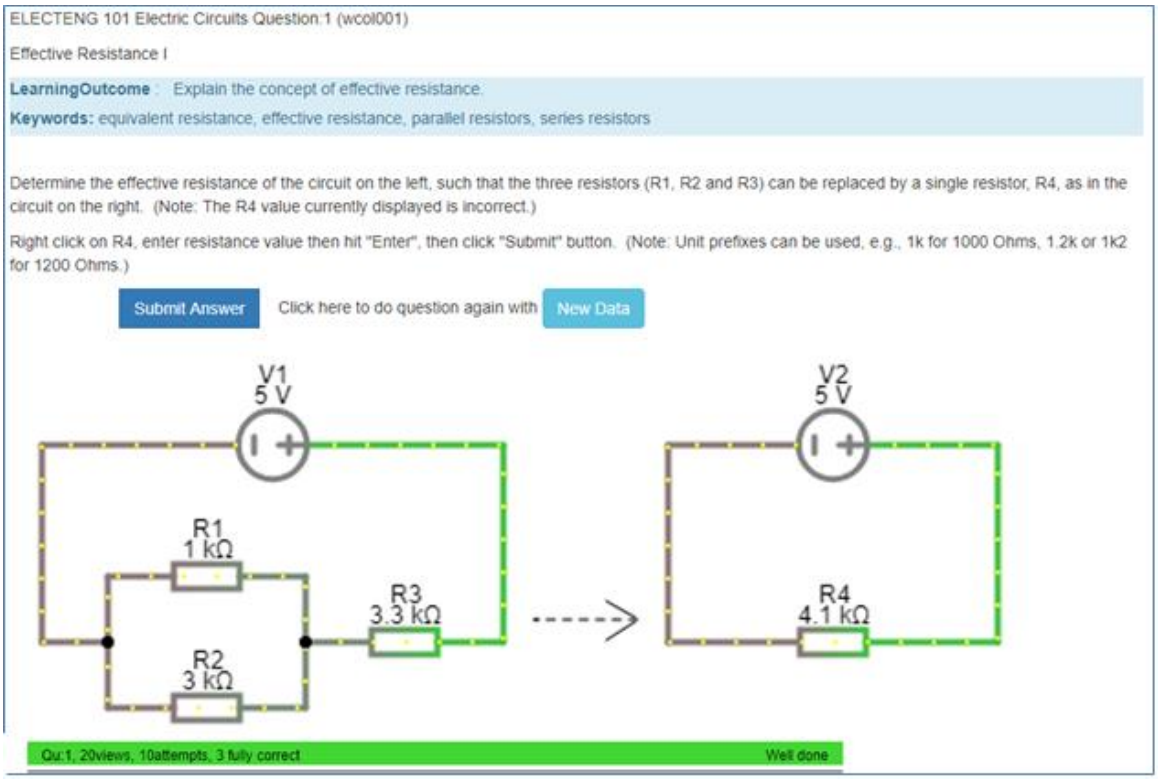


Figure 63: Circuit simulator based question

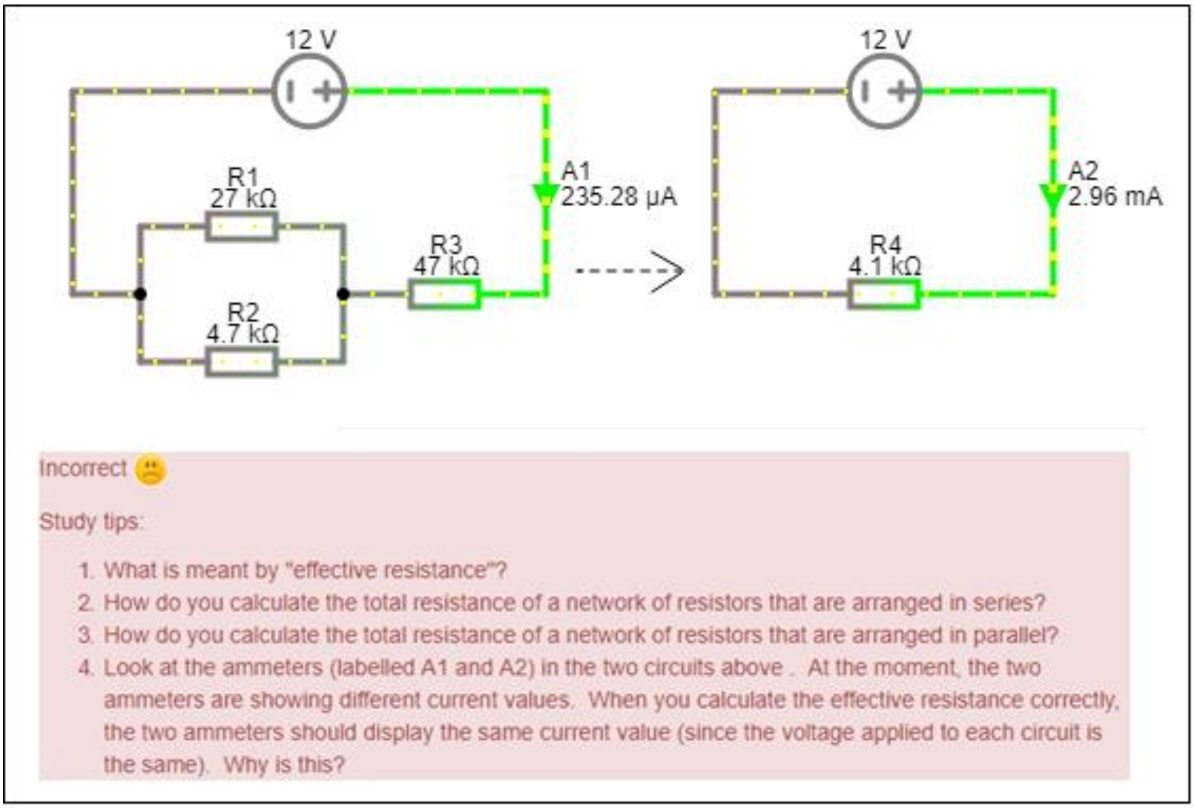


Figure 64: Circuit simulator question after incorrect answer

One way to move a question beyond a focus on KH-techniques into KT-inferring is to make the use of calculations implicit. In Figure 65, the concept of the voltage divider as a ratio is explored, here students have to work out which voltage divider has the highest voltage output and which the lowest. While no calculations are asked for, their use is implicitly required in answering the question. The view in Figure 65 is that shown when a student gets the answer correct or incorrect; prior to this students can see resistor values but no voltages are displayed. Without a source voltage, students have to focus on the voltage divider as a ratio.

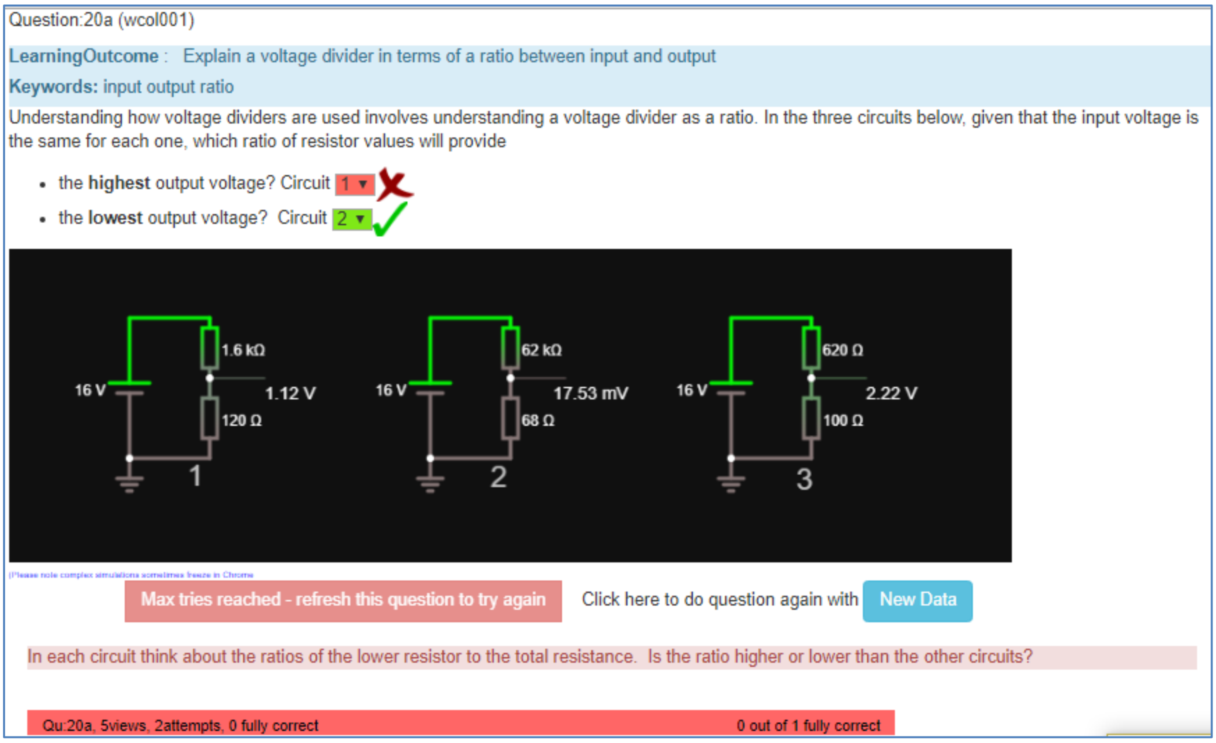


Figure 65: KH-skills based question about voltage divider ratios

GECKO was envisaged to allow writing complex questions. This involved designing the question editor tool with the flexibility to handle different types of questions, such as cloze, fill in the blank, radio, multi-choice and checkbox. It also has the facility to import images and display these. The circuit simulator retains much of its existing functionality in terms of drawing, loading and saving circuits (Falstad, 2016). In addition, a fully featured open-source text editor (ckeditor.com) was configured and incorporated into GECKO, with the toolbar for this shown in Figure 66.

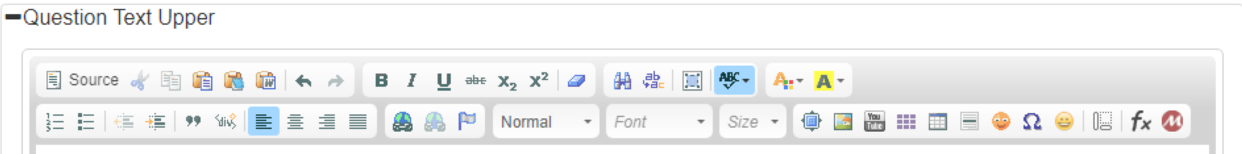


Figure 66: GECKO Editor

These features provide question writers with a flexible set of features to use when developing questions. The ability to write questions that encourage epistemic knowledge however requires more than features in a question tool. It requires that students engage with multiple connected pieces of information as described by the multi-structural level of the SOLO Taxonomy in section 2.5.3.3. Figure 67 is a question developed to encourage students' epistemic understandings about the link between a line of program code, the initial and final states of a register and output devices.

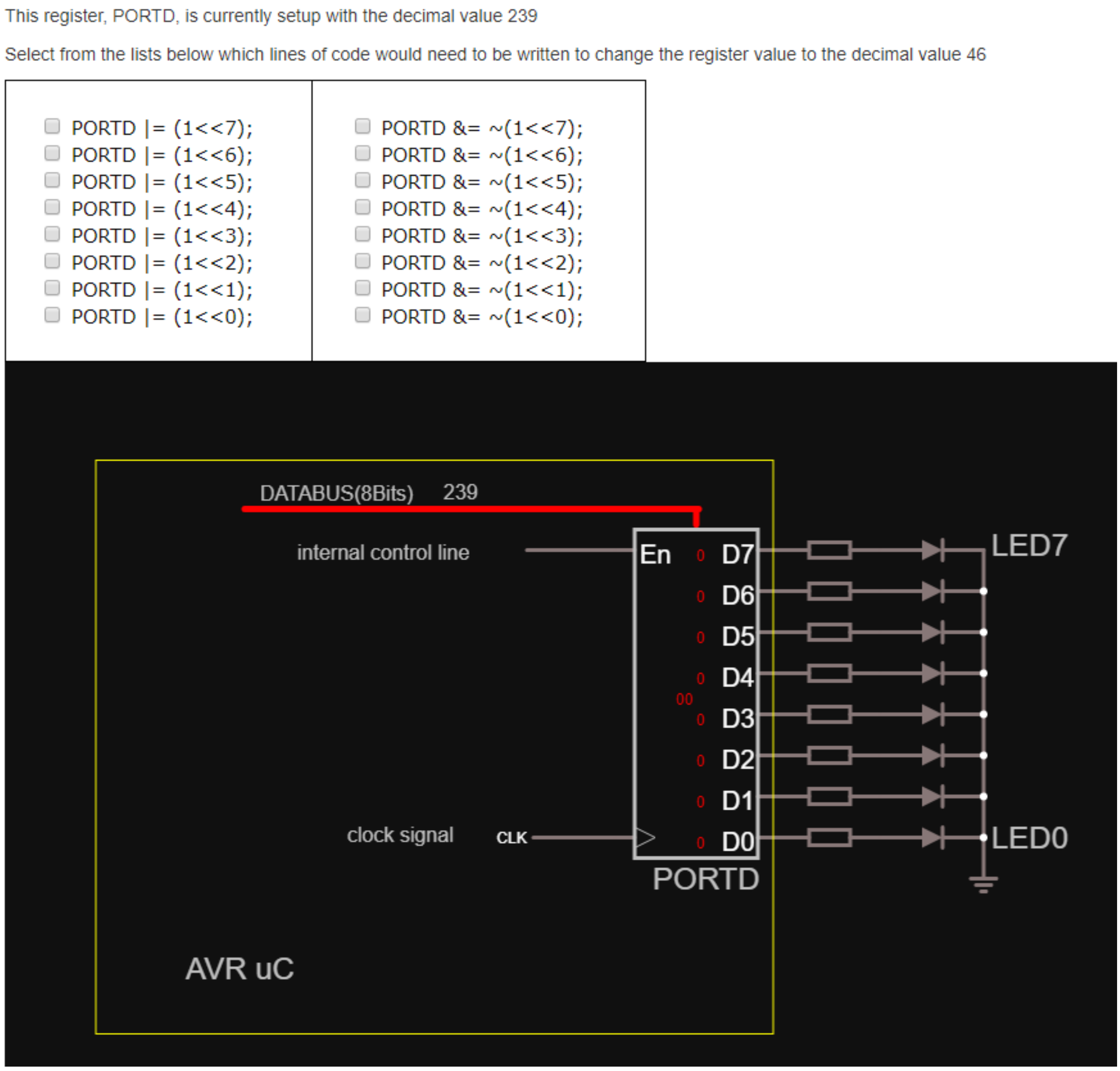


Figure 67: Epistemic –system of meaning - type question

6.5. Manipulating simulations through scripting

One of the key design features of GECKO is the ability for question writers to develop scripts to manipulate the circuit and AVR simulators, and question data for each. This provides the facility to develop complex scenarios for students to develop epistemic knowledge and capabilities with KT-inferring. An open-source mathematical parser (Los, 2016) was identified as a suitable starting point for the parser needed within GECKO. It was then modified and a number of new commands were developed.

Scripting provides the ability to randomly generate and manipulate variables, component values and simulator features. Parsing commands can generate random values (see #1 below) and also create random values from the E6, E12, and E24 series (see #2 below). Here are examples of lines from a question

1. **V1val = random(5,21) :V** //generate a random value from 5 to 20, units = V
2. **R1val = e12(100,1000001) :ohms** //generate a random e12 series value 100 to 10M, units = Ω
3. **R2val = e12limit (R1val, 8):ohms** //generate an E12 value limiting it to the range of R1val/8 to R1val*8
4. **R1ohms = R1val** //R1ohm - value in ohms without prefix or units
5. **set(V1, value, V1val)** // push randomly generated values into the sim
6. **set(R2, value, R2val)**
7. **set(V1, displaylabeloverride, true)** //turn off label V1 in the sim
8. **set(R4, highlight, true)**
9. **RResult = 1 / (1 / R1val + 1 / R2val) + R3val :ohms** // calculate correct answer for checking

The parser also takes care of automatically configuring a prefix for units so that 330000 would be shown as 330kΩ; this can be overridden as well to force a specific prefix e.g. 0.33MΩ or 330,000Ω.

Another command allows a previously generated value to be used to limit the range of values for a random value e.g. in line #3 **R2val = e12limit(R1val,8):ohms.** If R1val was 3k9 then R2val would be an e12 value from the range 3k9/8 to 3k9*8. In this way more realistic circuit values can be generated and nonsensical questions avoided. Component values are written into the simulator via the API command 'set' e.g. **set(R1, value, R1val)**.

Flexibility comes from being able to use variables from scripts within the instructions editor so they can form part of the question and part of the simulation. Values are written directly into question text as shown in Figure 68 and automatically replaced when delivered to the student.

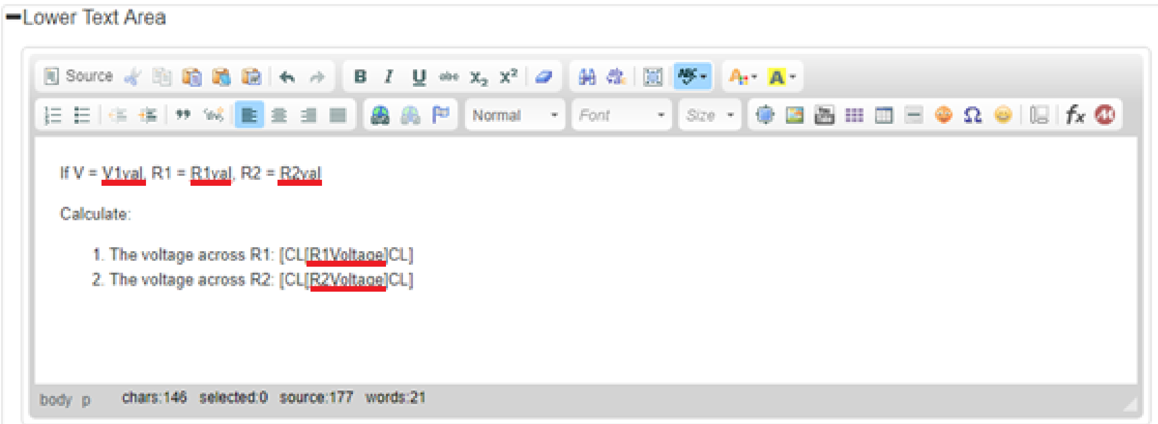


Figure 68: Variables within instructions

Figure 69 shows the question as shown to the student where variables are replaced with values e.g. R1val was replaced with 390kΩ. It also shows how the command **[CL[R1Voltage]CL]** – is used to create a cloze type question. Students will see a textbox to enter values into and when they press submit, their values will be sent to the server to be compared to the correct answers (to within 1% tolerance).

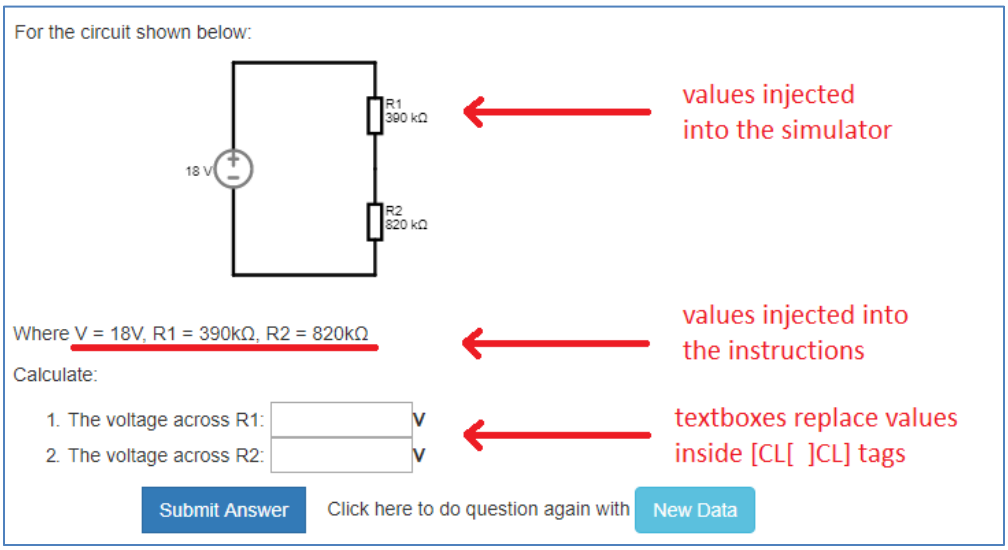


Figure 69: Variable values shown in the question instructions

In this way GECKO was designed to be as flexible as possible and not constrain question writers.

6.6. Feedback and feed-forward

Feedback and feed-forward are essential elements of developing the soundness of educational technology; as described in section 2.5.3.2 these are mainstays of teaching and learning. Feedback is about informing students how they are going and involves two important aspects of learning. Firstly it concerns students knowing *where to next* and secondly it is about reinforcing with students the aspect of the learning that you want them to specifically take away from the exercise, so it is the place to reinforce abstract concepts. These are integrated into GECKO as separate fields so that when a student gets a question incorrect they are shown the feedback field and when they get it correct they are shown the feed-forward field.

To maintain the strong focus on feedback, variables from scripts can be used directly in feedback and feed-forward fields. In Figure 70, variable names are used within part 2.1 of the feedback and will be replaced by actual values as in Figure 71

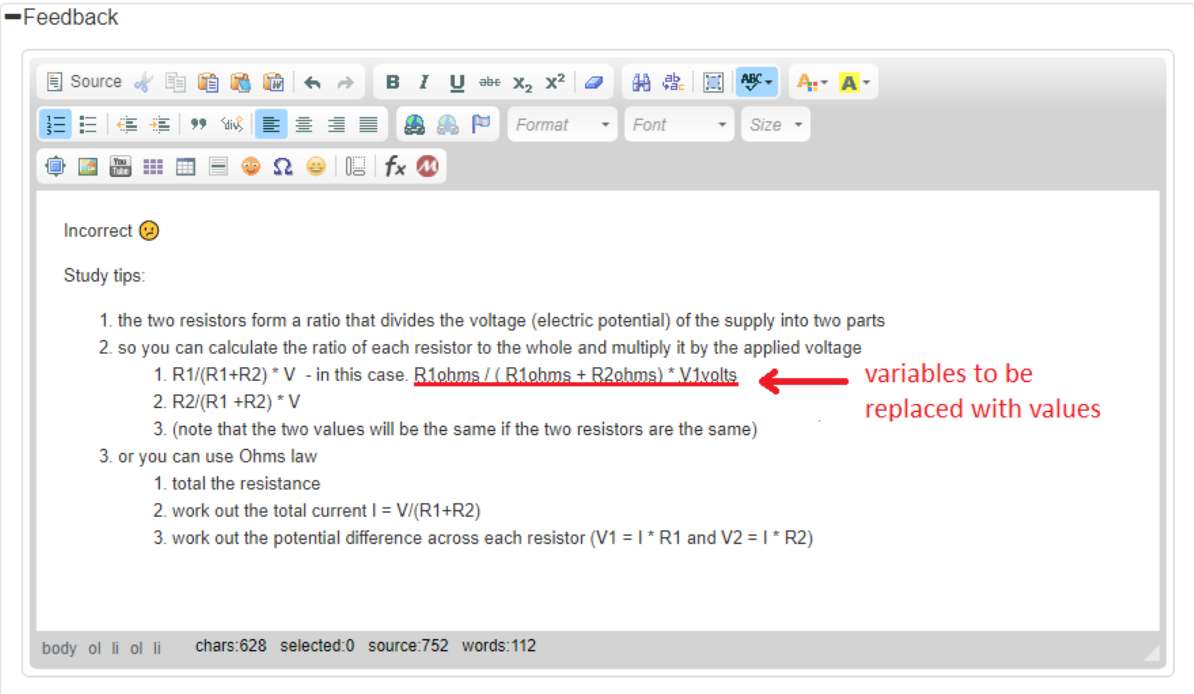


Figure 70: Variables used within feedback field of the question editor

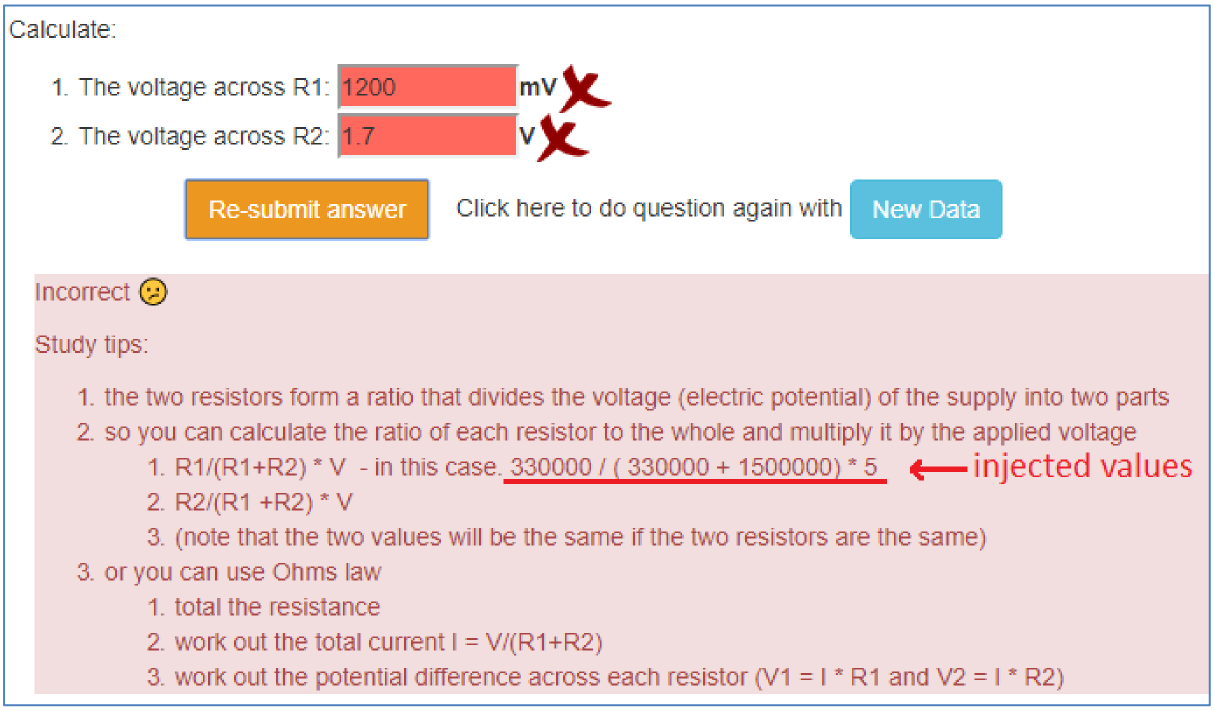


Figure 71: Variable names converted to values in feedback

In the same question, when a student enters a correct answer, variables can be used in the answer to support their learning. In Figure 72, variable names are replaced by actual values as in Figure 73. In the feed-forward, students' correct use of terms such as 'across' and 'at' with regard to electric potential are encouraged. Specifically the use of 'at' implies that the ground is the reference in interviews students often confused 'across' and 'at' when referring to electric potential.

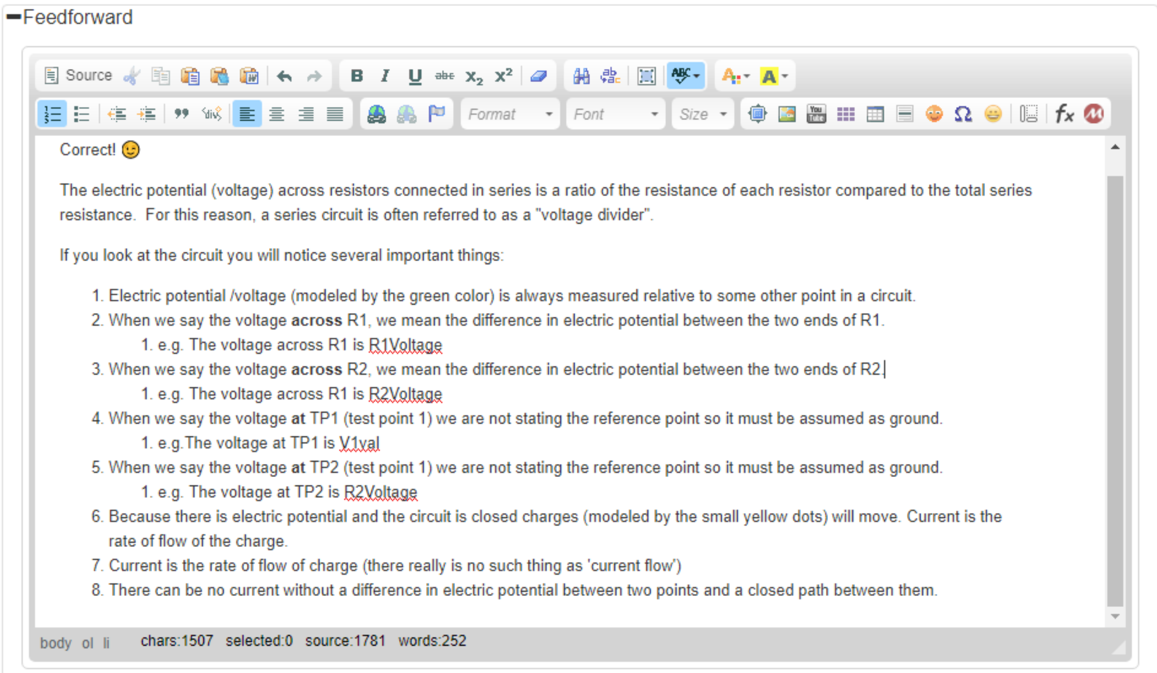


Figure 72: Variables used within feed-forward

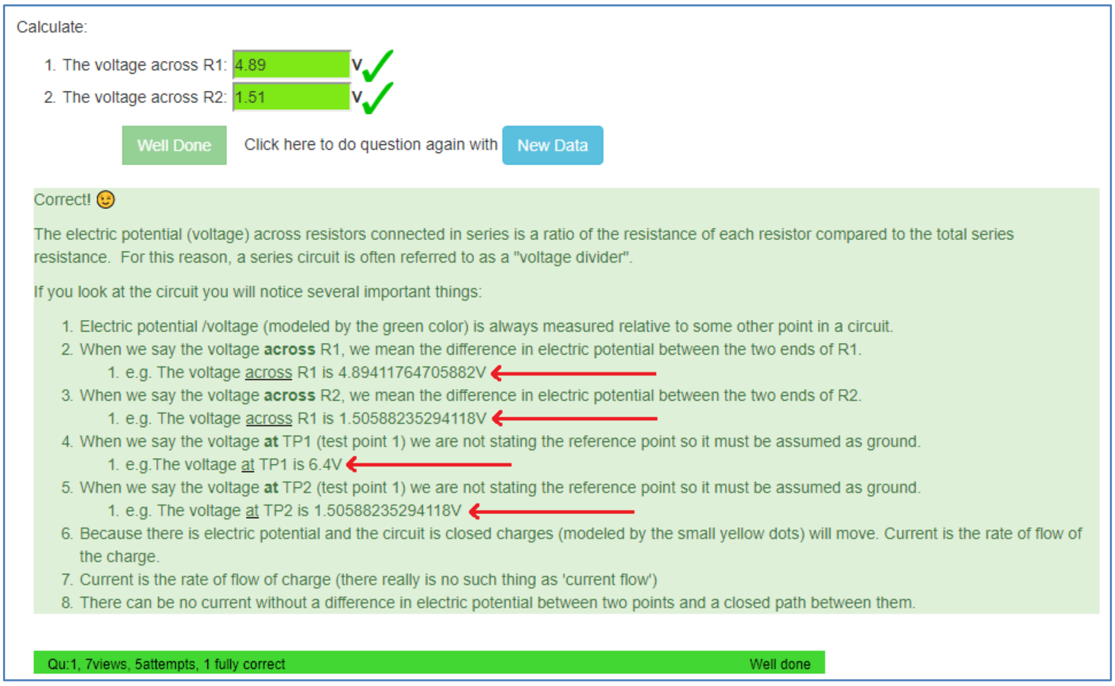


Figure 73: Variables replaced with values in feedback

To further increase feedback or feed-forward, scripts to control various aspects of the simulator can be written which will run when an answer is incorrect or correct. In Figure 74, a script is used to unhide/show three test points. These scripts can be used by the question writer to highlight components, to show/hide specific features or change values.

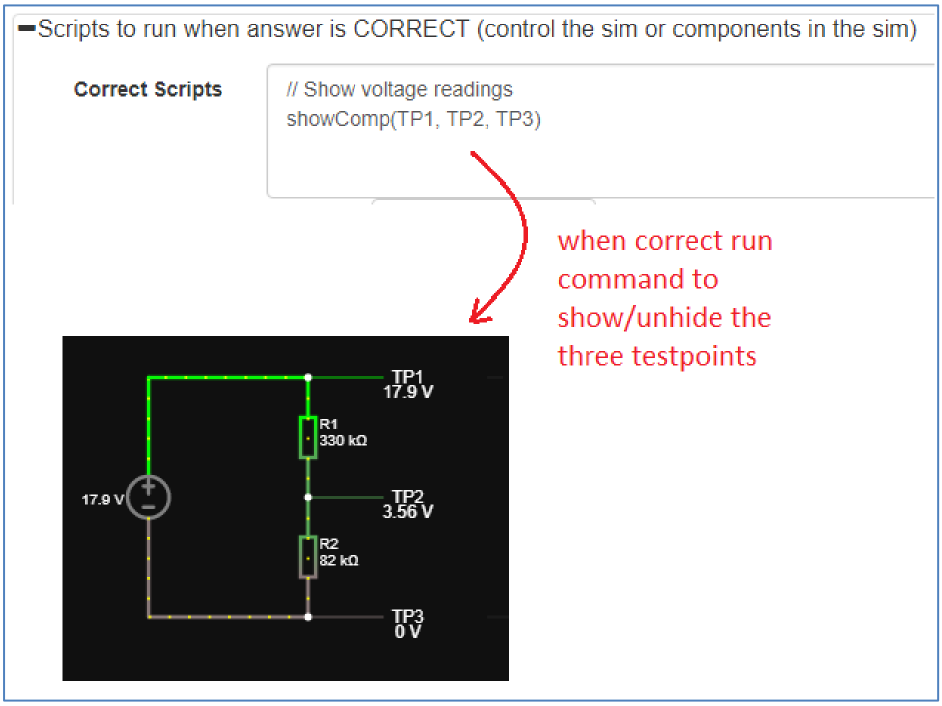


Figure 74: Simulator scripts when answer is correct

6.7. Student agency

When thinking about students' exam-taker or get-through identity and how structure can influence this; the assignment tool was designed to move away from the familiar models of assessment being purely summative or formative. GECKO allows three different types of assignment to be developed: only summative, only formative or a mix of both. A summative assignment does not make use of the feedback or feed-forward options in a question, and no marks are displayed until after the assignment closing date and time. With a formative assignment, students receive feedback on questions immediately and questions may or may not be awarded marks. If a question is marked, the requirement can be included to practice a question a specific number of times as well.

A mixed assignment can include aspects of formative feedback with summative marks; it acts in a similar way to the unlimited time test, which Case and Gunstone (2002) report as encouraging students to consider deep understanding (KT-inferring) rather than techniques (KH-techniques). The assignment can be configured to be time limited or open ended. Each question in the assignment can also be individually selected as to whether it will be formative or summative, how many marks it is worth and how many times it must be attempted. The mixed formative-summative assignment was developed to endeavour to integrate student's perceptions of learning and assessment rather than the singular view that summative assessment has for students - that of getting marks, which leads to why so many students fail to pick up marked assignments and consequently do little about the 'wake-up call' poor marks represent.

A portion of a mixed assignment is shown in Figure 75.

Question Number	Question Title	You have attempted it	You got it fully correct	You need to get it correct	Value of correct answer	Your Score	Out of possible	Students in COMPSYS201-2018 who have completed
1	Identify program commands that control uC outputs	3	0	1	1	0	1	30
2	Write program commands that control uC outputs	0	0	1	1	0	1	31
3	Identify incorrect commands that control hardware in a Cylon32	0	0	1	3	0	3	30
4	ES state concept	0	**	1	2	**	2	0
5	Decimal conversions - easy	0	0	2	0.5	0	1	0
6	Binary conversions - easy	0	0	2	0.5	0	1	0
7	Best variable type	0	0	4	0.5	0	2	1
8	variable addition	0	0	2	0.5	0	1	0

Figure 75: Part of a mixed formative/summative assignment

In Figure 75, question 4 is summative, the others are formative; this is indicated by the score fields being 'asterisked' out. With a summative question, students will not get their marks until a pre-set date and time, this gives the marker time to review or manually mark the answers (in this instance mark a short answer question). Formative questions are marked immediately and students can attempt them as many times as they want until they get it correct. The options for a formative question are that students can be made to attempt it multiple times, for example questions 5, 6 and 8 have to be answered correctly twice and question 7 four times to get the maximum possible marks.

Associated with this, is one of the important effects on achievement that Hattie's research group identified, that of spaced versus massed practice (Hattie, 2012). This means having students do regular practice over several days has more benefit than doing all mastery exercises at once. The assignment tool does not incorporate a feature to govern student behaviour in this way, for example by making certain questions only accessible for specific periods of time within the overall time frame for the assignment. This was considered, as spaced study has been shown to be more powerful than massed practice in online courses (Miyamoto et al., 2015); however the primary goal of the case study was to investigate student identity and agency. Future developments of GECKO may include features that allow finer grained management of access to questions.

6.8. Learning analytics

The catch phrase of Hattie's research (2012, 2014) is 'Know Thy Impact'; and behind this is his characterisation of the expert educator as someone who is persistent about analysing their effect on student understanding. To achieve this required the conceptualisation of data in ways to provide both students and educators with information about student progress as well as the performance of educators.

As with all educative interventions, if analytics are to become powerful, a sound grasp of theory is required (Wise & Williamson Schaffer, 2015), as is professional development on the design and use of analytics (Gunn, McDonald, Donald, Blumenstein, & Milne, 2016). Analytics also requires data and at the onset of GECKO's development it was decided to keep all data for analysis purposes. This included: when students accessed a question, when/if they answered it, which parts of a question they got in/correct, all their answers, their accuracy, the number of interactions they had with the simulator, and even the browser they use and their IP address. Data was stored in a flat rather than a relational database to make it as flexible as possible and not constrain its usefulness (Mutch, 2010).

Gunn et al. (2016), consider educators not to be highly data literate, so it was important to make analytics easily accessible and as intuitive as possible. The analytics displays in GECKO were developed using Google Charts to achieve this. One of these developed for educators, is shown in Figure 76.

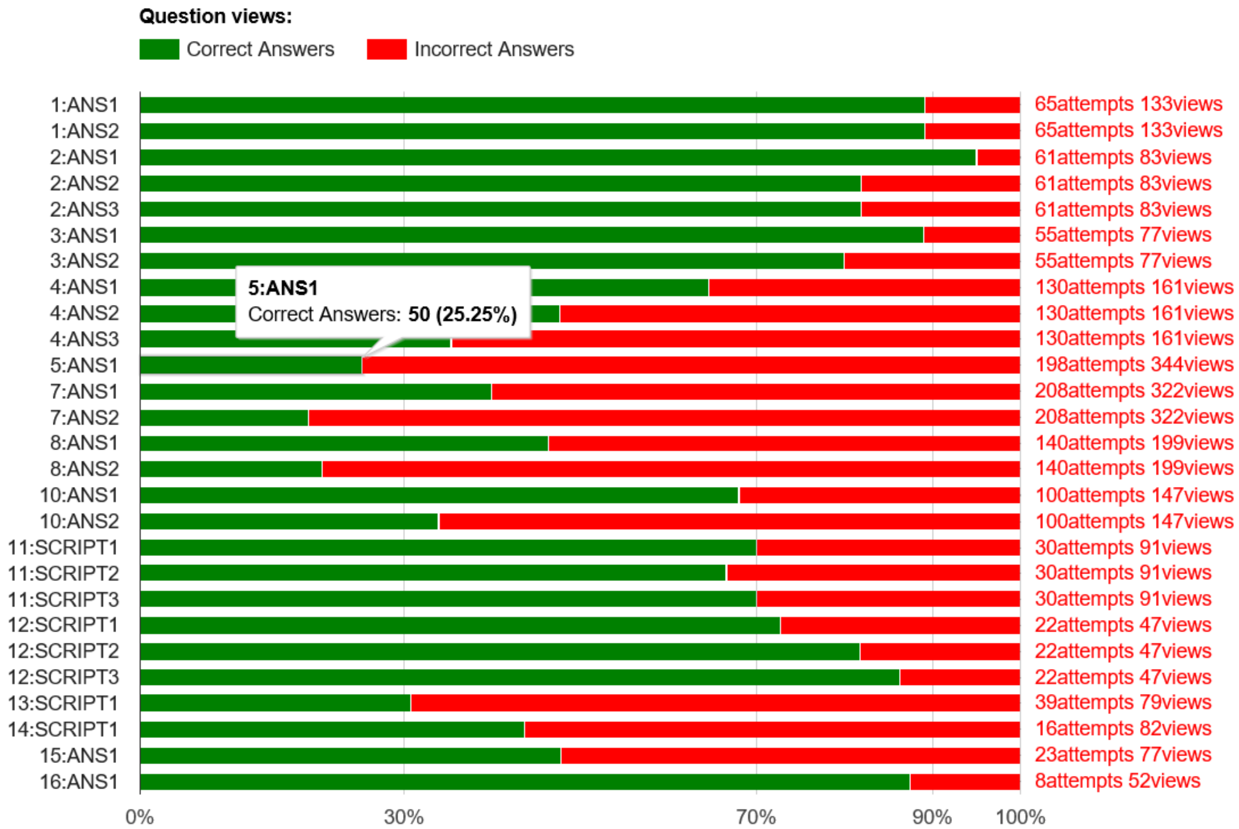


Figure 76: GECKO topic summary for 2nd year DC fundamentals

Figure 76 reveals data about each answer within each question in a topic (e.g. question 4 has three parts). Hovering over each section of a bar shows the actual number of answers e.g. there were 50 correct answers to part 1 in question 5 when this analytic was captured. This topic summary shows question 1 was typically answered correctly.

An aspect of inquiry for an educator relates to how data such as this could be interpreted? Using a useful-content instructional discourse, it would be tempting to say that the first question in Figure 76 had little benefit for students as 90% of students answered it correctly, so perhaps it could be dropped. However there are important pedagogical and knowledge perspectives that warrant asking a question that most students get correct, the least of these is as a reminder to students. Another is that for educators and students to know where students are going requires understanding what students know before learning begins. Using a question which is easily answered indicates that the material is correctly positioned for the majority of students. Another important aspect is that for epistemic knowledge to develop, students need to begin to connect knowledge in a question with what they already know. The introduction of the concept using an easily answered question means that it identifies an initial foundation to connect epistemic knowledge to.

In a similar way, analytics are used to encourage students to begin to develop metacognitively, to take responsibility for their own learning. This can be achieved when students monitor and begin to analyse their own progress; the analytics view in Figure 77 is a summary page of student progress in a topic.

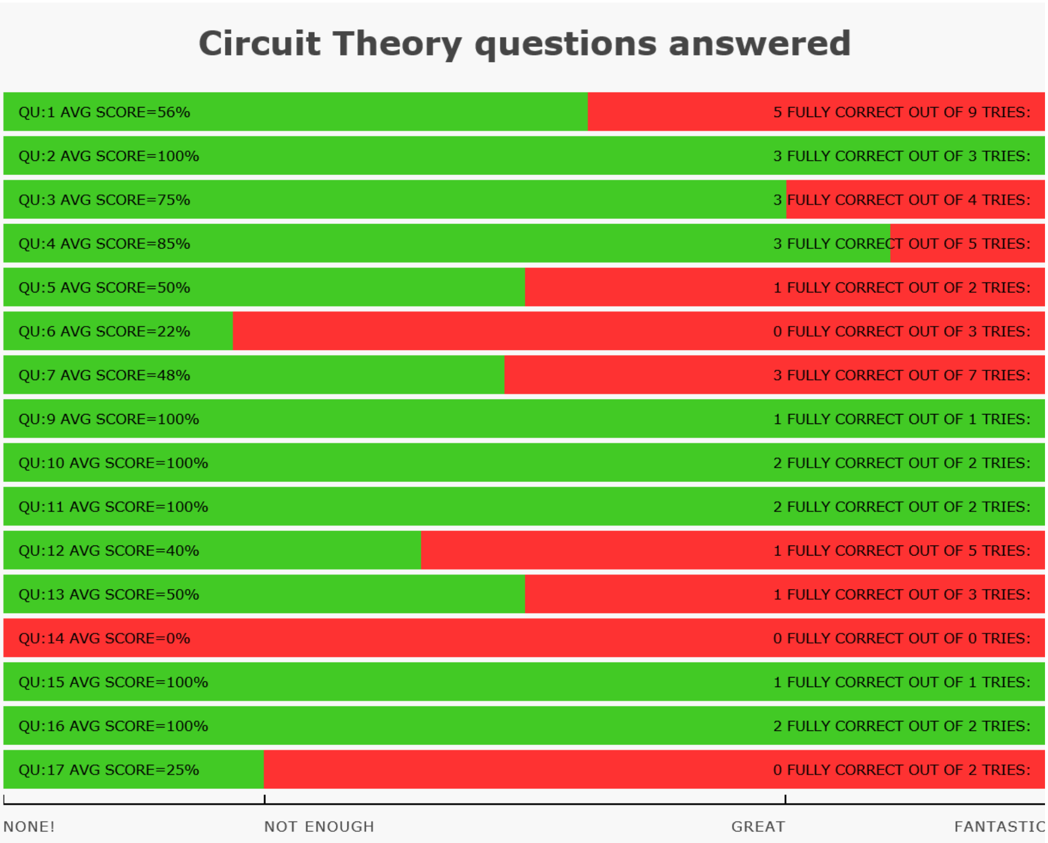


Figure 77 GECKO Question presenter summary analytics for students

An individual question analytic in a single line format similar to the above, is presented to students when they access each question, as seen at the bottom of Figure 73 on page 218. Analytics displays support students gaining insights into their agency and knowledge and allows them to identify areas of concern (Gunn et al., 2016). One feature to increase this was that students can see comparative statistics on the front page of GECKO's online assignment tool, that show the number of students in the course who have completed that particular question to date as shown in the last column of Figure 75.

The area of learning analytics is a developing one and the field of scholarship is growing. When considering analytics, the six dimensions by Greller and Drachsler (2012) were informative. Data privacy and ethics is one of these dimensions; these were important when considering who has access to data and making sure that information was abstract enough so identities could be protected. Stakeholder needs is another dimension, and these were considered in terms of what analytics would make sense to students, i.e. be succinct enough for them to engage with, yet rich enough to tell a story about their learning progress. In terms of teaching staff, the consideration was what information would be of benefit to them. OASIS had one analytic, an activity graph shown in Figure 35 on page 134. A comprehensive report that could isolate individual parts of questions for a full topic (as shown in Figure 76) could be used to enter into discussion with stakeholders about student learning.

Another stakeholder consideration was using GECKO for ongoing research. The assignment tool has an option where a research question (developed as another question in GECKO) can be added onto the end of any question to gain student feedback. It was through this facility that Likert scales and comments were collected for this research. One aspect of data integrity Greller and Drachsler (2012) draw attention to, is that data should not be polluted by 'test students', tool developers or question writers. This was countered by designing analytics in GECKO to recognise students by their role in the learning management system and to only include their data in the analytics.

Greller and Drachsler (2012) also raise a concern about shared identities – where students work on questions together. The system was developed so that students had to access it through their unique University of Auckland login, because this would discourage students sharing logins and passwords. However, there is a limitation in that if students work on an unmarked exercise together then it will appear as if only one student has done the work and the other(s) will be lost to the data set.

Another aspect of data Greller and Drachsler (2012) describe is the high degree of difficulty in getting organisations to release demographic data about students (e.g. ethnicity, university and school results) to make finer grained analyses about performance. This difficulty was encountered during the case study.

6.9. AVR simulator based questions

The second type of simulation in GECKO is for teaching about Atmel AVR microcontrollers. It relies on a microcontroller simulator (Figure 78) written for this research that leverages off aspects of Master of Engineering thesis work (Collis, 2013). The AVR simulator for that research was written in C# as a standalone package and did not include any question capability. The simulator for this research is written in JavaScript and rather than rewrite the C interpreter developed for the prior research, an open source CoffeeScript C interpreter (Hao, 2015) was integrated into GECKO.

The goal of this question tool is the same as the circuit simulator, that epistemic knowledge and KT-inferring can be developed by engagement with challenging questions that use visualisation. In the AVR simulator, this is the interaction between hardware and software. Figure 78 is an image of an AVR simulator type question simulating a running lights (Cylon) pattern. Students are required to run the code, fix the error, answer the questions then press the submit button[7].

As embedded systems are complex reactive processes, the automatic testing of student work within GECKO's AVR question tool is different to that developed for the electric circuit simulator. Testing was conceptualised as capturing consecutive states of the system and comparing those to a set of saved correct states. The scripting language within GECKO was further developed with commands to setup a background state machine that is used to run student code and capture its output. Scripts can be written

[7] This is the first question in the CompSys201 assignment found online at www.xplainittome.com.

to configure which I/O (input and output) devices and memory will be monitored, when their state will be captured and how many states will be captured in total.

Below is the script for the question in Figure 78. This configures the underlying state machine to log all LED states every time the text "_delay_ms" is encountered in a line of code, and to stop after 25 of these log events have occurred.

```
//capture all state changes of these IO devices
Log.logIODevice(LED_0, LED_1, LED_2, LED_3, LED_4, LED_5, LED_6, LED_7)
Log.codeEvent("_delay_ms")     //log whenever this line occurs in the code
Log.setMaxEvents (25)          //just count this many log events then stop
```

The next part of the script is used to setup the initial state of the question for the student. It identifies a random line of code and replaces it with another random line of code (as long as the two are not the same)

```
fromLineNumber = random(27, 43)*2 //random line number
toLineNumber= random (27, 43)*2  //2nd random line number
lineOfCode = code.getLine(fromLineNumber )
lineToCode = code.getLine(toLineNumber)
while (lineOfCode== lineToCode )  //if equal generate again
{
  fromLineNumber = random (27, 45)*2
  lineOfCode = code.getLine(fromLineNumber )
}
code.replaceLine(toLineNumber, lineOfCode) //lines unequal so swap
```

The sequence for developing a question of this type is:

1. Begin with an abstract learning outcome, in this case 'understand the interrelatedness of hardware and software in embedded systems'

2. Decide on the success criteria. In this instance ‘describe how program commands work that link hardware and software’
3. Design a question that would engage students with the success criteria, e.g. where they have to edit/write/fix program commands that control software
4. Plan the way the question will work. In this question the scripts are used to randomly create an error in the code which the student has to fix.
5. Create a correctly working model in the simulator and save it as a reference design to the server

Every time a student is presented with this question, a unique error is generated; once fixed and the answer submitted, it is compared to that stored on the server.

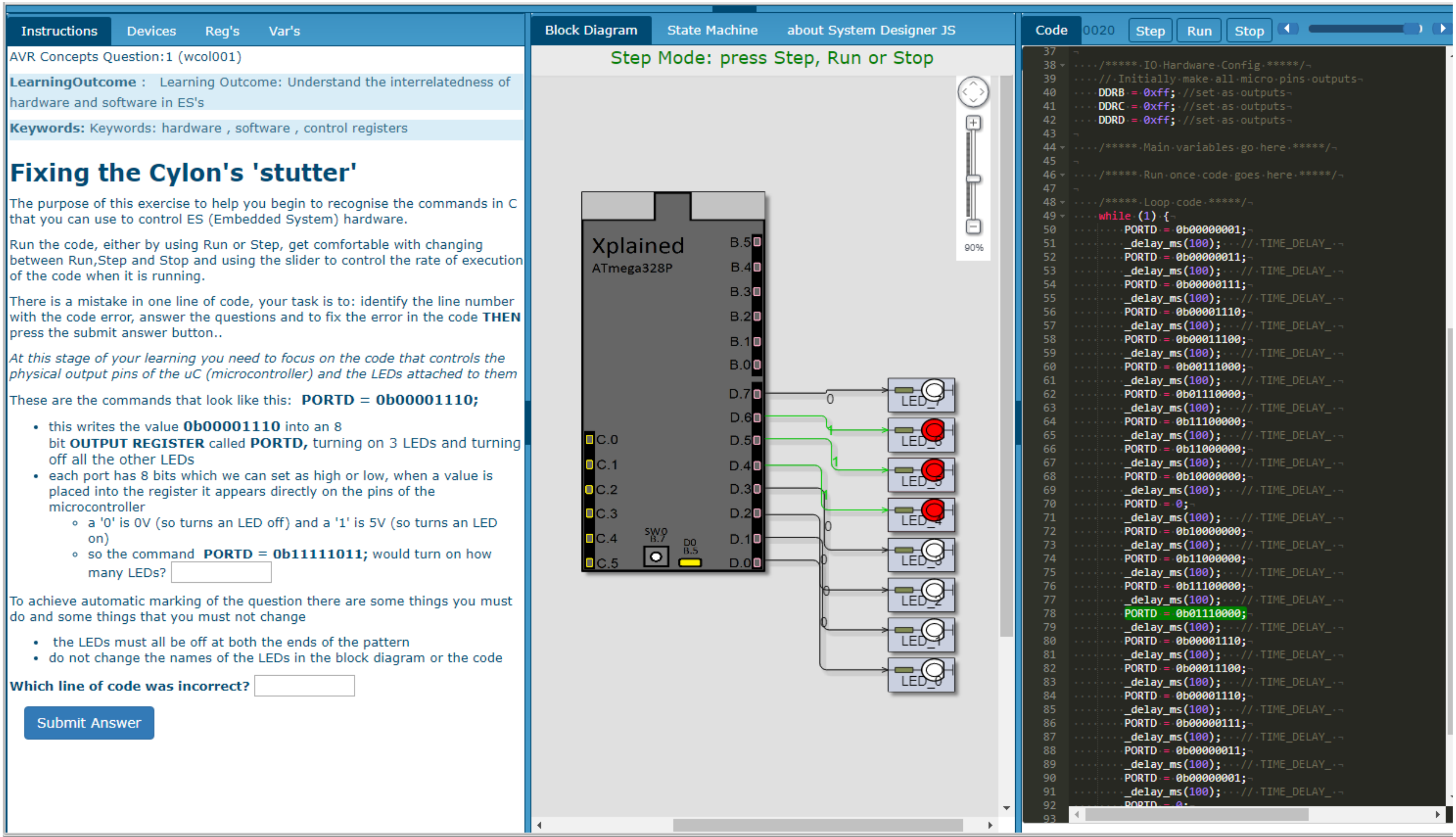


Figure 78: GECKO AVR type question

6.10. Conclusion

This chapter discussed the development of GECKO, a novel knowledge-based educational technology tool and a framework for its use. While the research had begun with concerns around electric circuits, the development of GECKO was informed by a significantly larger perspective on structure and agency across the first two years of electrical engineering. GECKO centred on using visualisation to reveal the hidden epistemic properties of electric potential and charge flow in electric circuits. GECKO was further extended by writing a microcontroller simulator where program code and how it controls hardware are made visible and explicit. GECKO's central process is that of engaging a large body of students with unique questions about visualisation. This is controlled through scripts that can manipulate and capture data from either type of simulator. Educational theory and best pedagogical practices were applied through automating feedback, feed-forward and usage analytics for students.

On its own any educational tool is subject to realignment by users to their instructional discourse centred within the prevailing identities and agency of users, and the structure and culture of teaching and learning. The pedagogic framework was developed to demonstrate the integration of pedagogy with educational technology and to exemplify a regulative discourse centred on educational values. In the next chapter the work carried out trialling GECKO and the framework are discussed in terms of their efficacy on student knowledge.

Chapter 7. Synthesizing theory and practice in a course

This chapter is a discussion about how the pedagogic framework and GECKO were used to redevelop and teach a unit on microcontrollers in a second year course, Fundamentals of Computer Engineering (CompSys201). This is the final stage of the case study, where epistemic knowledge and understandings of agency and structure are brought together. The effectiveness of this process is the fourth research question: What is the effect of an integrated approach to pedagogy and educational technology on student knowledge?

This discussion begins with an introduction to CompSys201 and its place within the scheme of learning in the department, and includes prior results from the course. Next the knowledge, theory and pedagogy used to inform course planning are discussed. This is followed by a discussion of the new learning materials that were generated and how GECKO was synthesized with these to support students developing epistemic knowledge and capability with KT-inferring. Then data from student feedback, assignments, and examination results in CompSys201 along with data from the subsequent project-based design course ElectEng209 are presented and analysed. The chapter concludes with discussions on the efficacy of GECKO and the pedagogic framework for teaching and learning.

7.1. CompSys201 Course redevelopment

7.1.1. CompSys201 background

CompSys201 is a second year first semester course for students in all three engineering specialisations in the department of Electrical, Computer, and Software Engineering (Table 5 on page 116). The course is one of the theory or engineering scientific courses students take as described in section 4.1 and Figure 27 on page 115. The course begins with a seven week unit on digital electronics followed by a four and a half week unit on microcontrollers. The microcontroller unit has four 50 minute lectures and one voluntary tutorial per week, an assignment worth 10% of the course mark and a single two-hour laboratory worth 2% of the course mark. In the final examination, there are four questions on digital electronics, and two on microcontrollers. Students are required to choose five of the six questions. The following semester students take ElectEng209, a project-based design course. This is the difficult knowledge transition discussed in Chapter 4; where students need to change their approach to learning (Case & Marshall, 2004) from a focus on KH-techniques to one of KT-inferring, as these are the KH-skills they need to perform well in ElectEng209. For a number of years student performance in the microcontroller unit of CompSys201 was poor, and there had been negative feedback about student's programming abilities and understanding from teaching staff in ElectEng209.

7.1.2. Student data from CompSys201 and ElectEng209 in 2016

Table 16 shows the examination results for CompSys201 in 2016.

Table 16: CompSys201 Examination Results 2016

2016 Students N= 255	
Part I Digital– number of students answering 4/4 questions	219 (86%)
Part 1 – average score	82.5%
Part II Microcontroller 2/2 – number of students answering 2/2 questions	36 (14%)
Part II – average score	59.1%

There are two important points about these results. First, student's achievement in the microcontroller unit was low with an average score of 59.1% compared to 82.5% for the digital unit. Secondly, agency was strongly evident in the way students chose the five questions to answer in the exam, with 86% of students choosing to do the four digital questions and one from the microcontroller unit. In contrast 14% chose to do both of the microcontroller questions and three from the digital section.

Much of the data collected from students involved observations and discussions with students in semester two of 2015 during ElectEng209 as this course used the knowledge gained from CompSys201. This project-based design course involves students (in groups of four) developing a remote power meter where current and voltage measurements of a load are converted to data using the ADC in an AVR microcontroller. These values are transmitted over an RF link to a CPLD and displayed on a seven segment display. Observations and discussions revealed that students' epistemic knowledge (understanding of what a microcontroller is) and their KT-inferring (how to get one to do something new or different) was very low. Initial dicsussions with students and staff identified four themes:

- engagement with the microcontroller apsects of the project in ElectEng209
- capability with accessing microcontoller resources needed for the project (e.g. using the datasheet)
- capability with researching needed information for the microcontroller part of the project (e.g. softare and hardware techniques)
- ability to use knowledge covered in CompSys201

Observations and discussions were carried out with 64 students during ElectEng209 using the research instrument in Appendix 1, Table 18. This centres on the SOLO Taxonomy (section 2.5.3.3). Data for the four themes is collated in Figure 79. This shows that 37% of the students I observed and discussed with, reported pre-structural understandings, that 46% of students reported single or multiple fragments of understanding and 11% reported epistemic or relational knowledge. The number of students who demonstrated extended-abstract capability was 6%.

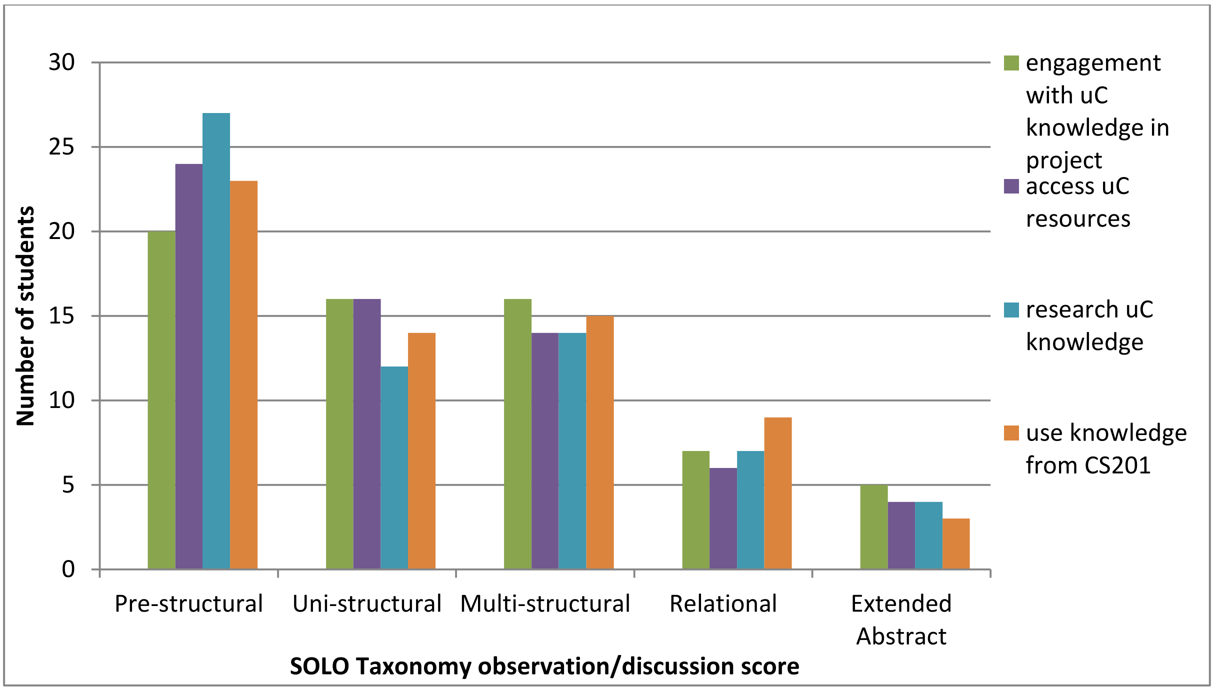


Figure 79: SOLO Taxonomy observation and discussion data for ElectEng209 from 2015

In 2015 when engaging with students in their project work in ElectEng209, they discussed aspects of the CompSys201 course. Many students appeared to have developed a 'get-through' identity described in section 4.6.1, with their study in CompSys201 consisting of using previous papers to identify KH-techniques and KT-propositions in questions that would most likely be in the exam. CompSys201 had a useful-content approach centred on knowledge highly important to embedded systems engineers. These included a disparate range of topics: C memory management, malloc, the heap, the stack, the stack pointer, stack operations, C storage classes, GCC, interrupt vectors, compilation, pointers, bitwise operations, status register, internal timers, program example for checking prime number, data structures, the program counter, and EEPROM use. While important understandings for embedded systems engineers, these remained as fragmented KT-propositions as demonstrated by many students in ElectEng209 who had no concept of what a microcontroller was.

> *The way that part was taught was just a bunch of slides with a whole bunch of code on it, which was like the worst way to teach it. (PhD candidate)*

Several students in ElectEng209 commented about assumptions made in CompSys201 about their level of understanding of what a microcontroller was, as well as a lack of explanations and too few examples being used. Student comments also indicated they lacked an appreciation of where their learning was going or how it was going, when they made statements about not knowing what they were learning the material for, or how it could be used.

7.1.3. Direct instruction and lecturing

CompSys201 is a theory or engineering-scientific course that exists within an established sequence of learning within the ECE department with four lectures per week. The three pedagogical question heuristic discussed in Chapter 2 includes a description of a successful teacher-guided pedagogical practice called direct instruction (section 2.5.2.9). Hattie's research (2009, 2012, 2014) identified it as one of the most successful pedagogies for teaching and learning and clearly superior to less effectual facilitatory practices. Whilst direct instruction can take place in a lecture room environment, it is not accurate to describe lecturing as direct instruction unless it is has the characteristics of direct instruction. These include: being centred around learning outcomes, having a 'hook' for student attention, full explanations of concepts, and a way to check understanding through independent practice in a new context. These principles were an integral part of the pedagogic framework in Figure 60 and formed the basis for redesigning the unit on microcontrollers for CompSys201.

7.1.4. Where am I going? The development of a literacy goal

Previously the unit on microcontrollers had an aim of 'using commercially available hardware and developing a solution using a high level programming language'. While this was the stated aim, students did not develop a solution in the single two-hour laboratory which was committed to the use of an AVR microcontroller. In redeveloping the course I replaced that goal with a literacy goal based on research from cognitive educational theories related to teaching and learning computer programming. It relates to the student developing a mental model for a 'notional machine' (Sorva, 2013) and became 'develop a viable mental model of a microcontroller-based embedded system'.

7.1.5. Where am I going? Development of ALOs (academic learning outcomes)

To become literate, the 'I know where I am going' learner needs learning outcomes that give structure to their learning path. After reviewing academic literature in embedded systems relating to the understandings that new learners need to develop (Koopman et al., 2005; Winzker & Schwandt, 2011) and applying experiences from 14 years of teaching microcontrollers and programming to secondary school students, the ALOs were developed around the important understandings students need to gain during their few weeks introduction to microcontrollers. These are:

- understand the <u>interrelatedness of hardware and software</u> in embedded systems (ES)
- understand the ES as an <u>automaton</u>
- understand the ES as <u>reactive and responsive</u> to its environment
- understand the importance of <u>transparent software practices</u> for an ES
- understand how '<u>fitness-for-purpose</u>' guides microcontroller choice for an ES
- understand the various roles of an IDE
- develop as an engineering student by responding positively to new, challenging and complex (multidimensional) tasks

In section 6.1, the idea of an abstract thought-holder was introduced using the term '*effective'* about electric circuits. The single words underlined in the ALOs above are the 'abstract thought-holders' identified as the KT-inferring goals for students. While the final ALO was not directly taught in the course, it was added to encourage students to begin to recognise what it was that they were becoming during the course and to help them focus away from their inclination toward learning as being reduced to KH-techniques in order to pass or get-through a course.

7.1.6. How am I going? Development of success criteria

ALO's are 'big picture' learning goals, which need concrete form for students; success criteria are the concrete activities of the course and tend to be written with action verbs. Here the experience of the educator becomes important in selecting the key aspects of the domain knowledge that exemplify the ALOs. For this course they were chosen after discussions with staff in ElectEng209 about the epistemic knowledge students required for the project-based design course and subsequent courses. In addition, some of the success criteria are also extended with the ALO, e.g. 'explain polling in relation to making an ES responsive' to purposefully keep students focussed on the academic or KT-inferring goals.

The ALO 'understand the ES as reactive and responsive to its environment' was unpacked into the following success criteria:

- explain polling and its timing limitations
- explain contact bounce issues with physical switches and software de-bounce code
- explain how internal uC timers are used to make an ES responsive and reactive
- setup a uC timer in software to make an uC responsive to an environmental event
- explain how uC external interrupts are used to make an ES reactive
- setup external uC interrupts in software
- describe the significant characteristics of an internal ADC
- describe the use of a sensor in a voltage divider circuit
- identify issues relating to dynamic range and quantization with analog sensors
- explain issues of an ES's responsiveness with regard to polling, blocking and interrupts.
- describe a software state machine in terms of states, actions, conditions and transitions
- turn a state machine model into C code, using while / switch software pattern

7.1.7. Epistemically scaffolding learning opportunities

The pedagogic framework (Figure 60 page 206) was developed for using GECKO within a course; this captures the important aspect of developing KH-skills and not just KH-techniques. As presented in section 2.2, the development of KH-skills requires epistemic knowledge and capability with KT-inferring as well as proficiency with KH-techniques. These requirements are unpacked into specific success criteria and are the major teaching segments in the development of student knowledge. It is important that these are not treated as something that students are told, but that epistemically scaffolded learning opportunities are appropriately designed to engage students with the success criteria. In redeveloping the unit, this was achieved through a blended summative-formative assignment[8]. To design an epistemically scaffolded learning opportunity requires knowing where the students are starting from and scaffolding toward the success criteria using a sequence of manageable chunks. Figure 80 is one example of two KH-skills questions from the assignment about ADC (analog to digital conversion) that required substantial scaffolding.

[8] The CompSys201 assignment can be found online at www.xplainittome.com

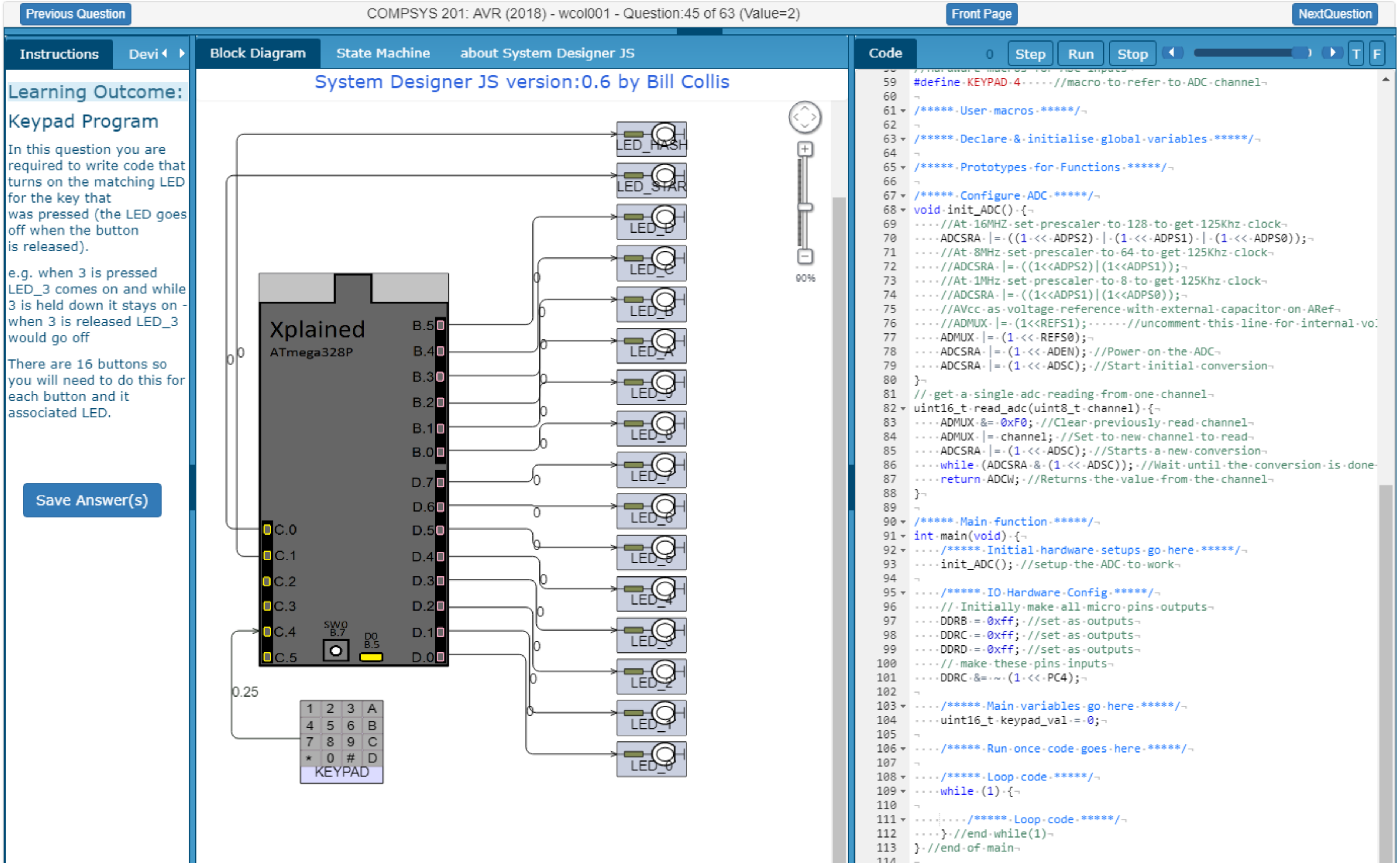


Figure 80: KH-skills ADC question

Figure 81 is the concept map developed for the epistemic foundation for these two questions; one of these is the keypad question in Figure 80. At the base of this map are two important starting points for students: binary number conversions and the voltage divider. Whilst this research broadened considerably to encompass the fuller context of teaching and learning, at its core is the need for students to have a sound episteme of fundamental electric circuit knowledge such as the voltage divider.

These two foundations were covered previously with students; binary number conversions in ElectEng101 and the first part of CompSys201, and the voltage divider in ElectEng101 and ElectEng202. The teaching sequence was scaffolded to begin from these starting points by refreshing students' knowledge with exercises relating to number conversion and voltage dividers and importantly to encourage students to see their different courses as interrelated. The sequence progressed through a hierarchy of questions in the assignment that cover the chunks required to build progressive understanding.

Having two high level questions was viewed as important in developing abstract knowledge; since having only one question might cause students to consider the learning not to be generalised but contextually related to either the keypad or the LM35.

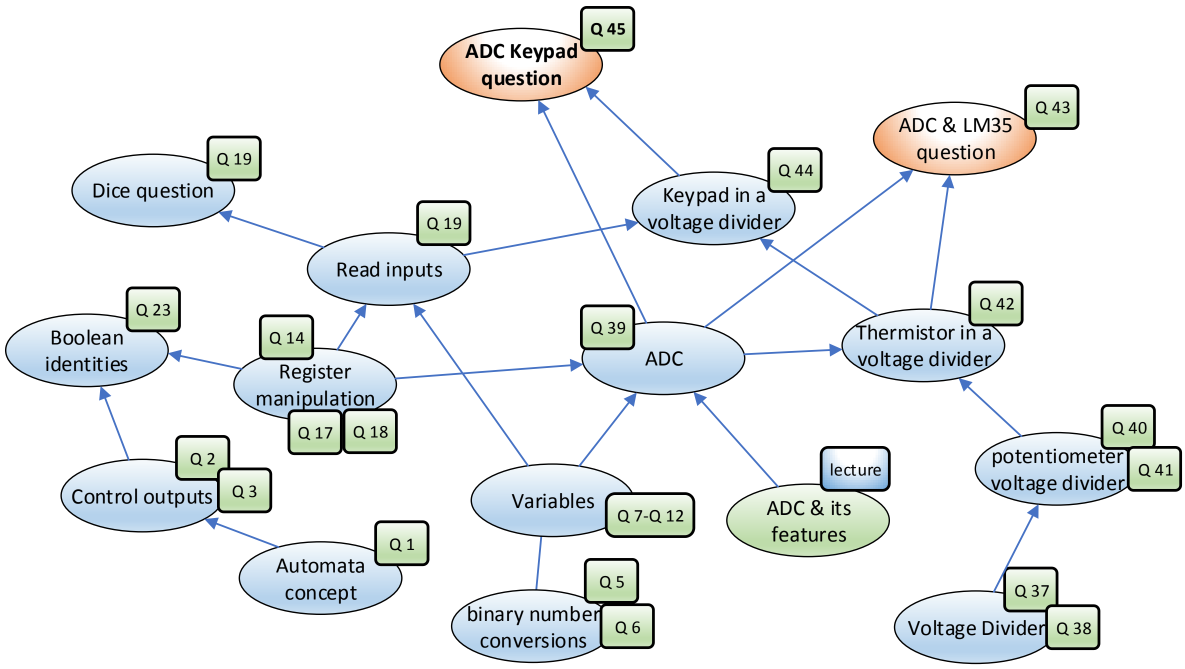


Figure 81: Episteme development for scaffolding questions for ADC knowledge

7.1.8. Microcontroller timer KH-skills development

A second example of epistemically scaffolding learning is the coverage of microcontroller timers. Microcontroller timers are complex and with each iteration of microcontroller development by a manufacturer, the capability of timers seems to only become more elaborate. In the lecture and assignment, rather than focus on introducing a definition for a timer and a formula for calculating timer values, i.e. something which is typical of a useful-content approach centred on KH-techniques, a sequence of questions in GECKO was developed aimed at building students epistemic knowledge of timers. This began with how microcontrollers' responsiveness to the external environment is limited by polling and introducing two contexts (anti-skid braking and petrol engine ignition) that require microcontrollers to respond in real-time. This was followed by building an epistemic understanding of the timer in an AVR. This involved a sequence of eight questions in the assignment that were developed as chunked understandings that the student could be scaffolded through to gain a full understanding of how an AVR microcontroller timer worked. No formula for calculating timing events was given but it was developed in stages during the lecture. This was deemed to be crucial for students to develop abstract generalised understandings of microcontroller timers, as manufacturers extend timer capabilities and features from time to time and also different manufacturers build timers into their microcontrollers that have different features and capabilities from those in the AVR. A single formula for one type of AVR timer was seen as inadequate and inappropriate for tertiary academic abstract learning. Through developing staged understandings of how one timer worked the students would hopefully be able to learn for themselves how to do the same for other timers.

The sequence began with establishing prior knowledge from the first part of the course – a simple digital counter. Figure 82 which a screen capture of the dynamic simulation from the question for the counter. The sequence of questions develops in eight scaffolded chunks culminating in Figure 83, it is the last circuit exercise for timers and demonstrates a working simulation of an 8 bit AVR Timer. In each of the eight questions in the sequence students are given random parameters such as frequency input and divider values to work out the output frequency or timing.

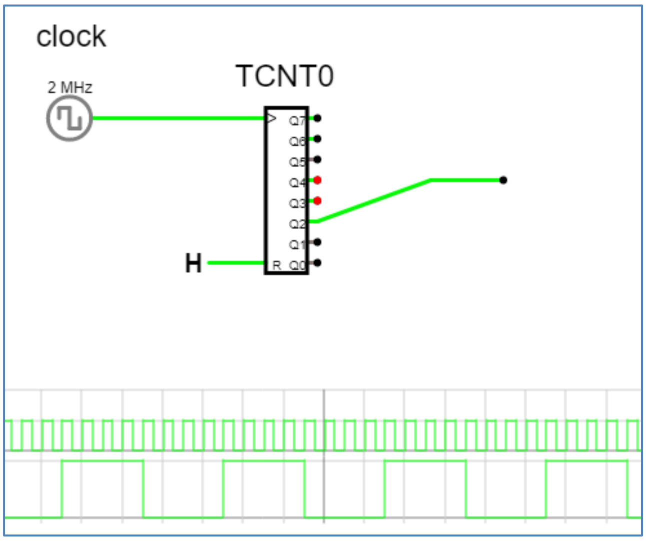


Figure 82: Simple counter circuit - exercise #1

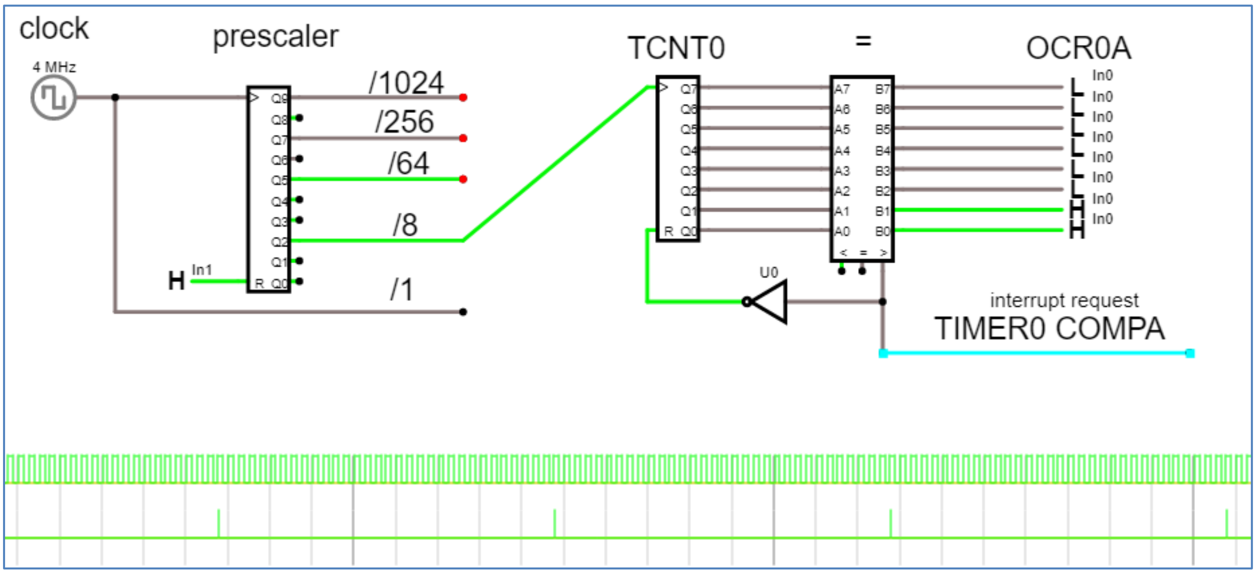


Figure 83: Full AVR timer circuit - exercise #8

In this way, GECKO was used to build students' epistemic knowledge of how the timer device works, as well as give students the opportunity to practice these understandings. The development of a KH-skills question for timers was not straight forward as GECKO cannot simulate timing (although the simulator has a tick counter which may be repurposed for this in the future). This question involved the operation of traffic lights with timing controlled by a timer. Figure 84 shows the block diagram and code for the question in GECKO and in Figure 85 the corresponding state machine diagram editor view for the traffic lights problem from GECKO is presented.

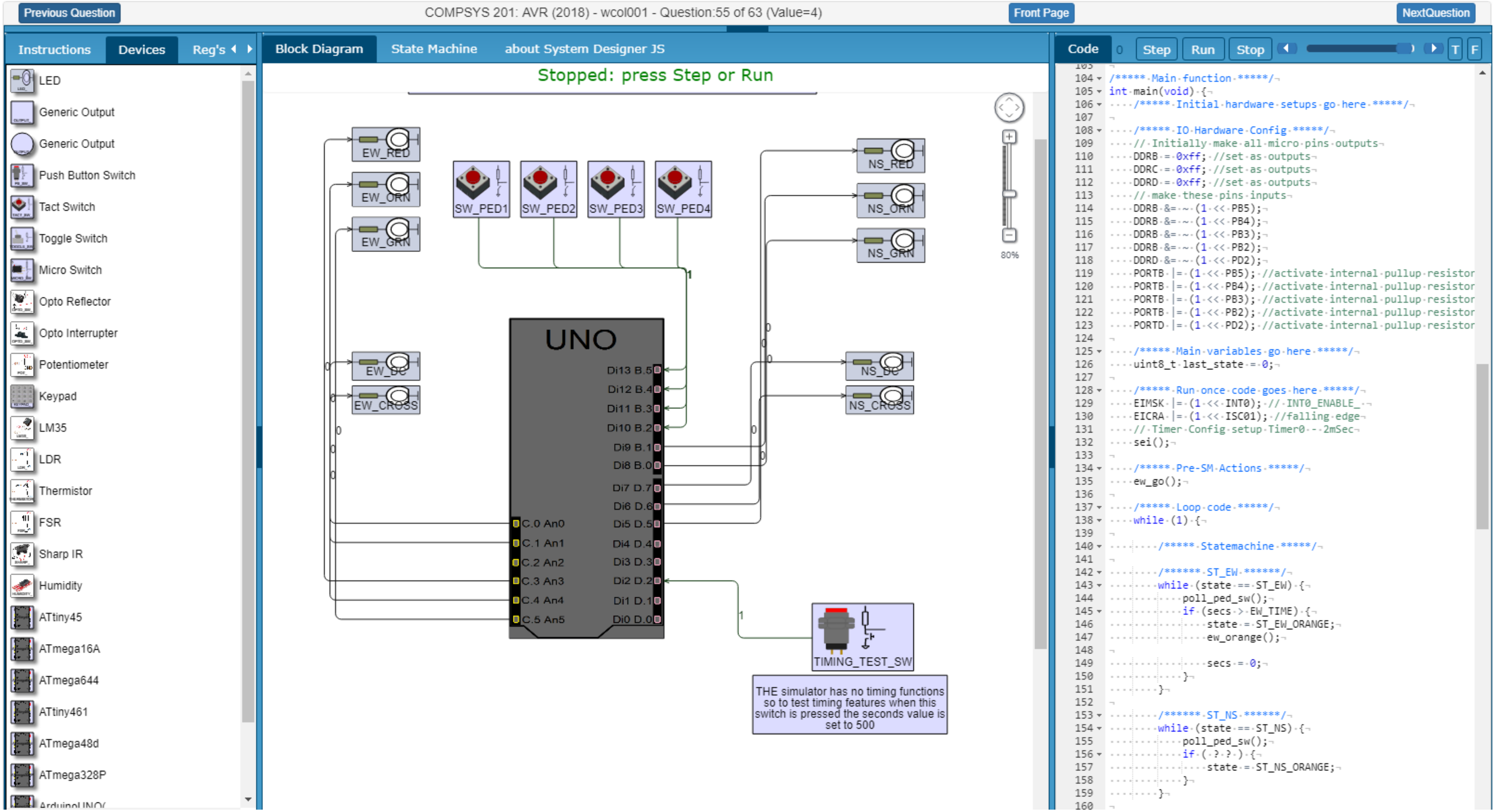


Figure 84: KH-skills timer question (block diagram view)

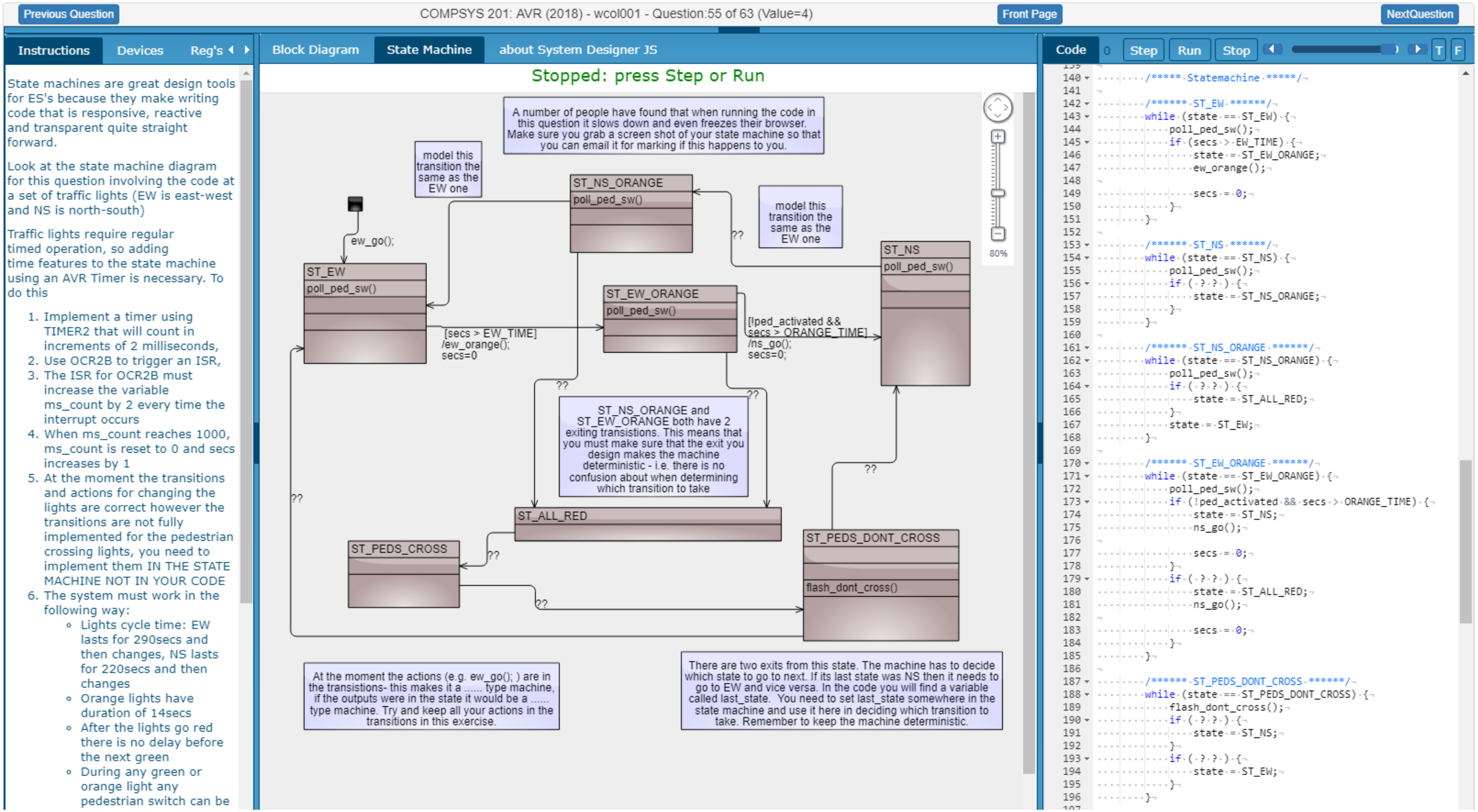


Figure 85: KH-skills timer question (state machine editor view)

The integration of a state machine editor grew from personal experience with teaching programming of microcontrollers to secondary school students. It was found that for the majority of students, the step from trivial or uni-structural code to non-trivial or relational coding practices was very challenging. Consequently their ideas for solutions were more advanced than their programming capability allowed; this then required too much teacher intervention in fixing student code. A drag and drop state machine editor that automatically produced program code for the AVR was produced and later this was extended into a standalone application that included a simulator as well as various other tools. This is described in the Master of Engineering thesis (Collis, 2013). The use of state machines is a recognised design pattern for embedded system software and was found to be transformational for school students' programming capabilities. The use of state machines is also synergistic with the first section of CompSys201 which focusses on digital circuits, using FPGAs and VHDL and the RTL design process.

The episteme for the KH-skills timer question is shown in Figure 86. It requires not only KT-inferring about timers, but the development of KT-inferring and KH-skills about the concept of state (question 4) and state machines from lectures and exercises.

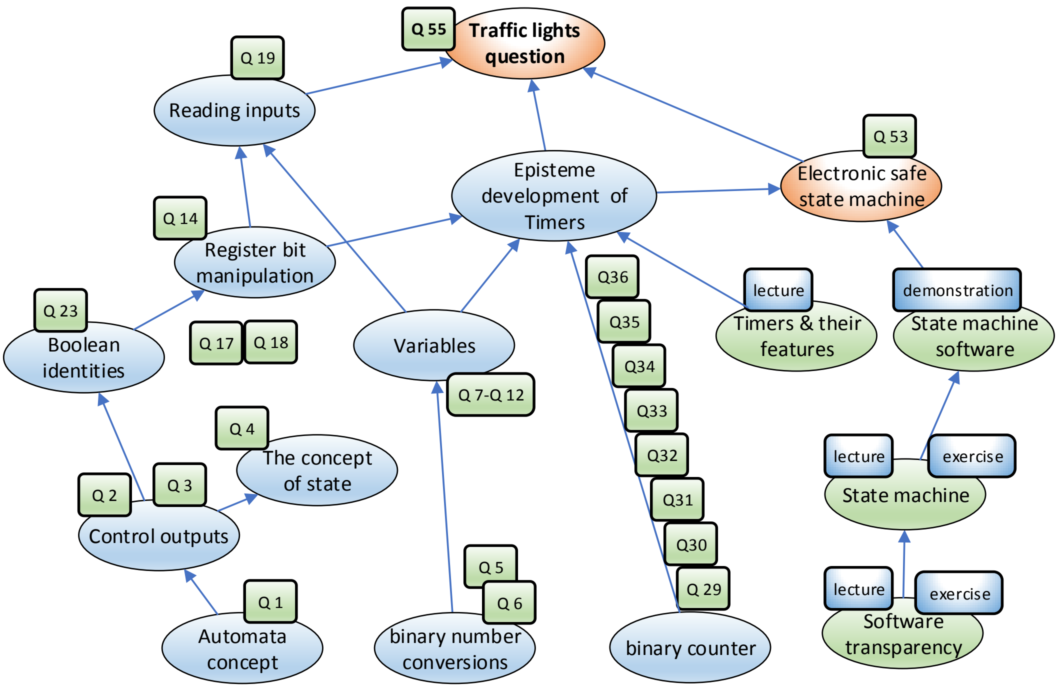


Figure 86: Episteme for timer KH-skills question

7.1.9. Demonstrations and KT-inferring

Demonstrations using specifically designed teaching artefacts were integrated into every lecture. Figure 87 shows a quiz game controller built to explain the abstract learning outcome of an embedded system being reactive and responsive and the success criteria to do with explaining polling. Polling in a computer system relies on the exact same abstract thought-holder 'polling' that political or telephone surveys do - the regular checking of something to become informed of its state and through KT-inferring determine what to do in response to that state.

Figure 87: Quiz game controller – demonstration of polling to develop epistemic knowledge of polling

This learning artefact operates at different levels. In terms of direct instruction, this is a useful 'hook' to engage student interest, operating at a social realist 'actual' level. This was recognised by one observer who on two different occasions referred to these teaching artefacts as 'toys'. They were, however, designed to operate at the level of the 'real', as rich learning contexts through which epistemic abstract knowledge could be explained and be seen in action. Seeing was extended from the physical artefact through simulation with GECKO, to demonstrate the hidden abstract nature of polling. Student learning about polling involved a four-way process of explanation, at the same time as physical demonstration and simulation in the lecture, and an assignment question (Figure 88) to develop epistemic knowledge.

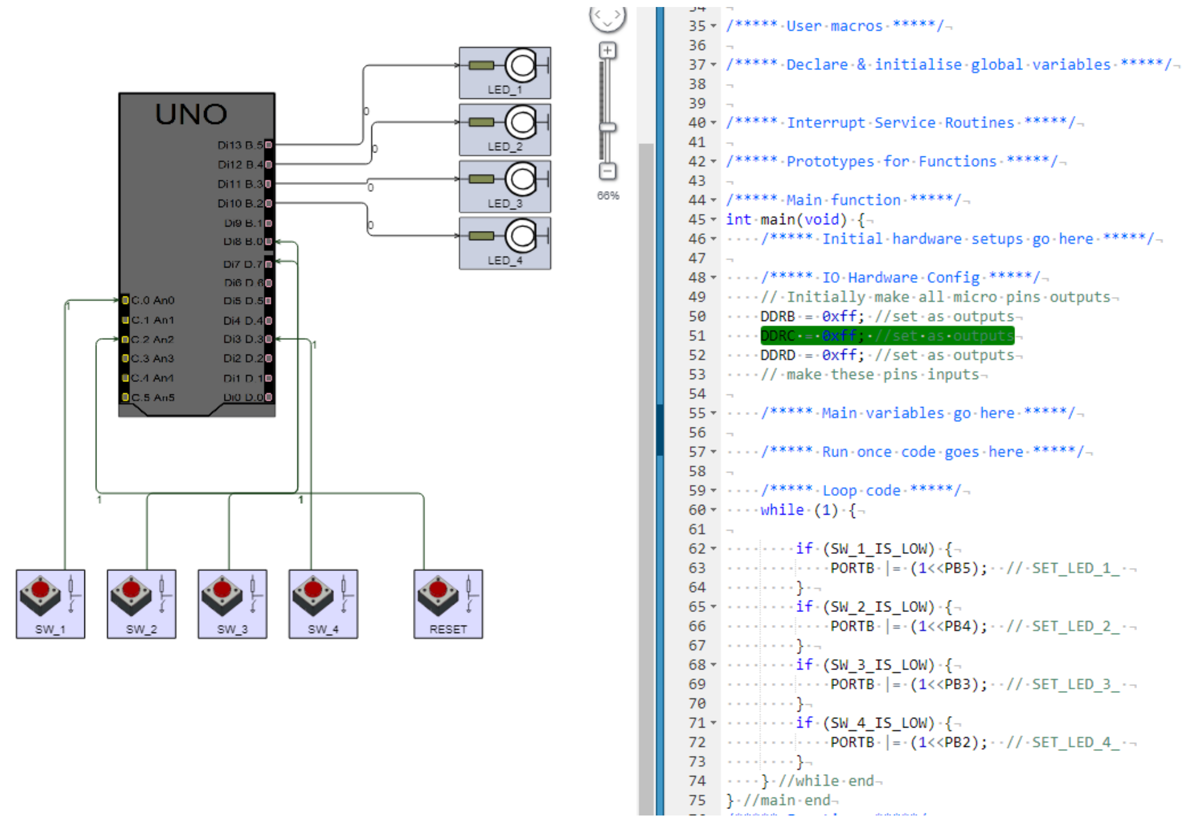


Figure 88: Quiz game controller simulation – epistemic knowledge of polling to support KT-inferring

The explanations were also more than explanations of the epistemic knowledge of polling; they were to connect this knowledge to the other knowledge in the domain that provides the necessary boundary conditions for an informed use of polling and to developing KT-inferring about its use.

7.1.10. How am I going? - Formative feedback using educational technology

In section 6.6 the general feedback and feed-forward capabilities of GECKO were explained, in this section feedback is described in relation to learning to develop software for microcontrollers. Hattie (2009, 2012, 2014) found that formative feedback has one of the most powerful effects on student learning. However, when learning to program, feedback is not always easy to interpret as the chain of events within a computer are invisible and consequently understanding of the development process involved with an ES is highly obfuscated and difficult for novices to understand.

Figure 89 is a diagram of the process of developing code for an embedded system. It begins with students writing program code (Figure 89 #1) where there is immediate feedback relating to syntax errors (#2). Feedback also comes in the form of errors after compilation (#3), which is an aspect which novice learners have a great deal of difficulty interpreting (Hartmann, MacDougall, Brandt, & Klemmer, 2010).

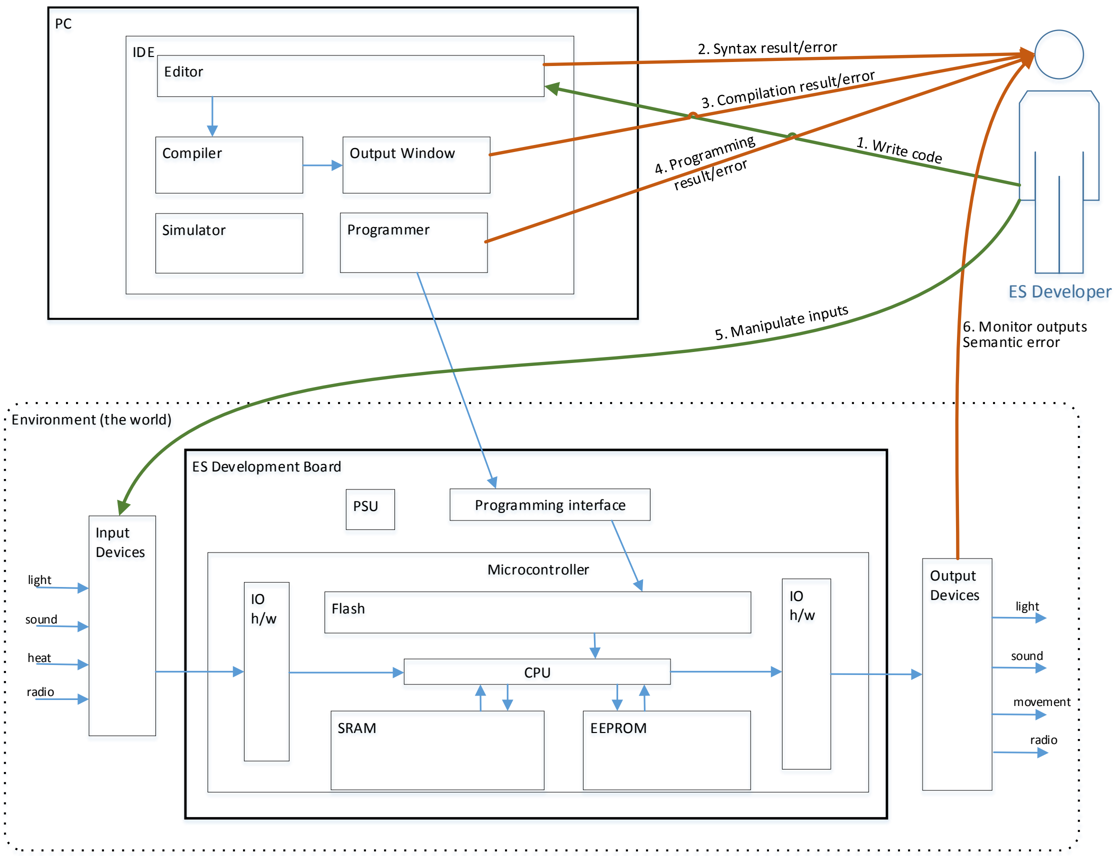


Figure 89: Interpretive process for debugging errors in embedded systems

If the code compiles and then fails to upload (#4) novice learners also have significant difficulty interpreting what is wrong. Once compiled and code is inside a microcontroller, the interactions between the inputs (#5), the code and the outputs are completely hidden from the student and semantic errors (#6) are often difficult to analyse as the code is not just hidden but reactive and running in real time. Previously when teaching novice learners, they were found to mistake the source of different error messages (2, 3, 4 and 6). This led to the diagram in Figure 89 being developed for use with students. The use of this diagram with students is an important part of giving students KT-inferring related insights into the KH-techniques they are working with.

Understandings about what happens within a computer is a significant field of research which often involves the use of simulation with novice programmers (Naps et al., 2002). Much of this relates to the slow running of programs (or algorithms) to see how the code works step by step, thus assisting with the development of students' mental models. The benefits to students are powerful because the process becomes transparent allowing the visualisation to make clear the hidden relationships that exist within the system. Within an ES, one significant relationship is the manipulation of values in registers. Figure 90 shows how students must learn to interpret a change to a register either due to an input being manipulated or in response to a line of code in the program.

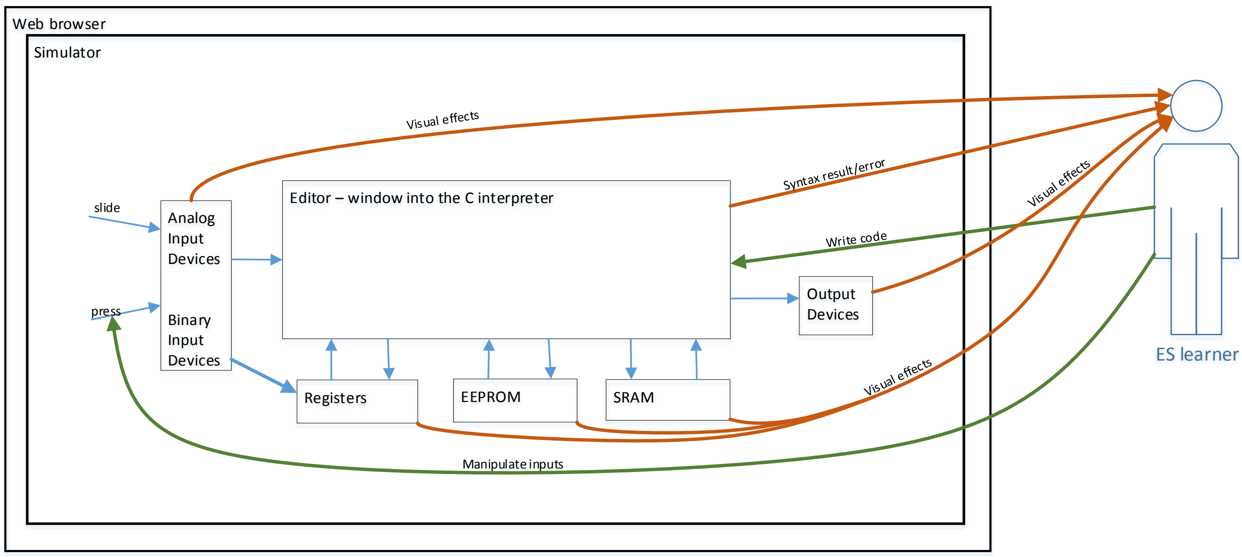


Figure 90: Interpretive process for ES simulation

Instructions Devices Reg's Var's

Addr	Name	Val	Val(bin)	Val(dec)	Description
0x23	PINB	0x00	0b00000000	0	Port Input Pins
0x24	DDRB	0xFF	0b11111111	255	Data Direction Register
0x25	PORTB	0x00	0b00000000	0	Port Data Register
0x26	PINC	0x00	0b00000000	0	Port Input Pins
0x27	DDRC	0xFF	0b11111111	255	Data Direction Register
0x28	PORTC	0x00	0b00000000	0	Port Data Register
0x29	PIND	0x00	0b00000000	0	Port Input Pins
0x2A	DDRD	0xFF	0b11111111	255	Data Direction Register
0x2B	PORTD	0x80	0b10000000	128	Port Data Register

Figure 91: AVR simulator register view

The register view for the microcontroller is shown in Figure 91. While these are features found in modern hardware debuggers and simulators (such as that in ATMEL Studio) these tools are often complex and difficult for novice learners to navigate and consequently to make inferences from. GECKO simplifies this for novice learners by showing them full names of registers and all three number representations.

7.1.11. How am I going? Automating semantic-error feedback

While making the software processes explicit is important for students, their experience with interpreting semantic errors is often limited. From experience in practical classroom situations it is possible for a teacher to provide assistance to up to 25-30 students. None-the-less in these practical situations it is too easy for teachers/GTAs to take a parsimonious approach to feedback typically by indicating to students the general (or specific) location of the error using comments such as 'have a look at that line of code there'. This process ultimately provides little benefit to students.

A feature was built into GECKO to address this. An automated feedback system was designed to provide assistance to students, one based upon experience in secondary school classrooms when dealing with students' semantic code errors. In GECKO when student code is run, a set of states are generated, and these are then compared to a correct set of states stored in the server. An error is indicated when these are different. Initially the student is presented with a single line error comment: 'There was an error, please check you program'. For those students close to the solution, they will go on and identify the error themselves and fix it. After a second erroneous attempt, the feedback becomes 'There was an error, have you thoroughly understood the specifications given in the question?' This attempts to draw the student away from a code or hardware error to reconsider what is not correct at a system level. This feedback was designed to mimic the previously used approach in one-on-one situations with students in a classroom setting. Future research is required to understand any benefits from this.

After a third error the student is presented with feedback that describes the error in terms of the specification for the program, i.e. what occurred on the output in relation to an input change. The automated testing feature does not indicate the line of code that the error was found in (although that is possible), but it indicates the incorrect state of the system and the condition that led to it. This focuses students on the function of their code and semantic or logic errors, as in Figure 92 where the error states what went wrong in terms of inputs and outputs.

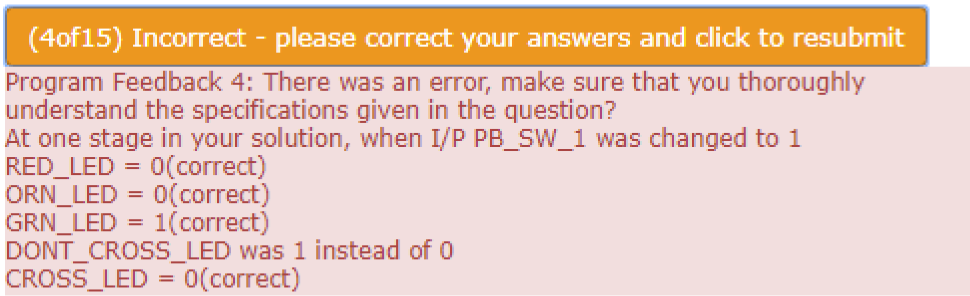


Figure 92: Question27 error feedback

This testing and feedback process allows students to solve complex problems in their own way, as testing the states of a system does not confine students to a particular way of thinking or KH-technique. This is useful in terms of one of the learning intentions for the course which is to 'develop as a learner/engineer by responding positively to new, challenging and complex (multidimensional) tasks'.

7.1.12. How am I going? - Feedback cues

Hattie and Timperley (2007) found cues were one of the most effective forms of feedback as they sensitise students by capturing and directing their attention which developed their search and strategizing skills. This type of feedback was built into the assignment question in Figure 93. A cue (a change in variable type) is used to draw student attention to the theory and potential problems discussed about variables in the lecture.

While this question asks students to make a change to a display system, its real purpose is more subtle. It is about the correct use of variable types in C, a crucial understanding for embedded systems engineers. Types were introduced in a lecture and case studies were presented where type errors had caused loss of life or major cost. Type usage was then practiced in the assignment via questions on type choice, overflow and underflow. The question was developed to investigate students' KH-skills. It uses three LEDs to display a number to a user as a sequence of flashes, with each LED representing a different digit. For example the number 21.7 would be displayed as 2 flashes of LED_TENS, one flash of LED_ONES and 7 flashes of LED_TENTHS.

Students were required to change the simulation from displaying numbers in the range 0 to 99.9 to the range 0 to 99.999.

The cue (subtle hint) was that the provided program used an 8 bit data type, however to display 5 digits would need a larger data type. The cue however, disguised the real problem in the question. The data type used in the 3 digit example was an unsigned byte which only has a capacity for numbers in the range 0 to 255, and the code never tested values from 256 to 999 (see the test array in the question). The test values also did not test numbers in the required range up to 99999, so students could simply replace the 8 bit data type with a 16 bit data type and the code would work but be incorrect. The code however required a 32bit data type to work correctly with five digits numbers over 65,535. In this way GECKO provides a safe environment for failure (as a well-planned laboratory experience could); following the adage by Mark Twain that 'good decisions come from experience and experience comes from making bad decisions'.

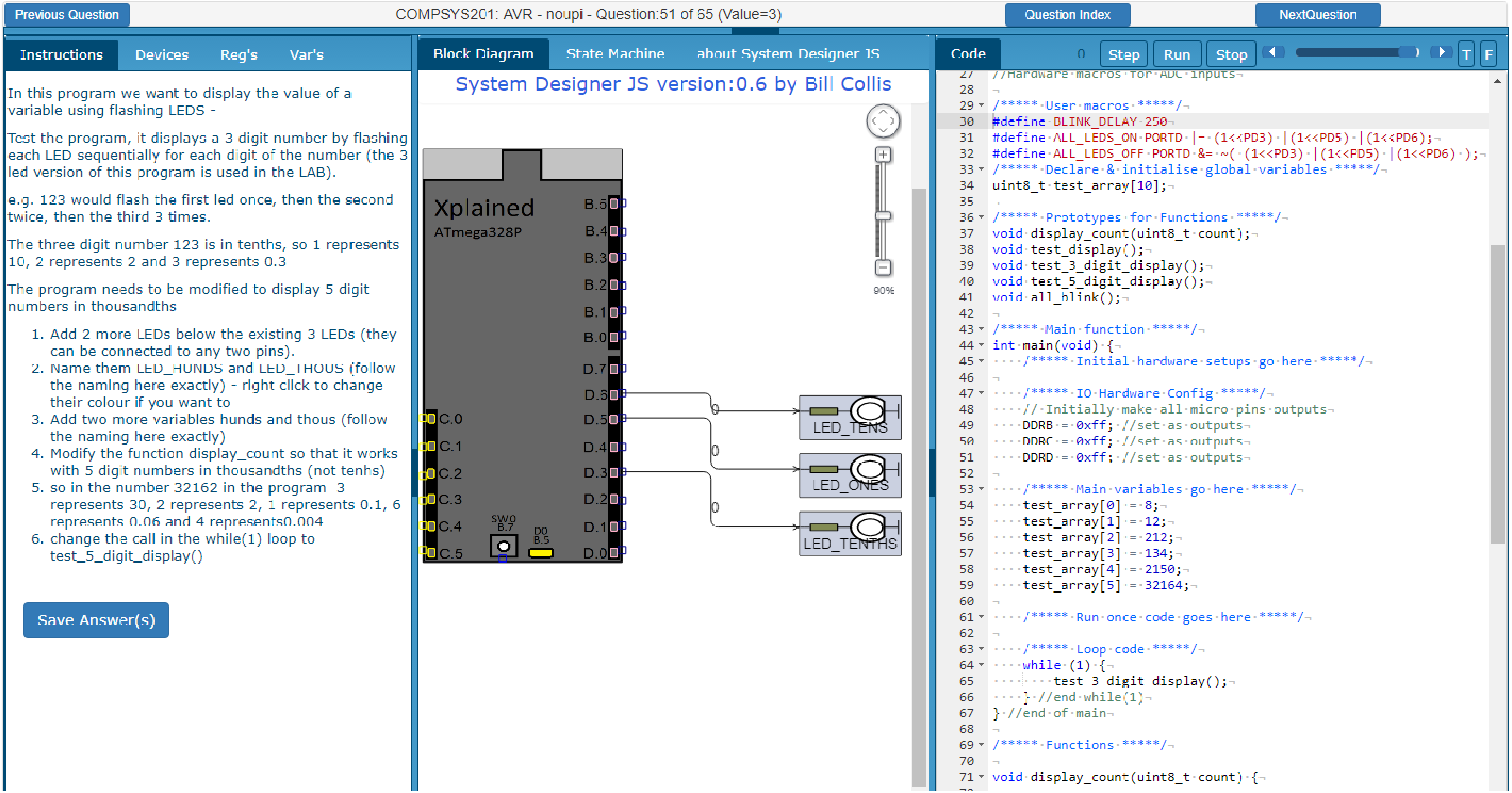


Figure 93: KH-skills assignment question on variable types

7.1.13. Where to next? – Student metacognition and learning dispositions

A number of strategies were employed to encourage students to develop positive dispositions towards their learning: overt use of the course goal and learning outcomes in lectures, lecture notes and assignment questions. Also students were regularly reminded to begin the assignment. Analytics integrated into the assignment front page also show students their own progress in comparison to that of all students in the course as shown in the right hand column of Figure 75 on page 220.

7.1.14. Where to next? – Challenge

Much learning in the first two years of electrical engineering was found to be KH-techniques and KT-propositions based with limited opportunities for students to develop KT-inferring with epistemic knowledge. Changes to CompSys201 centred on changing this by introducing challenges to use KT-inferring; one instance of this involved use of the microcontroller datasheet. In 2015 in ElectEng209 this had been one of the four themes identified with student knowledge. Students needed KH-techniques with the datasheet, however this needed to be underpinned by epistemic knowledge of registers, bit masking, macros etc., otherwise they would not be able to use it for KT-inferring about things they did not know.

For instance in question 50 of the assignment, students are asked to set register bits for the WDT (Watch Dog Timer) with no teaching about the WDT given to them in lectures. This required students to engage with the datasheet and an external resource on their own to identify the answers to the questions. This was repeated in the examination, where students had not been taught anything about the analog comparator in the microcontroller or even that one existed. They were given the section of the datasheet and had to interpret it to answer the question on setting up the registers; 74% of the students got full marks for it.

7.1.15. Where to next? – Turning summative into formative

Students often do not pick up marked assignment scripts to get feedback about their work; consequently they miss out on important learning opportunities. Using a mix of formative and summative questions in the assignment meant that students would not receive any immediate feedback on the summative questions. To ensure that students engaged with feedback on these questions and recognised the value for their learning, results were collectively analysed to identify concerns and written feedback was prepared and presented in a lecture rather than online. In this way students were encouraged to improve their thinking about assessment. Two examples of feedback attached to summative assignment questions (questions 45 and 54) are in Appendix 6.

7.2. Data collection and analysis

In section 3.5, credibility and dependability were presented as the basis for establishing the trustworthiness of qualitative research. These criteria were central in the decisions on how to investigate any changes to student knowledge due to the course changes in CompSys201. While this included collecting data from CompSys201, it primarily centred on investigating whether that knowledge had become usable in the subsequent project-based design course, ElectEng209. In 2015 this had been the gap identified, and to measure the efficacy of any changes, it was felt that a similar observation and discussion process with students in ElectEng209 would be advisable. In 2015 data were collected using a student observation template in Appendix 1, Table 18 which was based upon the SOLO Taxonomy. In 2017 data were collected from ElectEng209 through self-reporting using the form in Table 20 in Appendix 1. The form was given to students in one laboratory session; 55 students completed it and discussions were carried out with 20 of these students. One change was made to the form in 2017, where six categories were used instead of the five used in 2015. This was in effect to split the previous fifth category into two parts to create more differentiation at the higher levels of the Taxonomy. Sample forms from two students are in Figure 99 on page 280 and Figure 100 on page 281 in Appendix 1.

7.2.1. Results from using GECKO in conjunction with the pedagogic framework in CompSys201.

To capture aspects of student knowledge and agency, results from the GECKO based assignment and examination were collected and analysed for the 218 students who completed CompSys201 in 2017. The assignment consisted of 61 mixed formative and summative questions worth 10% of the course grade; the list of questions in the assignment are in Appendix 6. After the analysis of student agency in ElectEng101 in terms of the marked versus unmarked FCCTs, it was clear that formative questions had to be worth marks to students so that they would engage with the epistemic foundation they needed for more complex problems. Of the 61 questions, 46 were formative, and worth 6.5% of the course grade, and 15 were summative, and worth 3.5% of the course grade. Of the 218 students, one chose not to access the assignment, and 11 students did insufficient work in the assignment to get 50% in it.

Another result relates to student behaviour in the end of course exam. Table 16 (page 232) shows the results from 2016, where 86% of students had answered all four questions relating to the digital unit in the course before choosing one of the two microcontroller questions. In 2017 student behaviour reversed with 86% of students choosing to answer both microcontroller questions and three of the digital questions. At the same time, average scores in the examination changed with averages for the two microcontroller questions moving from 59% in 2016 to 69% in 2017. This appears to indicate that students were more confident in their knowledge of microcontrollers and more prepared to tackle questions that were previously deemed too difficult.

In the CompSys201 assignment, the assignment mark and the mark for the microcontroller questions in the examination were strongly correlated, $r=0.60$, $p<0.01$ $N=217$. The graph is in Figure 94.

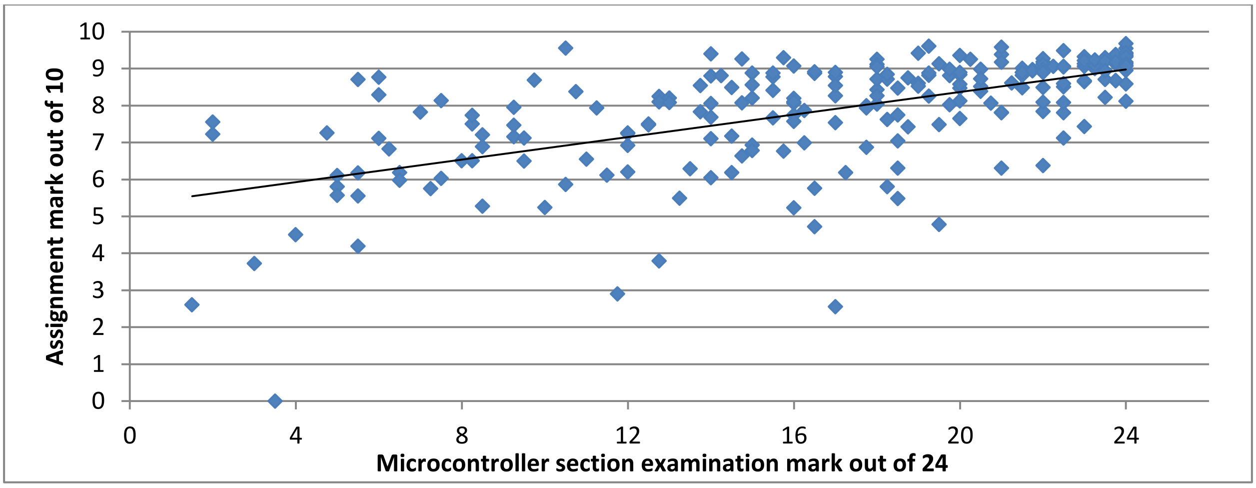


Figure 94: Assignment mark versus examination mark for AVR questions in 2017

This is in contrast to the correlation between the ElectEng101 assignment and examination scores which was r=0.30 (Figure 36 on page 135).

To investigate any effect of student agency, the data were used to identify any relationships between the timing of when students did the assignment questions and their mark for the microcontroller section of the exam. Figure 95 is a graph of the number of questions answered per day of the assignment. In total 41,261 questions were answered by 217 students, on average students answered each of the 15 summative questions once and the formative questions 3.7 times. The data also shows that 21,202 or 51% of the questions were answered in the last 4 days of the assignment. This suggests that marks are important drivers of student agency, which corresponds to the results from the FCCTs.

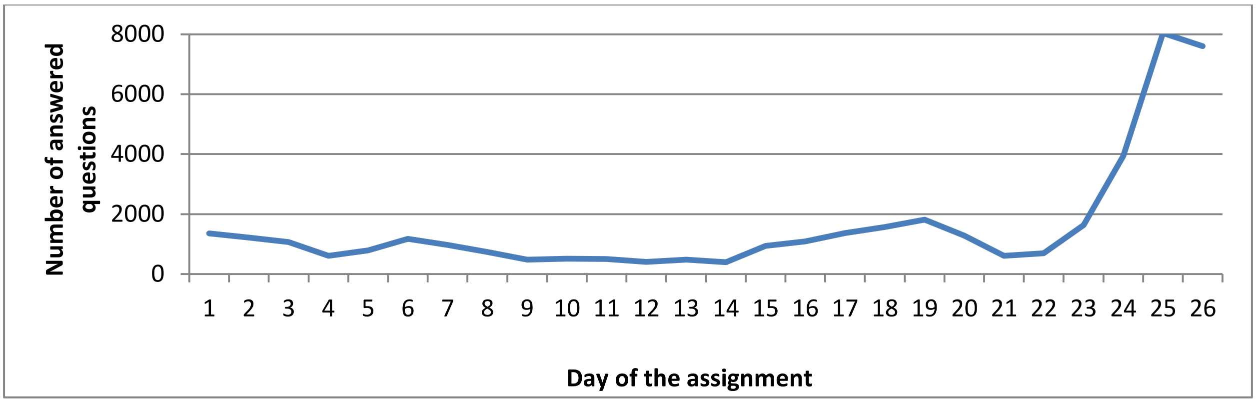


Figure 95: Number of assignment answers per day of the assignment

In Figure 96, the examination mark was plotted as a function of the day the first question was undertaken in the assignment. Although the correlation is low, Pearson's r=-0.38, p<.01, and there is significant scatter of the results, the graph shows a cluster of 79 students (green highlight- upper left) with passing examination marks who began their assignment in the first two days. There is also a smaller cluster of 14 students (brown highlight) who did not pass the microcontroller questions in the examination who began their assignment in the last two days. The graph shows that there are also students who did well in the examination questions yet left the assignment until the last 2 days and that there are some students who did not do well in the examination questions yet began the assignment early. This result indicates that future investigations would be worthwhile around breaking the assignment up into smaller more regular assignments. This is similar to the result for the FCCTs in 2016 when they were worth 4% of the course mark (section 5.5.1, page 185).

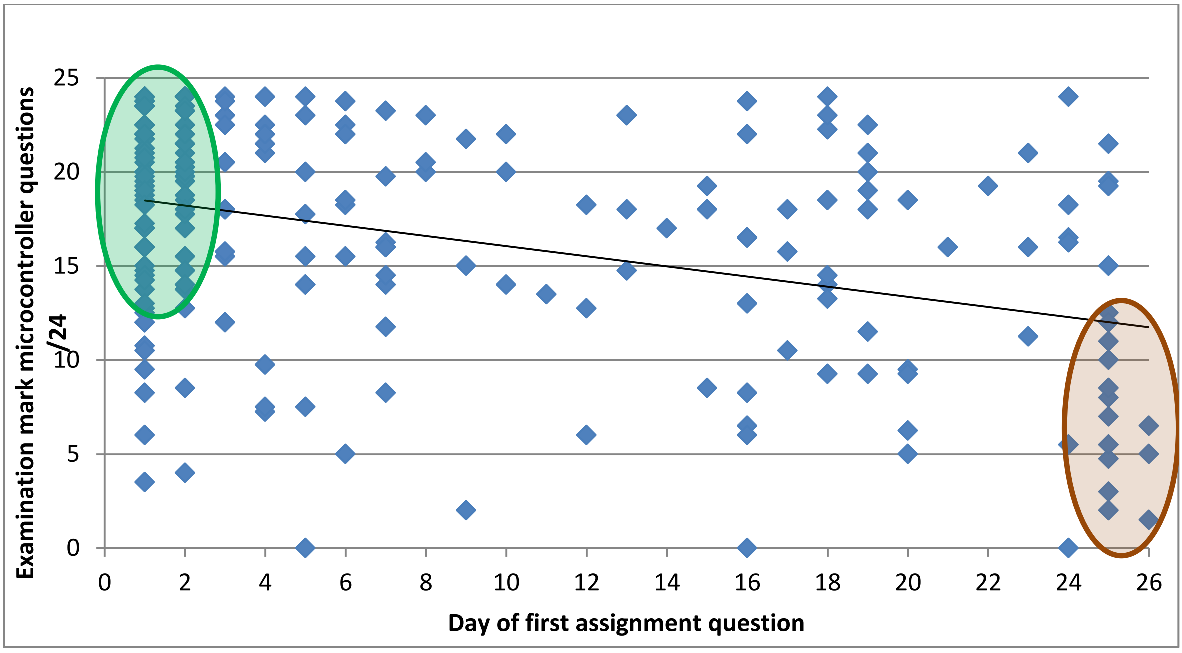


Figure 96: Examination mark as a function of day of first question answered in assignment, with trend line.

7.2.2. Student voice

During the third week of the microcontroller section of the course, students attended the laboratory session for the AVR. Over three days I briefly spoke with each of the 199 students who attended the laboratory to provide feedback about how they were finding the microcontroller section of the course, asking them to comment about whether the material was understandable and any difficulties they were having. The majority (174) commented that it was understandable, with 25 of those adding it was 'fun' or 'loving it'. The other 25 of the 199 students indicated that it was difficult. Comments made by students were written down and covered many aspects of the teaching about microcontrollers. Many students made comments relating to the course goals of develop a 'viable mental model' of a microcontroller based embedded system, and improving the experience of learning.

<u>Academic learning outcomes</u>

> *It's not like other courses you know what is expected of you;*

<u>Epistemic knowledge development</u>

Completely new, kind of easy to understand

Being taught C coding for micro-controllers without just making the assumption we know how to do this

Simulations make hardware and software understandable never done it before

<u>Visualisation as contributing to epistemic development</u>

I can see C in action

Connecting code and hardware was good

So much fun you can see the thing working

Neat seeing how hardware and software interact

Really helpful to see simulations

<u>GECKO assignment environment:</u>

Assignment fills in the blanks, makes good connections

I can do assignment questions on the bus, yeah!

I do the assignment on the train

Assignment is fun not like …

Assignment is well set out easy to get through

Simulations make it well worth doing the questions online

I definitely think it was one of the best learning tools of any course

I like the analytics, showing me what I have and haven't done

<u>Motivation</u>,

Easier to do work when I am interested in it

I really did find the microcontroller simulator helpful.., after working on all the code and state machine, to see it come together and actually visually use it is satisfying and exciting. Overall, I enjoyed this part of the course and found it exciting and interesting to see the world from an embedded systems perspective.

<u>Course notes:</u>

Notes make lectures interesting keeps me awake

Book makes you pay attention better

<u>Context-of-use,</u>

Enjoy simulations next to hardware cool

Good to go back and forth between hardware and software online

It let us practically understand the things we were learning which I think was very important because the content is something that I personally found difficult to get my head around due to all the technical terms

<u>Direct instruction</u>

Being shown the thought process our lecturers use when they solve problems

Seeing stuff do stuff is great

Gadgets and devices were super helpful to see what was actually going on at the physical level

Real world examples which seemed kind of silly but ended up being really useful

Practical you can see that you can do stuff with it

Examples applicable, easier to imagine

<u>Experience of learning,</u>

Straight forward you explain it pretty well

Only talk zones me out, so book and demos make it very interesting

Challenge

Not so easy, which is good

Formative feedback,

Feedback in questions is excellent

Identity development

I wouldn't have thought about it while playing a Gameboy but I got an insight and now can see the opportunities

A number of students made comments about this unit of the course only having a single laboratory

I would be keen to do some of the tasks with a real microcontroller instead of simulation

One student made a comment which could indicate a summative assessment driven approach to learning,

It's difficult to tell how this will relate to questions in the exam

Metacognition,

Assignment was actually pretty good at helping me evaluate my learning

Perhaps the most interesting comment from a student was this one, where the student appeared to be unaware of the nature of learning

Rather than theory which we are used to it's interesting

7.2.3. Results from assessing epistemic knowledge in ElectEng209 in 2017

While the results of using GECKO in CompSys201 seem indicative of change in epistemic knowledge of students, it is in the subsequent project-based design course where students actually need to use their knowledge to solve unfamiliar problems. The efficacy of GECKO and the changes made to CompSys201 were therefore best assessed through investigating students as they undertook their project work in ElectEng209.

Observation and survey data were collected using the instruments in Table 20 in Appendix 1. Observation and survey data for 2017 are collated in Figure 97 and can be compared against an equivalent measure overlaid onto the graph for the 2015 data found in Figure 79 on page 234. There was a significant change in observed and students' self-report ratings from 2015 to 2017. These moved from predominantly uni-structural to the relational level of the SOLO Taxonomy. This represents a significant change to student epistemic knowledge and capability with KT-inferring with micrcontrollers.

One of the most significant apsects found when comparing the data from 2015 and 2017 is that in 2015 students who engaged with and knew about the microcontroller aspect of the project tended to be only those individuals who carried out the microcontroller part of the project; while other students in their groups tended to avoid having to enagage with it at all. In the graph in Figure 97 for 2017 there is not only an increase in students enagaging with the microcontoller part of the project (the first of the four bars), but the capability of all students was found to be higher overall. Overlaid on Figure 97 is a line representing the mean of the values from 2015 to show the change between the two stages of the research.

Data for this graph is in Appendix 1, Table 19 and sample student responses are in Figure 99 on page 280 and Figure 100 on page 281.

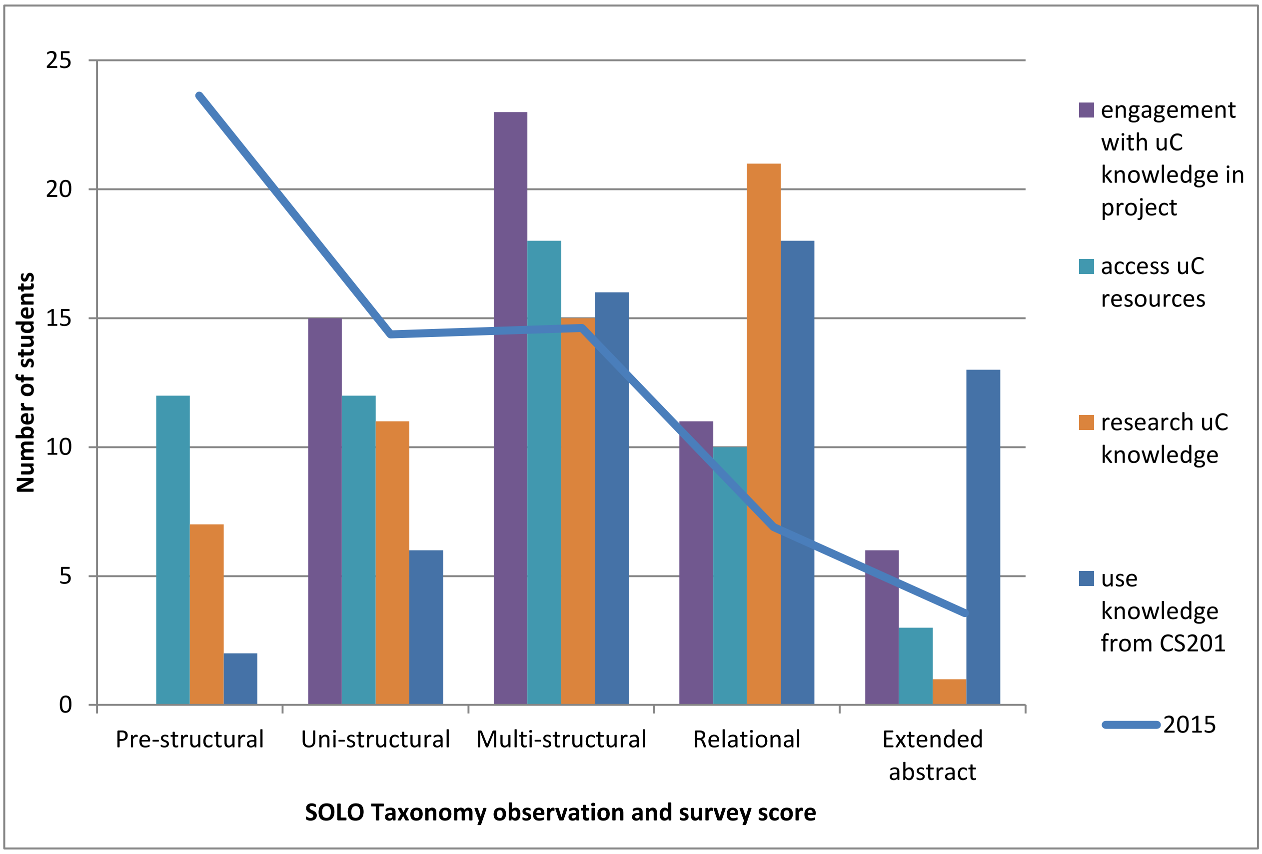


Figure 97: Observation and survey data for ElectEng209 in 2017

Students comments included knowledge about how to use the microcontroller.

It all makes sense to me, I know what to do and it's hard, but all OK

It is really gratifying being able to apply learnt concepts and physically see the results

The assignment in CS201 had us become so familiar with the datasheet...it made using it in the project much easier and could be done with little guidance

CS201 really helped me understand what I am doing now

Students were observed inteacting with the software and hardware aspsect of the project and the datsheet competently. This in contrast to 2015 when many students were unfamiliar with the hardware and writing software; and few students exhibited competence with identifying, interpreting and using data about the microcontroller from the datasheet.

7.3. Conclusion

The course goal chosen for CompSys201 was to help students build a 'viable mental model' of a microcontroller-based embedded system and improve their experience of learning. Mental model development aligns to students' epistemic knowledge, and being viable aligns with supporting students' capabilities with KT-inferring; while the goal to improve experience of learning aligns with student feedback about making learning visible, providing feedback and making the course work interesting and comprehensible. Whilst this was only a single iteration of the changes to the course, students' comments and exam results from CompSys201, and the way students approached their work in ElectEng209 were promising and indicate more detailed investigations would be worthwhile.

The change to results between 2015 and 2017 cannot be attributed to a single factor as there were many significant changes to the course materials and pedagogy. These changes included making learning visible through articulating abstract principles in learning outcomes and regularly focussing the concrete activities and success criteria back onto those abstract principles. Change also focussed on developing students' epistemic knowledge using richly contextualised examples that were systematically linked and developed using manageable learning chunks suitable for novice learners.

The course relied heavily on the use of GECKO within a mixed formative-summative assignment to guide conceptual understanding via visualisations and promote student engagement through automated formative feedback. Several students directly commented on how the visualisations significantly enhanced their understandings of the dynamic processes involved. The data that is not available in this research is whether there is any relationship between student knowledge development, the online assignment and lecture attendance. Investigations of whether the assignment and course notes alone could provide satisfactory scaffolds for learning would be one future direction for research.

Student agency was demonstrated by the timing of when students began the assignment; 20 students started the assignment in the last two days, 13 of these failed the exam questions on microcontrollers. While there was a significant group of students who had higher examination grades who began the assignment early, this does not demonstrate any strong or causal link between examination score and agency. The more significant evidence from the change to the course appears to be that students described how they understood the material and said they were able to apply what they had learned in the subsequent project-based design course ElecEng209. This was indicated through a survey and confirmed through observations and discussions with students of their increased levels of understanding and engagement in their ElecgEng209 project.

The research question required identifying effects from integrating pedagogy and educational technology. The redevelopment of the microcontroller section of the course centred on this and it appears the outcome was positive in terms of student epistemic understandings and capability with KT-inferring capability, and this seemed to carry over into the subsequent project-based design course.

Chapter 8. **Closing Discussion**

This chapter briefly summarises the research, the research questions and the findings from them, then identifies some of the limitations of the study and directions for future research.

8.1. Summary

The first chapter summarised research into student knowledge of electric circuit theory and revealed that it was fraught with issues. This led to the first research question: What is the real nature of the learning problem? A sequence of investigations led to a series of concept maps and a summary concept map, Figure 49 on page 168, that describe the factors that contributed to the situation. It was found that knowledge teaching and learning were focussed around a narrow subset of ways-of-knowing, with many students entering tertiary education with an identity of exam-taker and a personal project of passing. Students were identified as focussing on useful-content knowledge and mathematical techniques rather than epistemic knowledge.

For many students, the nature of teaching and learning in the first two years of electrical engineering encouraged this, sometimes intensifying into a parsimonious get-through identity. The structure of learning appeared to encourage this through a focus on smooth administration, significant summative assessment, useful-content knowledge and mathematical techniques. This appeared to be linked to two distinct aspects of teaching and learning. The first is the dual and often disparate identity of the researcher-educator; where the researcher identity is one of epistemic knowledge creator and the educator identity has limited underpinning of educational theory. Education however, is a complex domain of abstract epistemic knowledge in its own right, just as are the domains of knowledge encountered in engineering. Something not found in engineering but evident in education, is the lack of clear definitions of what different terms mean, even amongst educators. In education, terms such as active learning, engagement, learning outcomes, student-centred learning and improving students' experience are often used by educators in different ways.

Without an episteme or system of meaning of educational theory these terms lack the clarity needed to become used powerfully and can lead to errors in pedagogy. These errors may go unnoticed or be misinterpreted for extended periods of time. The second key aspect of teaching and learning was the reliance encountered on an online drill and practice tool. While this met the need for student practice with mathematical techniques, it lacked the theoretical educational underpinning needed to make it powerful for developing student knowledge. Instead it constrained studentst to a narrow subset of the required knowledge, one unsuitable for dealing with engineering problems which are usually complex and multifaceted. Consequently, when students undertook their first project-based design course, they lacked suitable epistemic knowledge and capabilities with using it for the challenges involved.

In the second stage of the research, the question was: Can an increased focus on epistemic knowledge help students in first year electrical engineering? A quiz and set of fundamental circuit concept tutorials, the FCCTs, were used to investigate the development of students' epistemic knowledge of electric circuit properties at the same time as investigating their agency relating to marked and unmarked work. The FCCTs were developed using theories about visualisation and engagement, and the Variation Framework. The data indicated that approximately 30% of students either did not have an exam-taker identity or had the agency to put it aside to undertake the beneficial unassessed work in the FCCTs. When the FCCTs were awarded 4% of the course grade 93% of students completed them; however some of those students expressed an agency where the FCCTs were only useful to obtaining marks. From three iterations, the FCCTs were found to be positively linked to students' epistemic knowledge development, especially if used early in the course. When a lack of knowledge was revealed to students through the pre-course quiz, the nature of student identity seemed to constrain student agency toward the FCCTs. The three iterations of the FCCTs also increased the awareness of how change is constrained by the structures of teaching and learning which are aligned to smooth administration and summative assessment.

The understandings from social realist theories, and educational theories along with knowledge about the situation of teaching and learning were used to inform the third research question: How can theory and understanding of the situation inform the development of a novel knowledge-based educational technology tool? Development of GECKO and a pedagogic framework for its use took place. The point of difference with GECKO is the degree to which epistemic knowledge is made visible and questions can be developed using scripting of simulations to encourage students to inferentially use epistemic knowledge to solve complex problems. Understandings from literature and the first stages of the research indicated that there while are no direct solutions to educational problems, there are heuristics and probabilities associated with pedagogical practices and educational theories that can provide sound direction for educators. The pedagogic framework was developed in parallel with GECKO using the three learning questions heuristic; centring on abstract knowledge it uses the pedagogical practice of direct instruction to structure teaching and learning.

This led to the fourth research question: What is the effect of an integrated approach to pedagogy and educational technology on student knowledge? GECKO and the framework were trialled in a second year course. This trial indicated positive results around developing students' epistemic knowledge, and inferential reasoning. Students found the work stimulating and comprehensible, and more importantly said and demonstrated that they were able to take epistemic knowledge into the subsequent project-based design course and use it meaningfully.

8.2. Limitations of the research

The nature of teaching and learning is complex. While the case study attempted to gain both a broad and detailed view of teaching and learning, to endeavour to capture both of these fully in the time taken, implies there may be factors which have not surfaced yet. While experience in secondary school education indicates this is quite possible, a number of processes were used to mitigate the risk. These included: prolonged engagement in the situation, triangulation of qualitative and quantitative data, member-checking and peer conferencing and the use of the data by other researchers. Educationally however, this is still a short timeframe, and prior experience in education indicates change takes concerted effort over time. For example, while three iterations of the FCCTs took place, the conditions each year changed. More stable conditions would need to be established to investigate any ongoing benefits or potential issues with them. Also only a single iteration of GECKO and the pedagogic framework were undertaken in CompSys201 in 2017. The data collected from observations and surveys with those students during the subsequent project-based design course ElectEng209 could have been complemented with more evidence of student thinking, particularly with regard to the software they developed for their projects. Also, one third of the cohort of students in CompSys201 do not take ElectEng209, these are the students in the Software Engineering specialisation. No data has been collected from these students about the efficacy of the knowledge gained in CompSys201. Another limitation is the large amount of data collected, where there are currently over 400,000 answers to questions made by students using GECKO. There is a considerable amount of unexplored data here that may reveal important information.

8.3. Future research

The results of this case study have important implications for the teaching and learning of knowledge in engineering, as it seems students will continue to enter courses with limited understandings and learning practices focussed on gaining summative assessment results. With use of GECKO growing in ElectEng101 and other second year courses to replace existing questions used with students, one question is: What effect has the change to demonstration of epistemic knowledge from these course had on student knowledge and agency in ElectEng209? Mining of the growing set of data in GECKO is crucial to this understanding. Further changes to questions in ElectEng101 need to be made to require students to use inferential reasoning and investigate effects from that change. In the second semester of 2018 I will be teaching in a third year project-based design course, CompSys301. The students in this course were amongst those taught in CompSys201 in 2017. It is anticipated that working closely with these students will highlight gaps in the research in CompSys201 by identifying gaps in their knowledge. One further opportunity for research involves using GECKO at secondary schools and the development of a unit of teaching and learning to trial with students in Year 11.

8.4. Conclusion

This case study has investigated teaching and learning within one situation and the development of a novel educational technology aimed at epistemic knowledge, along with a pedagogical approach for using it. While this is a single case, it is not a unique set of circumstances, as students and educators across learning situations share many of these complexities. The study revealed that for many students, their agency is subject to influence from the surrounding educational structures and culture. This can be seen as positive for student learning, as it indicates the potential for change to take place. Another area where change is critical is with the use of educational technologies, as reliance upon digital tools only seems to be increasing. Theoretically sound applications of educational technologies are required to leverage any benefits.

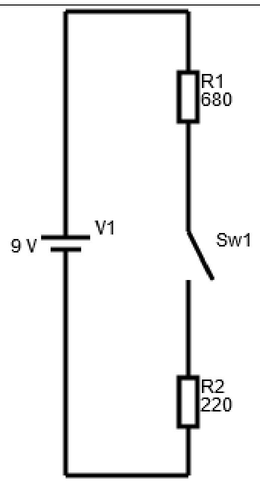
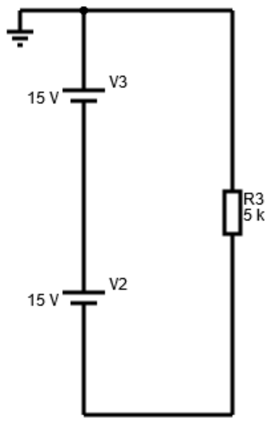
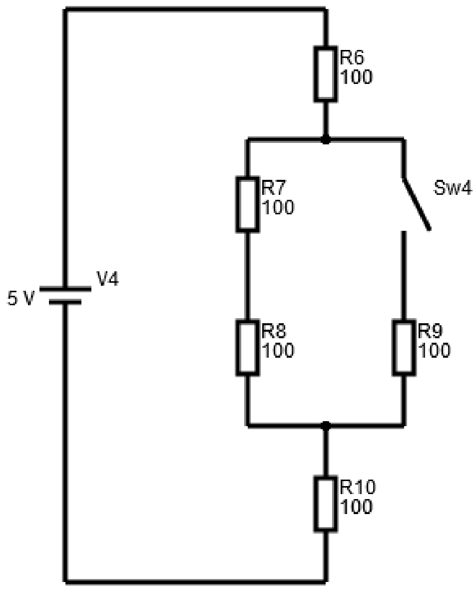
Underpinning change in disciplinary education is the need to recognise that education is a formal knowledge domain in its own right, with its own episteme of foundational principles. This case study revealed that it is possible to work in depth across different knowledge domains, and more examples are required that demonstrate this complex synthesis.

Appendices

Appendix 1. **Research instruments**

Protocol for semi-structured student interviews

<u>Question 1:</u> Please talk about the components, voltage, current, power and energy in the following diagrams

Circuit 1	**Circuit 2**	**Circuit 3**
		

- What do you understand about the term ‘voltage’?
- What do you understand about the term ‘energy’?
- What do you understand about the term ‘ground’?
- What is OHM’s law?
- How do you know when you have understanding?
- Do you have any concerns about learning electric circuit theory?

<u>Question 2: Tell me about your school based learning in Electric Circuits?</u>

- Tell me about your experiences of Year 13 physics in relation to electric circuits
- How long did you spend on circuits?
- What practical work did you do?
- What did your teacher do to help you understand/remember
- What content and concepts do you remember?

Question 3: Tell me about your experience of learning in EE101 about electric circuits

- How difficult did you find it?
- What did you find difficult?
- In what ways do you think your understandings about electric circuits have changed during the course?
- What specifically contributed to this?
- What motivates you about engineering / this paper?

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE ON 30 June 2015 for (3) years, Reference Number 014647

Student observation and discussion criteria

Table 17: Student Observation Criteria for use in lectures and laboratories

Criteria(0-not observed, 5=regularly/strength)	*0-5*		*0-5*
students demonstrate progression of learning		Students perceive a positive dynamic about their learning	
Students identify with learning goals		Students exhibit thinking and reasoning	
Students exhibit self-regulated / metacognitive learning		Students show interest in the subject	
Students can use various techniques to solve problems		Experience problems understanding new topics	
Students see assessment results as learning scaffolds		Students think through problems	
Students reflect on concepts		Demonstrate sound use of specialist subject language	
Student sees links between the subject and society		Student builds epistemic knowledge	
Student sees links to engineering practice		Students appear stimulated by the learning	
Students value KT-inferring		Student discourse around learning	
Students value KT-propositions,		Students associate with instruction discourse	
Students value KH-techniques and rules		Students associate with summative assessment	
Notes			

Note: Adapted from "The development and validation of a student evaluation instrument to identify highly accomplished mathematics teachers" by Earl Irving (2004), and from "A Systematic Review of the Impact of Summative Assessment and Tests on Students' Motivation for Learning" by W. Harlen and R.D. Crick 2002. Copyright 2002 by University of London.

Self-Report Questionnaire

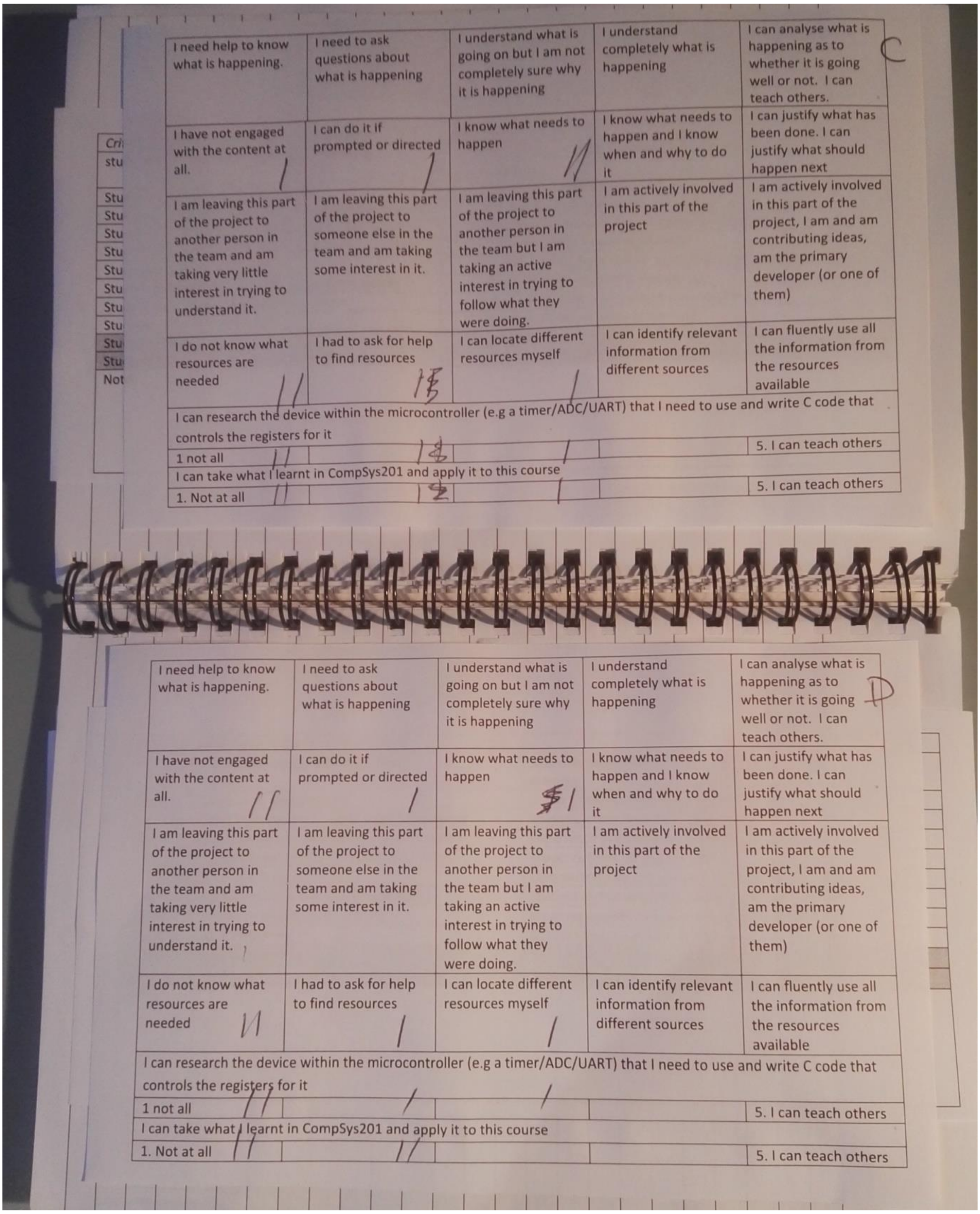
Table 18: CompSys201 Self-Report Questionnaire, used directly with students and as part of observations in 2015

With regard to the microcontroller part of the project

I need help to know what is happening.	I need to ask questions about what is happening	I understand what is going on but I am not completely sure why it is happening	I understand completely what is happening	I can analyse what is happening as to whether it is going well or not. I can teach others.
I have not engaged with the content at all.	I can do it if prompted or directed	I know what needs to happen	I know what needs to happen and I know when and why to do it	I can justify what has been done. I can justify what should happen next
I am leaving this part of the project to another person in the team and am taking very little interest in trying to understand it.	I am leaving this part of the project to someone else in the team and am taking some interest in it.	I am leaving this part of the project to another person in the team but I am taking an active interest in trying to follow what they were doing.	I am actively involved in this part of the project	I am actively involved in this part of the project, I am and am contributing ideas, am the primary developer (or one of them)
I do not know what resources are needed	I had to ask for help to find resources	I can locate different resources myself	I can identify relevant information from different sources	I can fluently use all the information from the resources available
I can research the device within the microcontroller (e.g. a timer/ADC/UART) that I need to use and write C code that controls the registers for it				
Not at all				5. I can teach others
I can take what I learnt in CompSys201 and apply it to this course				
1. Not at all				5. I can teach others

This is not an assessment; it is for teaching and research purposes only, it has no bearing on your grade.

Optional comment:



C

I need help to know what is happening.	I need to ask questions about what is happening	I understand what is going on but I am not completely sure why it is happening	I understand completely what is happening	I can analyse what is happening as to whether it is going well or not. I can teach others.
I have not engaged with the content at all.	I can do it if prompted or directed	I know what needs to happen	I know what needs to happen and I know when and why to do it	I can justify what has been done. I can justify what should happen next
I am leaving this part of the project to another person in the team and am taking very little interest in trying to understand it.	I am leaving this part of the project to someone else in the team and am taking some interest in it.	I am leaving this part of the project to another person in the team but I am taking an active interest in trying to follow what they were doing.	I am actively involved in this part of the project	I am actively involved in this part of the project, I am and am contributing ideas, am the primary developer (or one of them)
I do not know what resources are needed	I had to ask for help to find resources	I can locate different resources myself	I can identify relevant information from different sources	I can fluently use all the information from the resources available
I can research the device within the microcontroller (e.g a timer/ADC/UART) that I need to use and write C code that controls the registers for it				
1 not all				5. I can teach others
I can take what I learnt in CompSys201 and apply it to this course				
1. Not at all				5. I can teach others

D

I need help to know what is happening.	I need to ask questions about what is happening	I understand what is going on but I am not completely sure why it is happening	I understand completely what is happening	I can analyse what is happening as to whether it is going well or not. I can teach others.
I have not engaged with the content at all.	I can do it if prompted or directed	I know what needs to happen	I know what needs to happen and I know when and why to do it	I can justify what has been done. I can justify what should happen next
I am leaving this part of the project to another person in the team and am taking very little interest in trying to understand it.	I am leaving this part of the project to someone else in the team and am taking some interest in it.	I am leaving this part of the project to another person in the team but I am taking an active interest in trying to follow what they were doing.	I am actively involved in this part of the project	I am actively involved in this part of the project, I am and am contributing ideas, am the primary developer (or one of them)
I do not know what resources are needed	I had to ask for help to find resources	I can locate different resources myself	I can identify relevant information from different sources	I can fluently use all the information from the resources available
I can research the device within the microcontroller (e.g a timer/ADC/UART) that I need to use and write C code that controls the registers for it				
1 not all				5. I can teach others
I can take what I learnt in CompSys201 and apply it to this course				
1. Not at all				5. I can teach others

Figure 98: Observation/discussion data sample Groups C and D ElectEng209 in 2015

.

Table 19: Collated observation and discussion data for ElectEng209, 2015

Group	engagement with uC					access uC resources					research uC knowledge					use knowledge from CS201				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
A	2	2				2	2				2	2				2	2			
B	2	2				2	1	1			2	1	1			2	1	1		
C	1	1	2			2	1	1			2	1	1			2	1	1		
D	2	1	1			2	1	1			2	1	1			2	2			
E	2	1	1			4					4					3	1			
F	2	1	1			2	2				3	1				2	1	1		
G	2	2				2	1	1			3	1				2	1	1		
H	2	1	1			2	1	1			2	1	1			2	1	1		
I	2	1	1			2	1	1			2	1	1			2	1	1		
J		2	1	1			2	1	1		1		1	2				1	3	
K		1	2		1		1	2		1			3		1			2	1	1
L			1	2	1		1	2	1				2	1	1			3	1	
M			1	2	1			1	2	1			2	2				1	2	1
N				2	2				2	2				2	2			1	2	1
O	3	1				4					2	2				2	2			
P			4				2	2			2	1	1			2	1	1		

Student Self report Questionnaire

Table 20: Student Self-Report Questionnaire ElectEng209, 2017

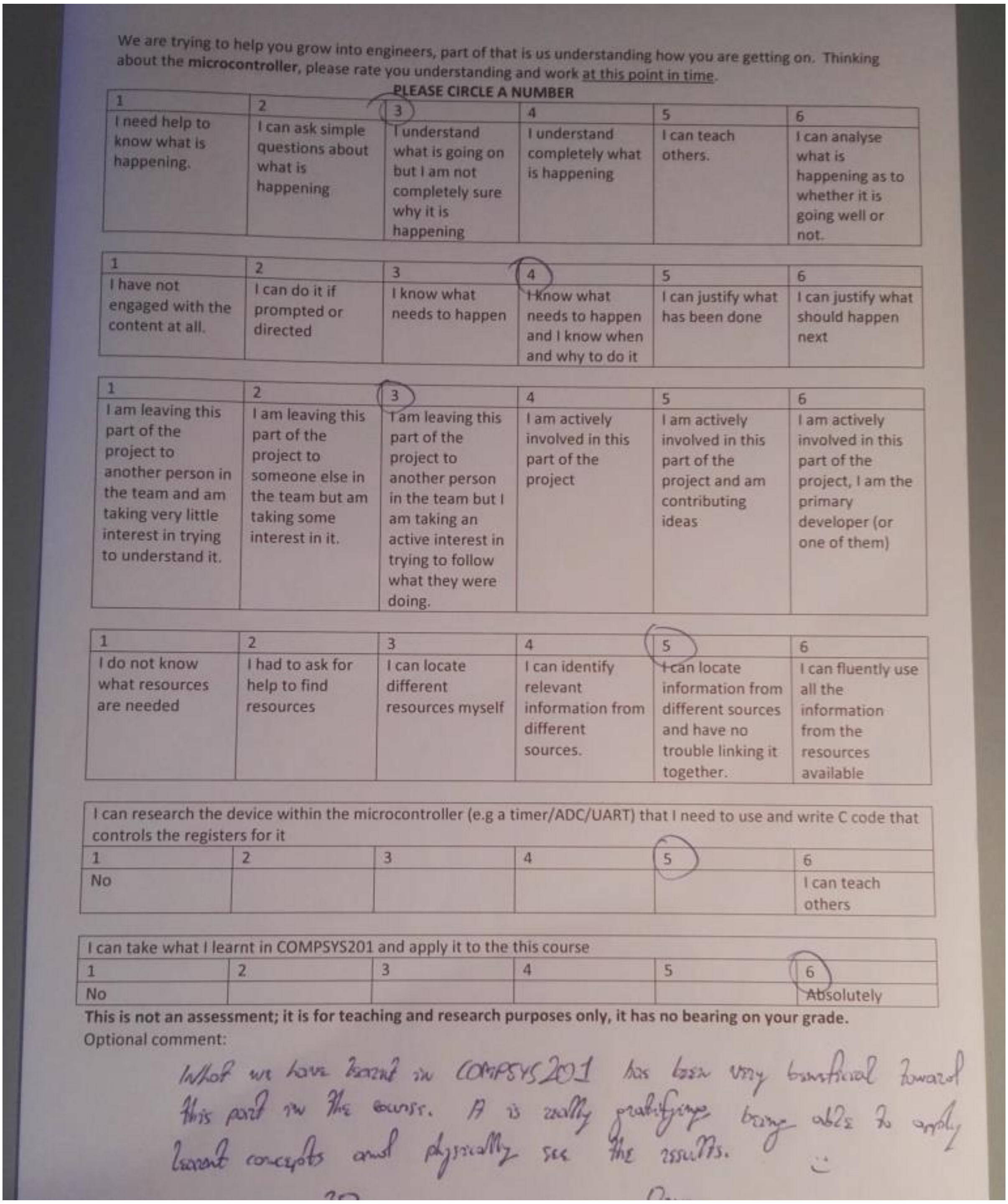
1	2	3	4	5	6
I need help to know what is happening.	I can ask simple questions about what is happening	I understand what is going on but I am not completely sure why it is happening	I understand completely what is happening	I can teach others.	I can analyse what is happening as to whether it is going well or not.
1	2	3	4	5	6
I have not engaged with the content at all.	I can do it if prompted or directed	I know what needs to happen	I know what needs to happen and I know when and why to do it	I can justify what has been done	I can justify what should happen next
1	2	3	4	5	6
I am leaving this part of the project to another person in the team and am taking very little interest in trying to understand it.	I am leaving this part of the project to someone else in the team but am taking some interest in it.	I am leaving this part of the project to another person in the team but I am taking an active interest in trying to follow what they were doing.	I am actively involved in this part of the project	I am actively involved in this part of the project and am contributing ideas	I am actively involved in this part of the project, I am the primary developer (or one of them)
1	2	3	4	5	6
I do not know what resources are needed	I had to ask for help to find resources	I can locate different resources myself	I can identify relevant information from different sources.	I can locate information from different sources and have no trouble linking it together.	I can fluently use all the information from the resources available
I can research the device within the microcontroller (e.g. a timer/ADC/UART) that I need to use and write C code that controls the registers for it					
1	2	3	4	5	6
Not at all					I can teach others
I can take what I learnt in COMPSYS201 and apply it to the this course					
1	2	3	4	5	6
Not at all					Absolutely

This is not an assessment; it is for teaching and research purposes only, it has no bearing on your grade.

Optional comment:

OPTIONAL

Group #: ____________________ First Name ___________________________________



We are trying to help you grow into engineers, part of that is us understanding how you are getting on. Thinking about the **microcontroller**, please rate you understanding and work at this point in time.

PLEASE CIRCLE A NUMBER

1	2	3	4	5	6
I need help to know what is happening.	I can ask simple questions about what is happening	I understand what is going on but I am not completely sure why it is happening	I understand completely what is happening	I can teach others.	I can analyse what is happening as to whether it is going well or not.

1	2	3	4	5	6
I have not engaged with the content at all.	I can do it if prompted or directed	I know what needs to happen	I know what needs to happen and I know when and why to do it	I can justify what has been done	I can justify what should happen next

1	2	3	4	5	6
I am leaving this part of the project to another person in the team and am taking very little interest in trying to understand it.	I am leaving this part of the project to someone else in the team but am taking some interest in it.	I am leaving this part of the project to another person in the team but I am taking an active interest in trying to follow what they were doing.	I am actively involved in this part of the project	I am actively involved in this part of the project and am contributing ideas	I am actively involved in this part of the project, I am the primary developer (or one of them)

1	2	3	4	5	6
I do not know what resources are needed	I had to ask for help to find resources	I can locate different resources myself	I can identify relevant information from different sources.	I can locate information from different sources and have no trouble linking it together.	I can fluently use all the information from the resources available

I can research the device within the microcontroller (e.g a timer/ADC/UART) that I need to use and write C code that controls the registers for it

1	2	3	4	5	6
No					I can teach others

I can take what I learnt in COMPSYS201 and apply it to the this course

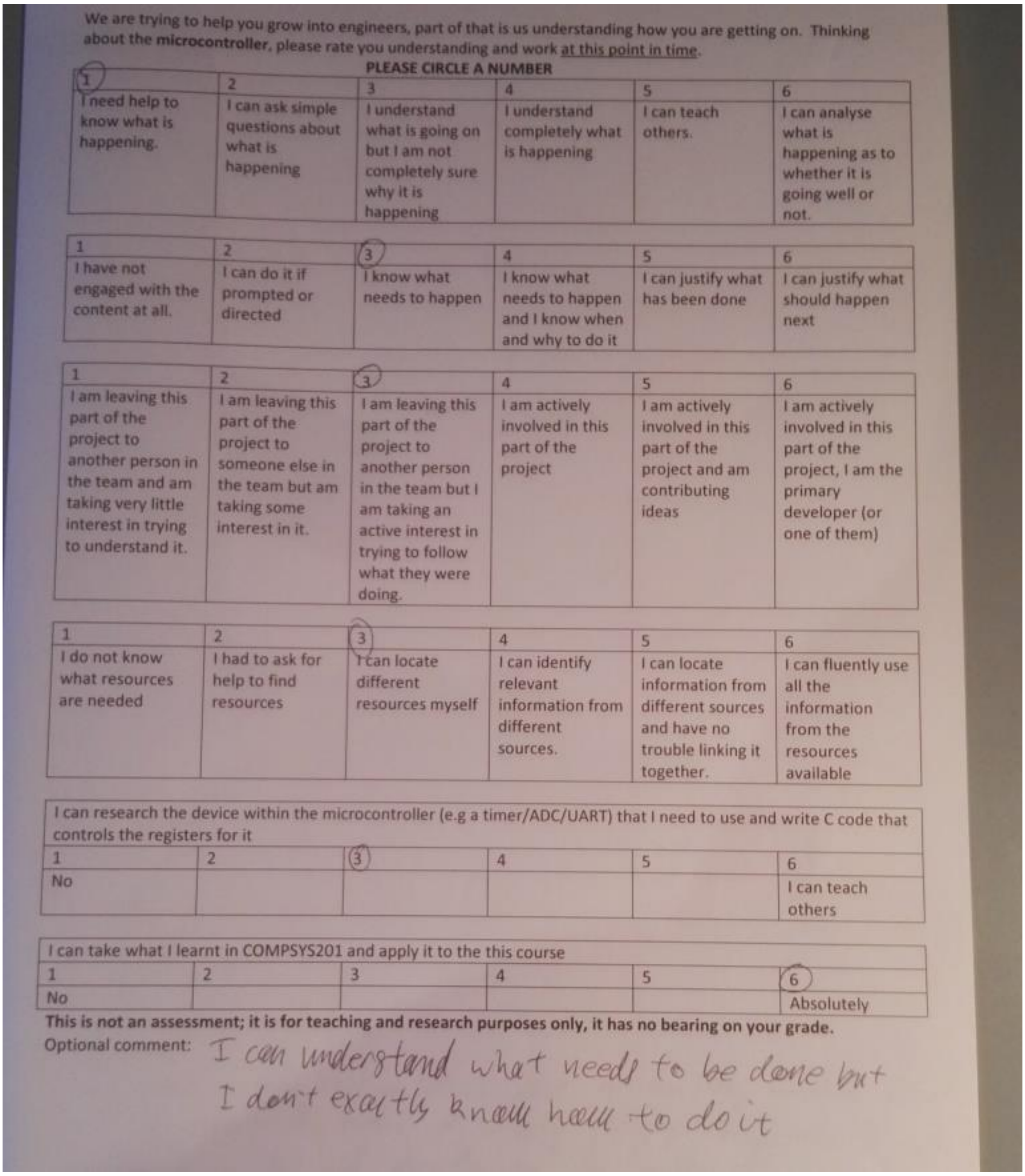
1	2	3	4	5	6
No					Absolutely

This is not an assessment; it is for teaching and research purposes only, it has no bearing on your grade.

Optional comment:

What we have learnt in COMPSYS201 has been very beneficial toward this part in the course. It is really gratifying being able to apply learnt concepts and physically see the results. :)

Figure 99: ElectEng209 sample data student-A, self-report questionnaire about CompSys201, 2017



We are trying to help you grow into engineers, part of that is us understanding how you are getting on. Thinking about the **microcontroller**, please rate you understanding and work at this point in time.

PLEASE CIRCLE A NUMBER

1	2	3	4	5	6
I need help to know what is happening.	I can ask simple questions about what is happening	I understand what is going on but I am not completely sure why it is happening	I understand completely what is happening	I can teach others.	I can analyse what is happening as to whether it is going well or not.

1	2	3	4	5	6
I have not engaged with the content at all.	I can do it if prompted or directed	I know what needs to happen	I know what needs to happen and I know when and why to do it	I can justify what has been done	I can justify what should happen next

1	2	3	4	5	6
I am leaving this part of the project to another person in the team and am taking very little interest in trying to understand it.	I am leaving this part of the project to someone else in the team but am taking some interest in it.	I am leaving this part of the project to another person in the team but I am taking an active interest in trying to follow what they were doing.	I am actively involved in this part of the project	I am actively involved in this part of the project and am contributing ideas	I am actively involved in this part of the project, I am the primary developer (or one of them)

1	2	3	4	5	6
I do not know what resources are needed	I had to ask for help to find resources	I can locate different resources myself	I can identify relevant information from different sources.	I can locate information from different sources and have no trouble linking it together.	I can fluently use all the information from the resources available

I can research the device within the microcontroller (e.g a timer/ADC/UART) that I need to use and write C code that controls the registers for it

1	2	3	4	5	6
No					I can teach others

I can take what I learnt in COMPSYS201 and apply it to the this course

1	2	3	4	5	6
No					Absolutely

This is not an assessment; it is for teaching and research purposes only, it has no bearing on your grade.

Optional comment: I can understand what needs to be done but I don't exactly know how to do it

Figure 100: ElectEng209 sample data student-B, self-report questionnaire about CompSys201, 2017

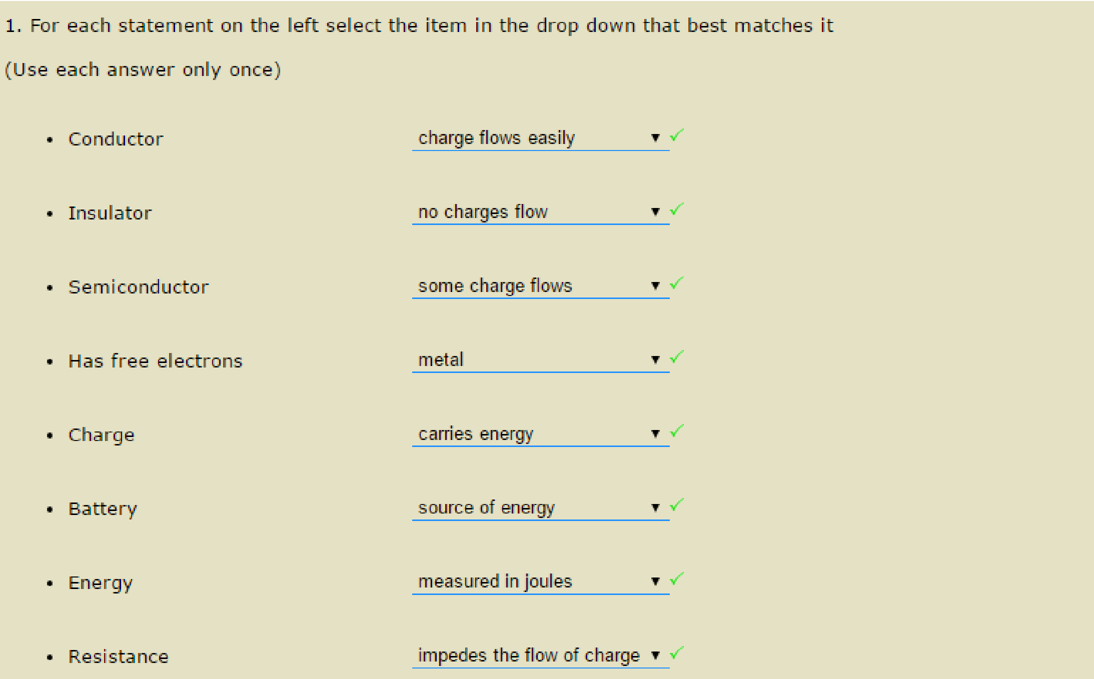
Appendix 2. **Pre-course concepts quiz results**

Note the number of participants who began the quiz was 477 and 468 completed it.

The quiz was marked out of 26 possible points

Question 1: focus: KT-propositions

N=477, 63% correct on first try.

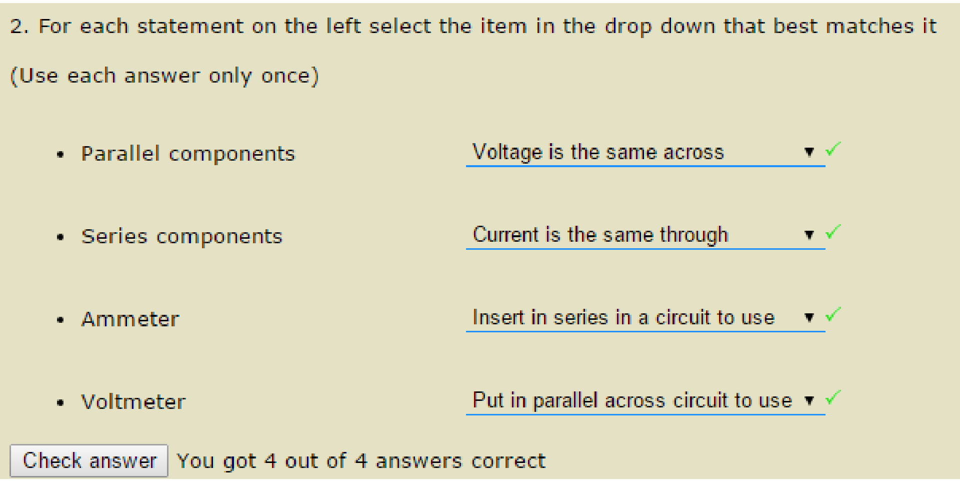

1. For each statement on the left select the item in the drop down that best matches it

(Use each answer only once)

- Conductor — charge flows easily ✓
- Insulator — no charges flow ✓
- Semiconductor — some charge flows ✓
- Has free electrons — metal ✓
- Charge — carries energy ✓
- Battery — source of energy ✓
- Energy — measured in joules ✓
- Resistance — impedes the flow of charge ✓

Question 2: focus: epistemic understandings

N=473, 31%, correct on first try


2. For each statement on the left select the item in the drop down that best matches it

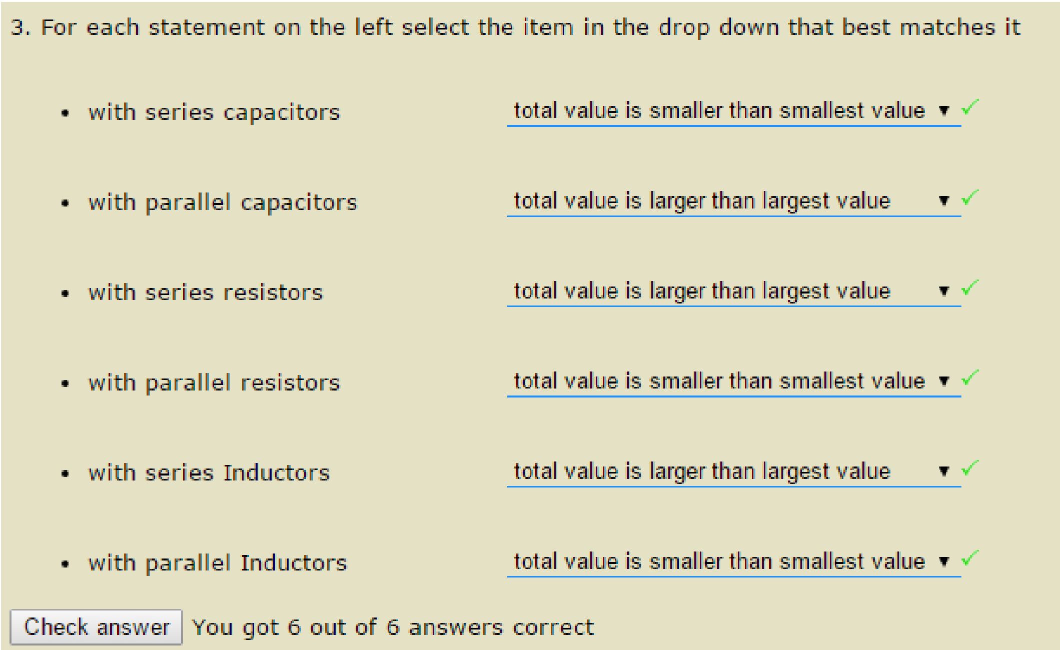
(Use each answer only once)

- Parallel components — Voltage is the same across ✓
- Series components — Current is the same through ✓
- Ammeter — Insert in series in a circuit to use ✓
- Voltmeter — Put in parallel across circuit to use ✓

Check answer You got 4 out of 4 answers correct

Question 3: focus: KT-inferring

N= 473, 30% correct first try



3. For each statement on the left select the item in the drop down that best matches it

- with series capacitors — total value is smaller than smallest value
- with parallel capacitors — total value is larger than largest value
- with series resistors — total value is larger than largest value
- with parallel resistors — total value is smaller than smallest value
- with series Inductors — total value is larger than largest value
- with parallel Inductors — total value is smaller than smallest value

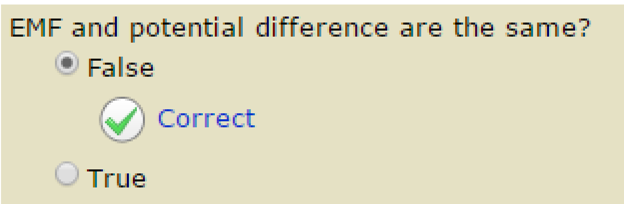
Check answer You got 6 out of 6 answers correct

Question 4:

N=468

4(a) focus: KT-propositions

66% correct on first try



EMF and potential difference are the same?

False

Correct

True

4(b) N=468

focus: KT-propositions

50% correct on first try

A battery is a source of current?

- (selected) False
  - Correct
- True

4(c) N=468

focus: KT-propositions

67% correct on first attempt

Charge (select all answers you think are correct)

- [x] occurs when there are more protons than electrons
  - Correct
- [x] occurs when there are more neutrons than electrons
  - Incorrect
- [x] occurs when there are more electrons that neutrons
  - Incorrect
- [x] occurs when there are more electrons that protons
  - Correct

4(d) focus: Epsitemic knolwdge,

30% correct first try

Which statement is correct about a circuit

- ○ Voltage and current are independent
- ◉ Voltage causes current

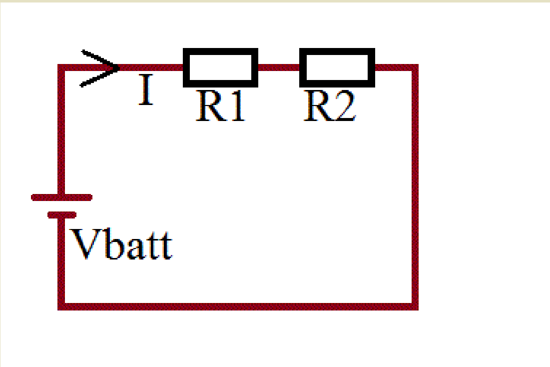
  ✓ Correct

- ○ Current causes voltage
- ○ Voltage and current are both the same thing

4(e) focus: epistemic knowledge

12% correct on first try

Current weakens as it flows around a circuit



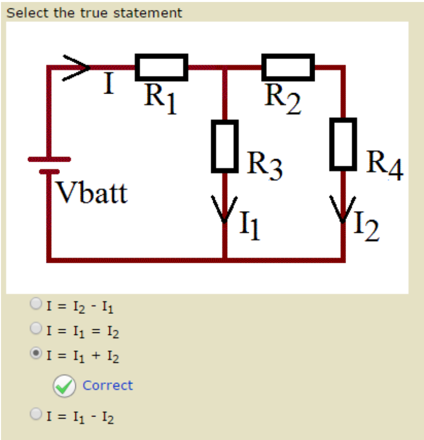
- ◉ False

  ✓ Correct

- ○ True

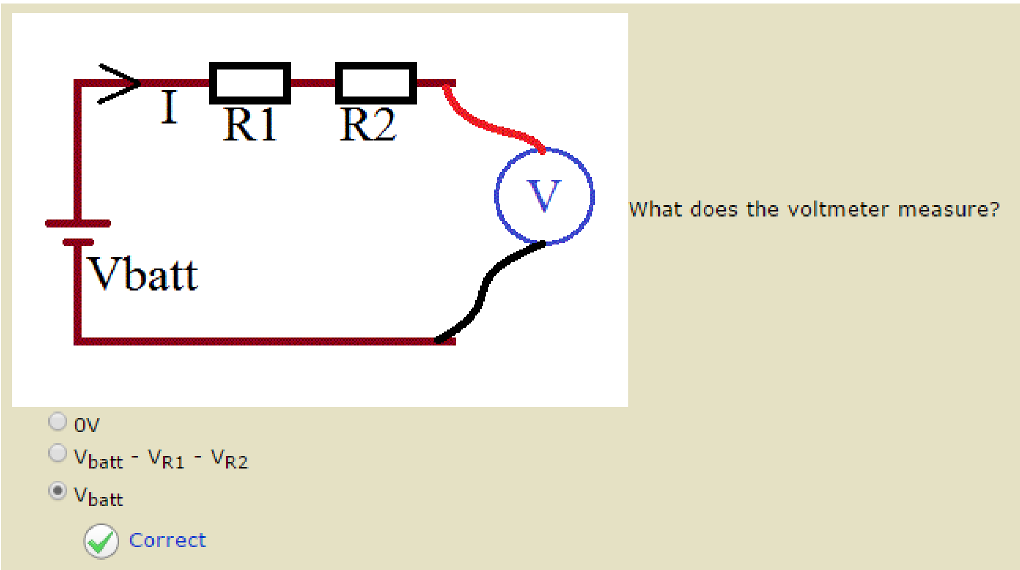
4(f) focus: KH-techniques

86% correct on first try



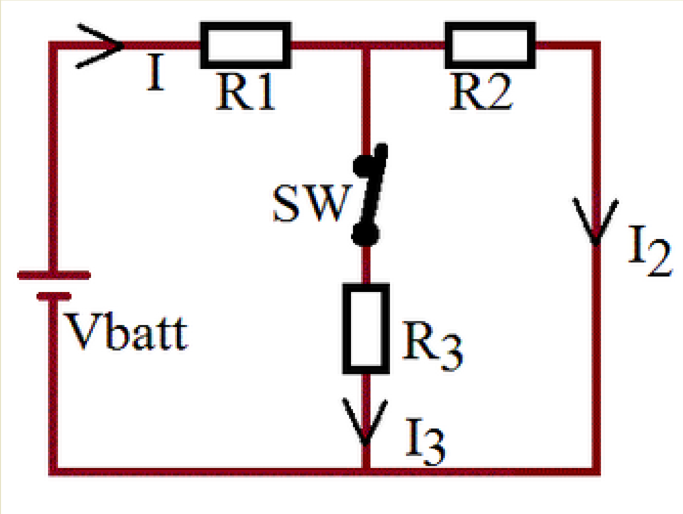
4(g) focus: KT-inferring –electric potential

21% correct on first try



4(h): focus: KT-inferring

7% correct first try



What happens when the switch is opened?

- Vbatt stays the same
  - Correct
- I_3 increases
  - Incorrect
- I_2 will become half I
  - Incorrect
- Vbatt increases
  - Incorrect
- I stays the same
  - Incorrect
- Vbatt reduces
  - Incorrect
- I decreases
  - Correct
- you cannot tell without any values
  - Incorrect
- I_2 Increases
  - Correct
- I_2 reduces
  - Incorrect

Appendix 3. **The FCCTs Fundament Circuit Concept Tutorials**

FCCT questions, 2017

Previous Question | ELECTENG 101: Circuit Concepts 2017 - wcol001 | Front Page | NextQuestion

For many years we have measured students understandings of fundamental electrical concepts as they begin ELECTENG101, and while they have great grades from school, each year we find 80-90% of students will have incorrect electrical concepts that this course relies upon. To help you we have developed these tutorials to assist with the concepts at the core of electric circuit theory giving you a firm foundation for the course.

The primary goal of these tutorials is for students to see **an electric circuit as an energy conversion, storage and transfer process** - after all that is why engineers design and make circuits!

Students who have previously engaged with the tutorials have said positive things about them and do better in the course and end of course exam. So spend some time thinking about them and not rushing through them.

results for: wcol001

Copy | CSV | Excel | PDF | Print

Question Number	Question Title	You have attempted it	You got it fully correct
1	Explain a simple electric circuit in terms of energy transfer	1	1
2	Describe charge in terms of atomic particles	1	1
3	Describe how separation of charge creates electric potential	1	1
4	Explain charge flow in an electric circuit	0	0
5	Explain the different types of models used in electric circuits and the purpose of each	0	0
6	Describe circuit topologies: closed, open, short	0	0
7	Identify levels of electric potential around a circuit	1	0
8	Identify levels of electric potential with respect to ground in a circuit	0	0
9	Create sources with both positive and negative values with reference to ground	0	0
10	Identify causes and consequences of short circuits	0	0
11	How energy sources are actually drawn in electric circuits	3	1
12	Describe Ohm's Law as a model for circuit behaviour	0	0
13	Replace simple series or parallel combinations with an equivalent resistance.	0	0
14	Explain electric circuits in terms of energy conservation using KVL	2	1
15	Explain electric circuits in terms of conservation of energy using KCL	0	0
16	Practice conversions between metric prefixes	0	0

Figure 101: FCCT front page and analytics

FCCT question 1

Previous Question | ELECTENG 101: Circuit Concepts 2017 - wcol001 - Question:1 of 16 (Value=0) | Front Page | NextQuestion

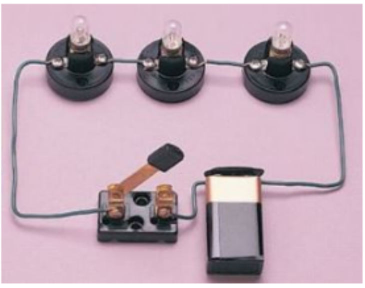
Learning Outcome: Understand fundamental electric circuit concepts as transfer, conversion and control of Energy

Keywords: Energy transfer, conversion and storage, Charge, Electric potential, Potential Difference, Voltage, Charge Flow, Current, polarity

Explain a simple electric circuit in terms of energy transfer

This is a very simple circuit, it has three types of **COMPONENTS**:

- one **BATTERY**
- three 90Ω (ohm) **BULBS**
- one **SWITCH**



You probably know some things and can calculate them about this circuit.

But before we go there, I want to take you back a few steps, because what we do in engineering has a purpose and the purpose relates to energy.

We build circuits to transfer, store and control energy.

What is the purpose of this circuit? It is to control lights, this in general terms is to transfer energy from a **source** to a **load**.

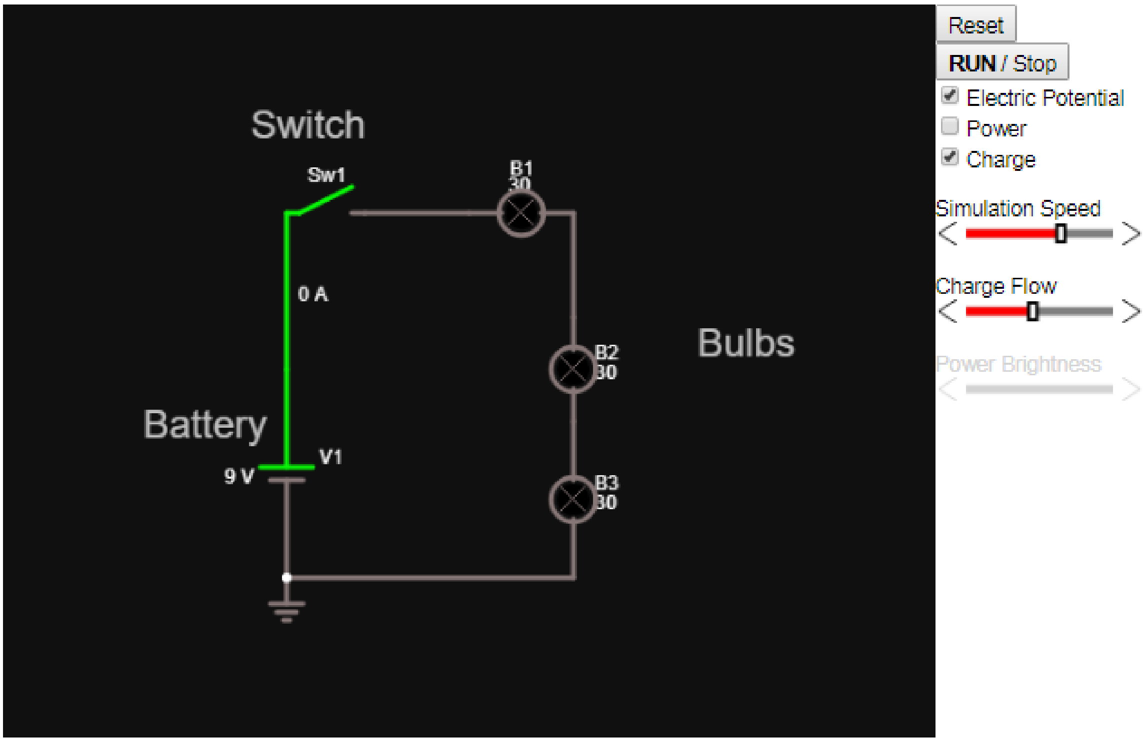
The **source** of the energy in this circuit is the [▾]

Control of the energy in this circuit is the [▾]

The **load** (destination) of the energy for this circuit is the [▾]

The **topology** (connections) determines where the energy can move, the topology is determined by the [▾]

You can click the switch in the simulator below to 'see' the consequence of energy transfer.



Save Answer(s) | Get New Data

FCCT question 2

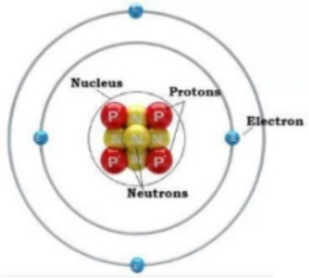
Previous Question | ELECTENG 101: Circuit Concepts 2017 - wcol001 - Question:2 of 16 (Value=0) | Front Page | NextQuestion

Learning Outcome: Understand fundamental electric circuit concepts as transfer, conversion and control of Energy

Keywords: Energy transfer, conversion and storage, Charge, Electric potential, Potential Difference, Voltage, Charge Flow, Current, polarity

Describe charge in terms of atomic particles

Charge is a basic property of the particles within an atom.



Often students have forgotten these, so as a reminder. The three main particles are

Protons which have a [▾] charge

Neutrons which have a [▾] charge

Electrons which have a [▾] charge

You can read more about an atom here if you need to.

In a circuit the energy source is a device where the two types of charge (positive and negative) have been separated by a chemical, electro-static (friction), photo or electro-magnetic action. What this means is that energy in one form is used to move the charge, thus transferring energy to the charge.

A chemical process can create an imbalance of charge e.g. in a simple battery or cell - it all sounds simple but of course 'simple' is a relative term, it wasn't so simple when Alessandro Volta invented the voltaic pile.

Electrostatic friction creates separation of charges, did you do these experiments at school with glass/plastic rods and wool/fur to show how like charges [▾] and opposite charges [▾] ?

Photoelectric devices make use of the fact that electrons can be moved by photons .

In a generator or alternator the relative motion of wires in a magnetic field creates a separation of charge.

The first step in understanding electric circuits is realizing that energy is used to create a separation of charge. The energy that the charges have becomes the source of energy for our electric circuits

Save Answer(s) | Get New Data

FCCT question 3

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Learning Outcome: Understand fundamental electric circuit concepts as transfer, conversion and control of Energy

Keywords: Energy transfer, conversion and storage, Charge, Electric potential, Potential Difference, Voltage, Charge Flow, Current, polarity

Describe how separation of charge creates electric potential

In a circuit the energy source is some device where the two types of charge (positive and negative) have been separated by a chemical, electro-static (friction), photo or electro-magnetic action. What this means is that energy in one form is used to move the charge, thus transferring energy.

A chemical process can create an imbalance of charge e.g. in a simple battery or cell - it all sounds simple but of course 'simple' is a relative term, it wasn't so simple when Alessandro Volta invented the voltaic pile.

Electrostatic friction creates separation of charges, did you do these experiments at school with glass/plastic rods and wool/fur to show how like charges [▾] and opposite charges [▾]?

Photoelectric devices make use of the fact that electrons can be moved by photons .

In a generator or alternator the relative motion of wires in a magnetic field creates a separation of charge.

The first step in understanding electric circuits is realizing that energy is used to create a separation of charge. The energy that the charges have becomes the source of energy for our electric circuits

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This imbalance of electrical charge we call electric potential energy.

A really big issue in beginning to understand electric circuits is the confusing word - VOLTAGE - and it is something we have found that on average only about 20 students in a class of 1000 have a good understanding of.

Some secondary school physics teachers refuse to teach their senior students about voltage but instead insist on using the more accurate terms of electric potential and potential difference. Did your physics teacher teach you about electric potential and potential difference or say voltage all the time? [▾]

Close the switch and hover the mouse over a bulb to see the value of the electric potential across it (the potential difference).

What is the electric potential **across** the RED bulb? [ ] **V**

What is the electric potential **across** the GREEN bulb? [ ] **V**

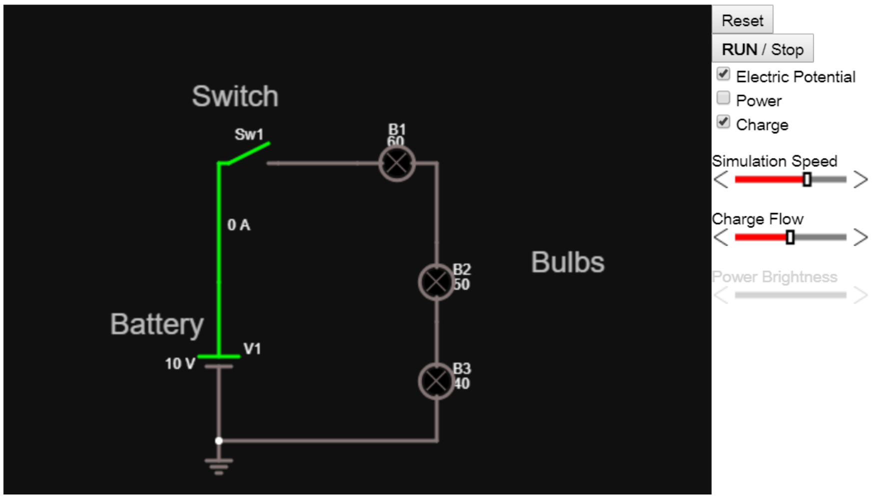
What is the electric potential **across** the BLUE bulb? [ ] **V**

What is the electric potential **across** the RED AND GREEN bulbs? [ ]

What is the electric potential **across** the GREEN AND BLUE bulbs? [ ]

The electric potential across all 3 bulbs when added together is the is the battery voltage [▾]

Electric potential ony has meaning when we talk about the difference in potential between two points. We will do more on this.



FCCT question 4

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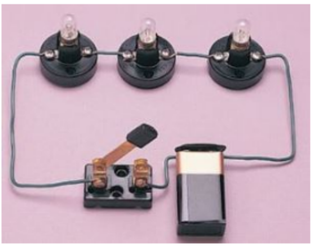
Learning Outcome: Understand fundamental electric circuit concepts as transfer, conversion and control of Energy

Keywords: Energy transfer, conversion and storage, Charge, Electric potential, Potential Difference, Voltage, Charge Flow, Current, polarity

Explain charge flow in an electric circuit

When the switch is closed - what moves?



You probably know that when you close the switch that there will be an electric current. But what is **Current?**

Circuit concept: current = rate of flow of charge

In the simulator you can see a simulation of charge moving, the small yellow dots that move along the wires and through components.

~~Current flow~~: Students and engineers often use the term *current flow* - YUK, that is incorrect. It goes back a few hundred years ago when the early scientists were figuring out what electricity was and thought it might be like water that flowed. Engineers, technical people, teachers, in fact almost everyone uses the term current flow; however current does not flow, charge flows. Does current flow in a river? No water flows and current is the rate of flow of water in a river. Because *current flow* is so widely used, students almost always do not get the right understanding, so for now think the word current even if your lecturer keeps saying current flow! If you are talking to someone and you need to put current into context so that it is not confused with current in a river then use electric current.

Did you ever have a teacher at school that really helped you understand this [▾]

Did your teachers in physics use the term [▾]

Circuit concept: conventional current

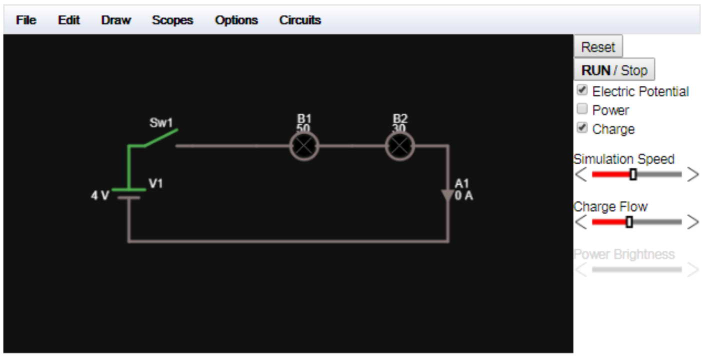
We say charge moves from the positive terminal (connection) of the battery to the negative terminal (connection) of the battery through the load. What actually moves? Electrons are mobile, they can move, they are negative charge carriers. The protons in the atoms that make up the wire conductor have positive charge and they do not move. Before scientists had the flash equipment that we have today they made a best guess at what was moving and thought it was positive charge. So we tend to talk about positive charge moving. A positive flow of charge can be thought of as when an electron moves from negative to positive it leaves a vacancy in the shell of the atom, a hole, behind it that has a net positive charge, so the vacant spaces (holes) appear to move in the opposite direction to the electrons. This gives the effect of moving positive charges. In this course we will only look at current as the movement of positive charge.

At school did you learn about [▾] charge flow (current).

Circuit concept: Why does charge move?

Here is a really really big idea that so few students really understand: **separation of charge causes a difference in electric potential, and when the difference in potential is applied to a closed circuit charges move.** A lot of people incorrectly say that a flow of charge causes a potential difference, this is not the case even though we often hear technical people and engineers say things like "a current of ... amps through a resistor will cause a voltage drop of ... volts". In this case the sentence would be better said "a current of ... amps through a resistor means there is a difference in electric potential of ... volts across the resistor".

Think about electric potential and electric current in a circuit this way. **Have you every tried to suck jelly through a straw? Saying current causes voltage is like saying the moving jelly causes the suck.**



We can actually work out the amount of charge that moves and the rate at which it moves. But you have done lots of math about that already for now just read the value of current from the ammeter in the circuit.

When the switch is closed In the circuit the rate of charge flow (the current) is: [ ] **mA** [ ] **A**

(All numerical questions require better than 1% accuracy to get marked correct)

Save Answer(s) | Get New Data

Qu:4, 3views, 0attempts, 0 fully correct | 0 fully correct and 0 required

FCCT question 5

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Learning Outcome: Understand fundamental electric circuit concepts as transfer, conversion and control of Energy

Keywords: Energy transfer, conversion and storage, Charge, Electric potential, Potential Difference, Voltage, Charge Flow, Current, polarity

Explain the different types of models used in electric circuits and the purpose of each

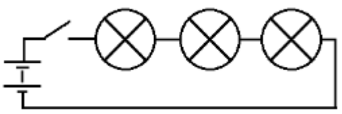
Modeling and being able to see models as ways of thinking about the real world is at the very core of all engineering.

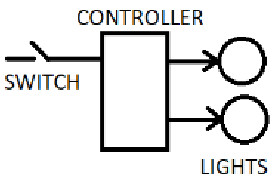
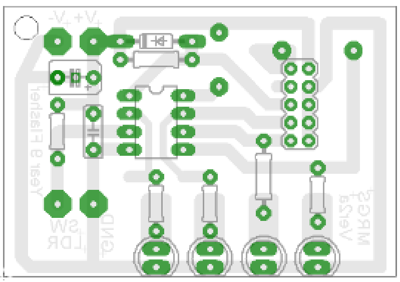
What is a model in electrical engineering?

A model is a description of a real object or phenomenon that communicates:

1. **function** or
2. characteristics, which can be
    1. **physical characteristics** such as shape, size and weight
    2. **energy related phenomena** such as voltage, current, power specifications

A model helps us in a very important way, the model communicates only the function or characteristics we want to deal with at that point in time .

Model	Use
Component Symbols 	Although a component like a switch can come in any size and shape its **function** is communicated and understood by drawing its **symbol.** By using a simple symbol we are able to think about what the switch's function and not be confused by all the extra detail of what it looks like
Schematic (often called a circuit diagram) 	We use a schematic to represent **circuit function,** it is much quicker to **think** with schematics than using real images because we want see the component's function not what it looks like. Do you recognize the symbols for a bulb, a switch and a battery in this schematic? It does not matter what the switch or bulb actually look like, we can use the general symbol for any bulb

System block diagram 	Here we use a conceptual diagram to model the **energy transformations** in a system, it has three parts: 1. **Input devices** transform energy from one form (e.g. kinetic, chemical, thermal, nuclear) to electrical energy 2. Inner **transformation processes** using electrical energy (sometimes we draw blocks inside this if it is a very complex transformation process) 3. **Output devices** transform electrical energy to some other form (e.g. kinetic, light, thermal)
Layout 	Here we use a scaled diagrams of the circuit board and components to model some of the **physical characteristics (the components 'foot print')**, so that we can design the circuit into the real world (e.g. on a printed circuit board inside a case)

Mathematical models e.g. Ohm;s Law "the current through a conductor between two points is directly proportional to the electric potential across the two points" often written as a formula **I = V / R**	OK so what's new here! Engineers think about Ohm's Law quite differently to school students. When we ask students what Ohm's Law is, they almost always respond incorrectly, they say V=I R. That's one way of writing the formula representation of Ohm's Law. However **Ohm's law is not a formula it is a model** (an explanation of a circuits behaviour), and states that the current through a conductor between two points is directly proportional to the electric potential across the two points. When an engineer looks at the formula, they think of it as a model not a formula. here is the way to think about Ohm's law in each algebraic form: I = V / R - Current is produced when an electric potential is applied to a closed circuit. The current will be in proportion to the voltage and inversely in proportion to the resistance of the path. R = V / I - When I measure current through and the difference in electric potential across a resistance it means that the resistance must be this value of Ohm's. V = I x R - The electric potential (or potential difference) across a resistive component is V volts if there is a current of I amps through it.

When you have a good understanding of models you begin to look at real objects or phenomenon and 'see' the model in your mind. This is not easy to begin with but it is something that is required in all engineering specializations.

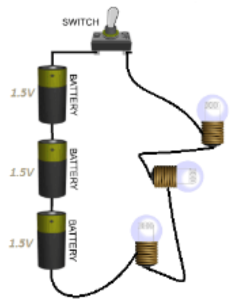
Simulations

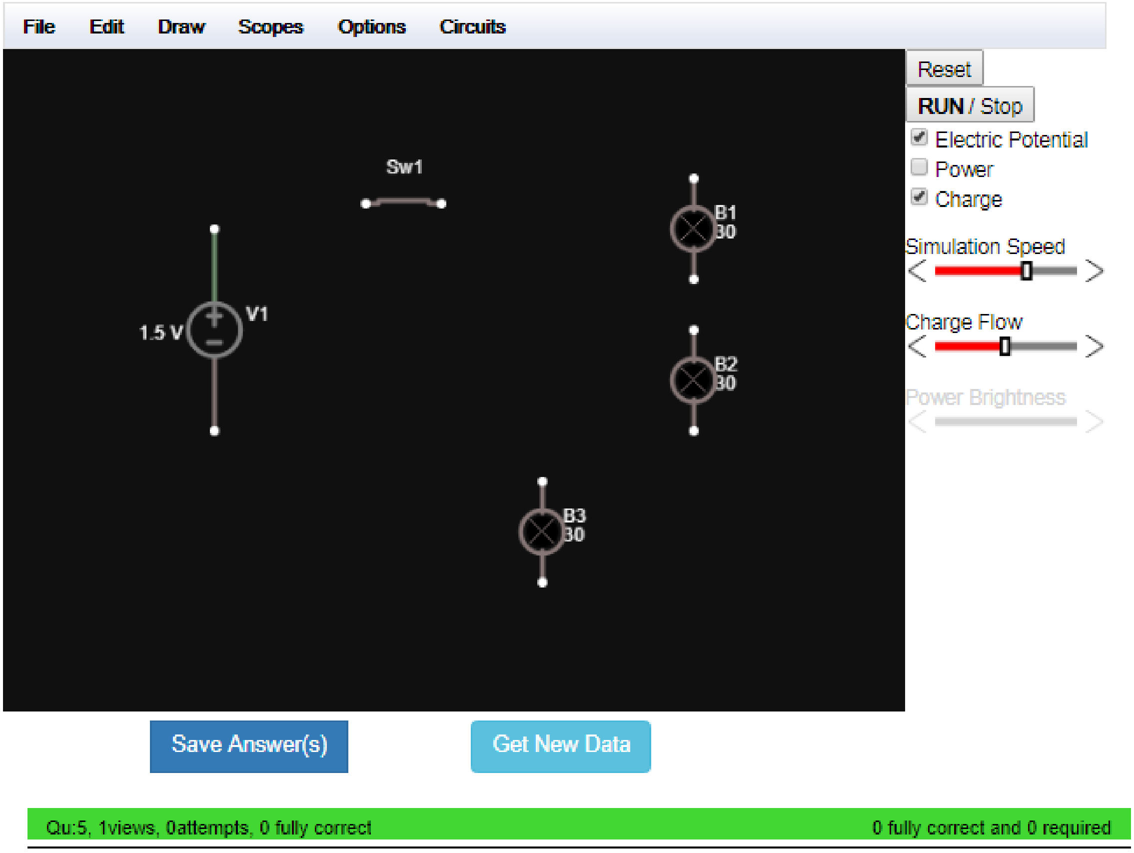
Models and real circuits do not always help us build deep understandings of what is happening inside circuits. This is because students have not been taught to see mathematical models such as Ohm's Law as describing circuit behavior but just as formula. And also because they have not been taught very well about electric potential and charge.

In the simulator is a switch, a constant voltage source and three bulbs.

Note the change from using a battery or cells for an energy source to a more accurate model a **constant voltage source.** Batteries are actually complex devices so in electric circuit theory we use a 'perfect' or 'theoretical' energy source - the constant voltage source.

Model this circuit. NOTE that the circuit has three cells each of 1.5V, in the simulator you do not need three cells you can model all three with one constant voltage source of 4.5V (right click on the source symbol in the simulator to get the edit menu to change the voltage to 4.5V, then complete the circuit by drawing wires and moving components, then press submit answer




File
Edit
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Scopes
Options
Circuits
Sw1
B1
30
1.5 V
V1
B2
30
B3
30
Reset
RUN / Stop
Electric Potential
Power
Charge
Simulation Speed
Charge Flow
Power Brightness
Save Answer(s)
Get New Data
Qu:5, 1views, 0attempts, 0 fully correct
0 fully correct and 0 required

FCCT question 6

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Learning Outcome: Understand fundamental electric circuit concepts as transfer, conversion and control of Energy

Keywords: Energy transfer, conversion and storage, Charge, Electric potential, Potential Difference, Voltage, Charge Flow, Current, polarity

Describe circuit topologies: closed, open, short

We often use these three terms with electric circuits:

closed: electric potential is applied to a circuit or part, of it so there will be a flow of charge and energy transfer can take place

open: no electric potential is applied to a circuit or part, of it so there will be no flow of charge and no energy transfer can take place

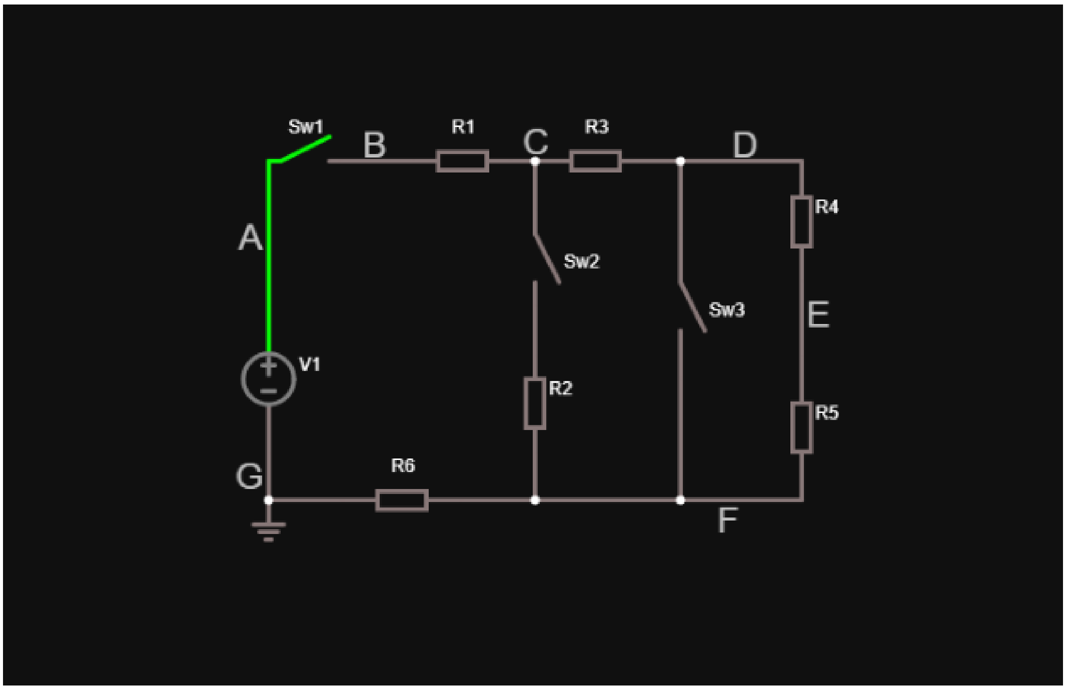
short: there is 0V potential difference across a circuit or part of a circuit, so there will be no flow of charge and no energy transfer can take place

---

Refer to the circuit in the simulator (the simulator is not active yet so the switches will not work and there will be no electric potential or charge visible)

1. Starting with all switches open in the simulator.
   - there [▾] electric potential applied to the resistors as so there is [▾] circuit
2. With **Sw1 closed**
   - there [▾] electric potential applied to resistor(s) ☐R1 ☐R2 ☐R3 ☐R4 ☐R5 ☐R6 which is/are in the closed circuit path
   - there [▾] electric potential applied to resistor R2 so it is [▾] circuit
3. With **Sw1 and Sw3 closed**
   - There is a [▾] circuit across R4 and R5 so there [▾] electric potential across them
   - there will be electric potential across ☐R2 ☐R3 ☐R5 ☐R4 ☐R6 ☐-r R1

On a scale fo 1 to 7 how confident are you in your answers? I haven't got a clue no ○1 ○2 ○3 ○4 ○5 ○6 ○7 Absolutely sure! yes



Save Answer(s) Get New Data

Qu:6, 2views, 0attempts, 0 fully correct 0 fully correct and 0 required

FCCT question 7

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Learning Outcome: Understand fundamental electric circuit concepts as transfer, conversion and control of Energy

Keywords: closed circuit, open circuit, short circuit, series circuit, parallel circuit, electric potential

Recognise circuit topologies: closed, open, short

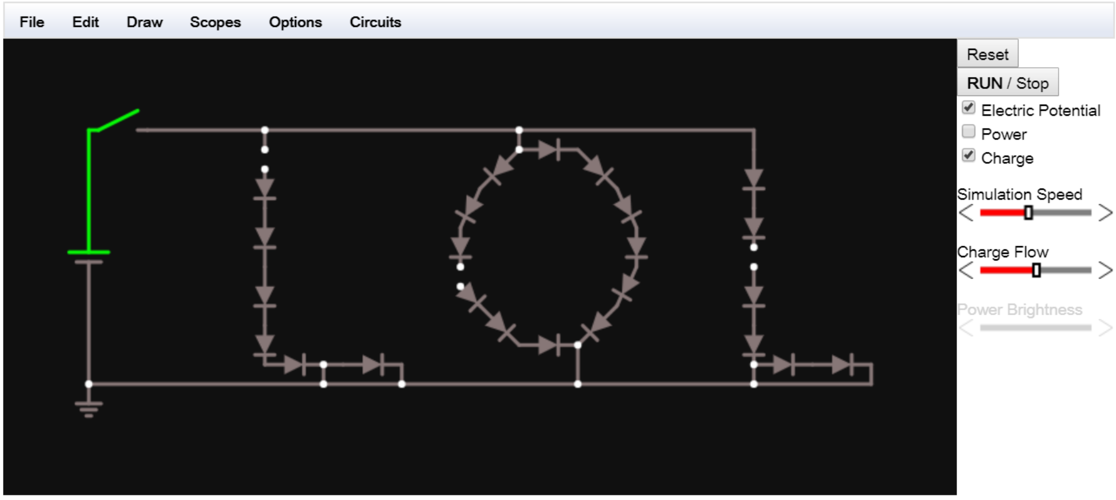
Refer to the circuit in the simulator

Due to poor soldering the LED sign doesn't work fully - close the switch to see that only some of the LED's light up. Fix the open and short circuits in the simulator to the message

(While the LED symbol usually has two small arrows to show it emits light - the LEDs in the simulator do not have the arrows - but they will glow red if the LED is on!)

Fix the open circuits by adding wires from the Draw menu or by selecting the end of an LED and dragging it to the other LED

Remove the short circuits that are stopping some of the LEDs from working



(note if you get a convergence error in the simulator it will stop - **de-select Stopped** when you have finished fixing the open circuits)

Save Answer(s)

FCCT question 8

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Learning Outcome: Understand fundamental electric circuit concepts as transfer, conversion and control of Energy

Keywords: Energy transfer, conversion and storage, Charge, Electric potential, Potential Difference, Voltage, Charge Flow, Current, polarity

Identify levels of electric potential with respect to ground in a circuit

Electric potential is the measure of relative level of electric potential around a circuit In the simulator are three portions of a circuit.

When we place a ground or in a circuit that becomes the 0V or reference point for the rest of the circuit.

In the simulation each source is 5V.

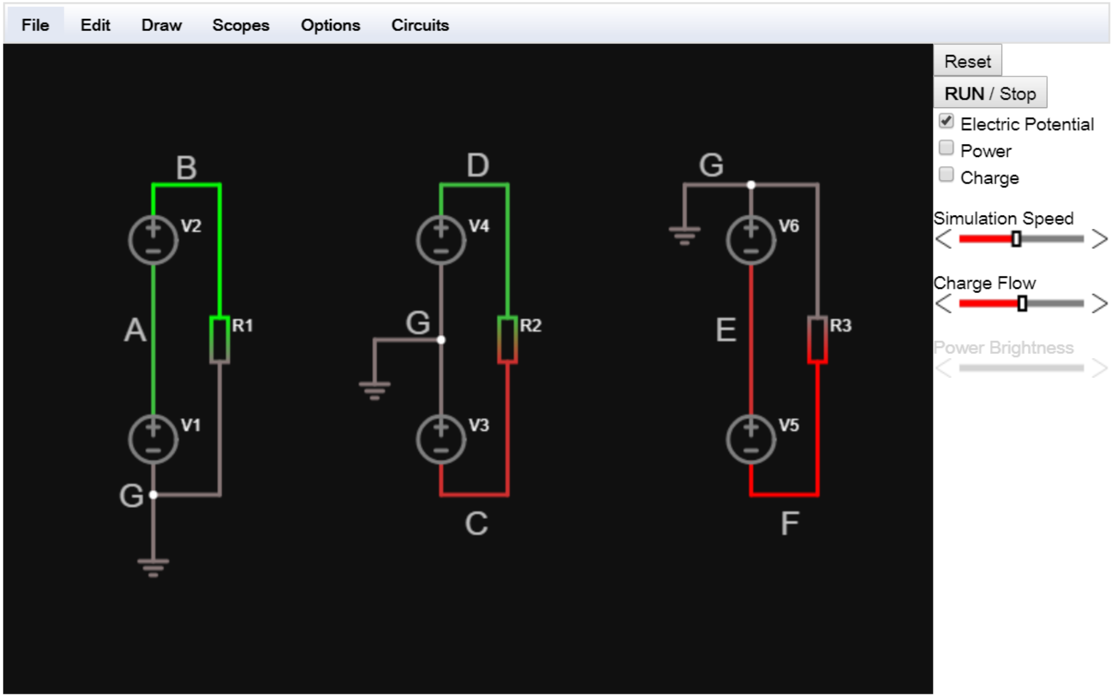
So on the left, A = 0V+5V and B = 0V+10V (or B = A+5V).

In the middle C = 0V-5V

On the right E = 0V-5V and F = 0V-10V (or F = E-5V)

Which nodes in the ciruit have the same electric potential?

- [ ] A&D
- [ ] C&F
- [ ] B&D
- [ ] C&E
- [ ] D&C
- [ ] A&E



FCCT question 9

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Learning Outcome: Understand fundamental electric circuit concepts as transfer, conversion and control of Energy

Keywords: Energy transfer, conversion and storage, Charge, Electric potential, Potential Difference, Voltage, Charge Flow, Current, polarity

Create sources with both positive and negative values with reference to ground

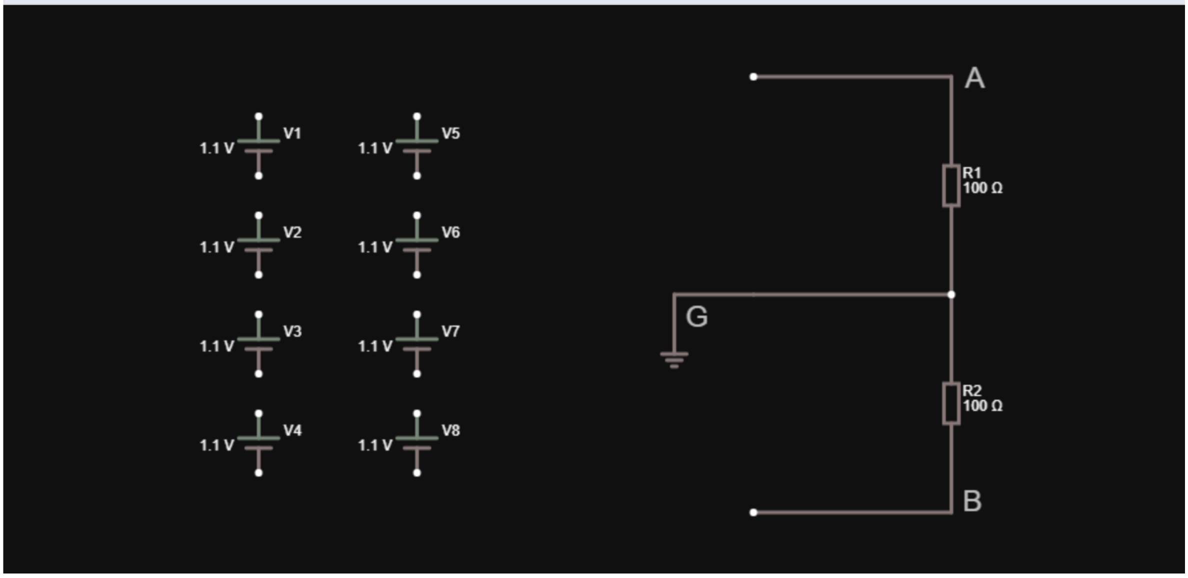
There are 8 cells in the simulator. Each has a value of 1.1V

Using the cells in the simulator build a circuit that has:

4.4V at node A

-2.2V at node B

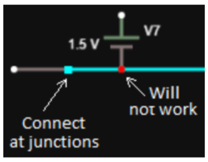
File Edit Draw Scopes Options Circuits



Click on the middle of a component to move it

Click on the junction at the end of a component to resize it

You must connect components at junctions in the simulator - they will not work if connected to the middle of a wire.



FCCT question 10

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Learning Outcome: Understand fundamental electric circuit concepts as transfer, conversion and control of Energy

Keywords: Energy transfer, conversion and storage, Charge, Electric potential, Potential Difference, Voltage, Charge Flow, Current, polarity

Identify causes and consequences of short circuits

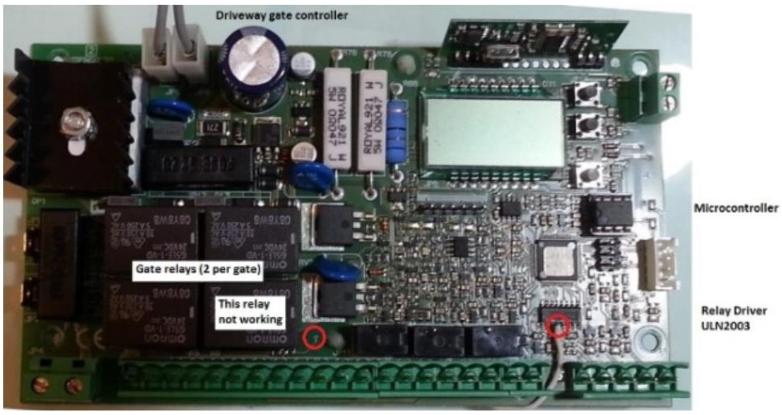
Not long ago, I arrived home late one evening, pressed the remote control for the electric gates and only one of the two gates opened!!

How inconvenient! I had to get a spanner and disconnect the gate motor from the gate so we could get in.

The next day I began fault finding the system.

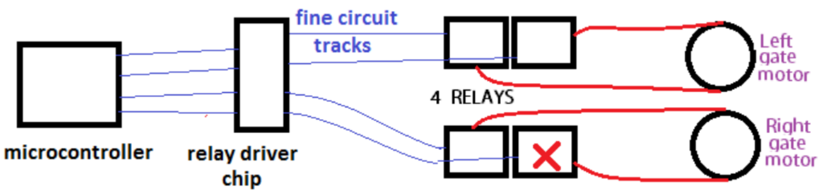
Important knowledge point #1 : The first thing I did was clearly understand the issue and so I tested every feature and I quickly realized that the one gate worked correctly but the other would electrically close but not open.

Next to the gate is the control box, this is the circuit board from it.



Important knowledge point #2: As an engineer I think in terms of models, so I mentally created a system block diagram to model the systems behavior.

You cannot see inside my mind (fortunately) so I have actually drawn the block diagram below.



Then using the model of the system to understand what was going on, I got my meter out, connected the black lead to ground and measured the voltage coming out of the gate relays and I found one of the relays was not operating

Important knowledge point #3: <u>thorough</u> testing - not guess work. Still thinking about the system block diagram and while activating the gates, I connected the red lead of the meter to various tracks on the board that drove the relays. I measured the input to the relays and found that one of the relays had no electric potential (voltage). MMMMMM - the other three did do it should have had some!!

I then measured the electric potential coming out of the microcontroller gong to the relay driver chip - mmm that was right, I then measured the electric potential coming out of the relay chip going to the relay that was ok!

Important knowledge point #3: thorough testing - not guess work. Still thinking about the system block diagram and while activating the gates, I connected the red lead of the meter to various tracks on the board that drove the relays. I measured the input to the relays and found that one of the relays had no electric potential (voltage). MMMMMM - the other three did do it should have had some!!

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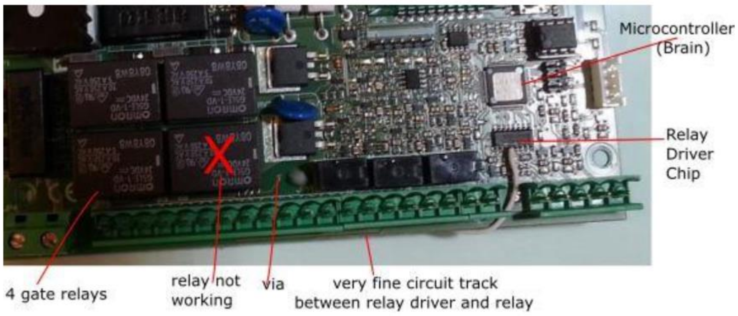
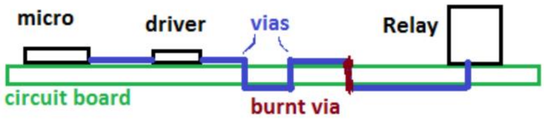


In my mind I created a partial schematic of the part of the board that was not working. I then began testing the circuit board track (copper wire connection on a circuit board).

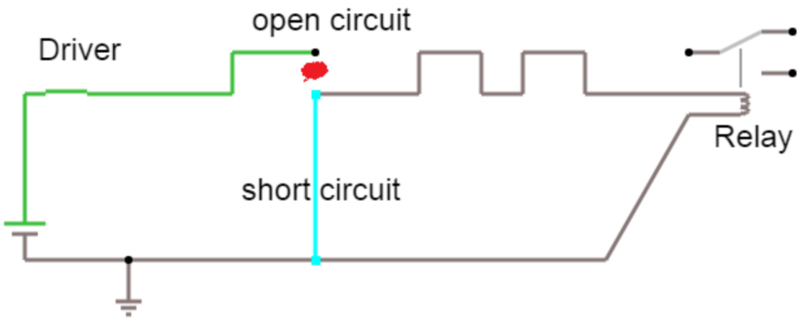
AND, I found that there was no connection at one of the vias (points where the track goes between the layers of the board). In fact it had burnt out (mini explosion actually!!).



Important knowledge point #3: reflective thinking using a schematic model.

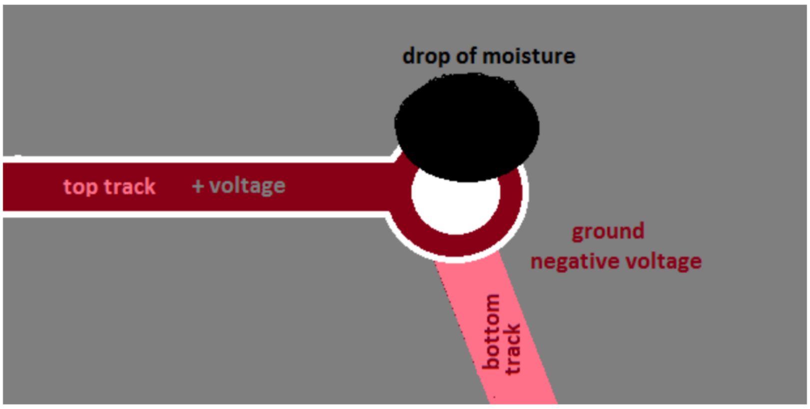
I then needed to do a bit of thinking as to what could have caused the problem and if I could fix and what could I do to stop it occurring again.

I started by creating a schematic in my head something like the one drawn below, the energy source was being switched by the driver chip which is an electronic switch so you model it with a switch. The short circuit is modeled by the light blue colored wire and the open circuit the red puff of smoke!



I then needed to do a bit of thinking as to what could have caused the problem and if I could fix it, and what I could do to stop it occurring again.

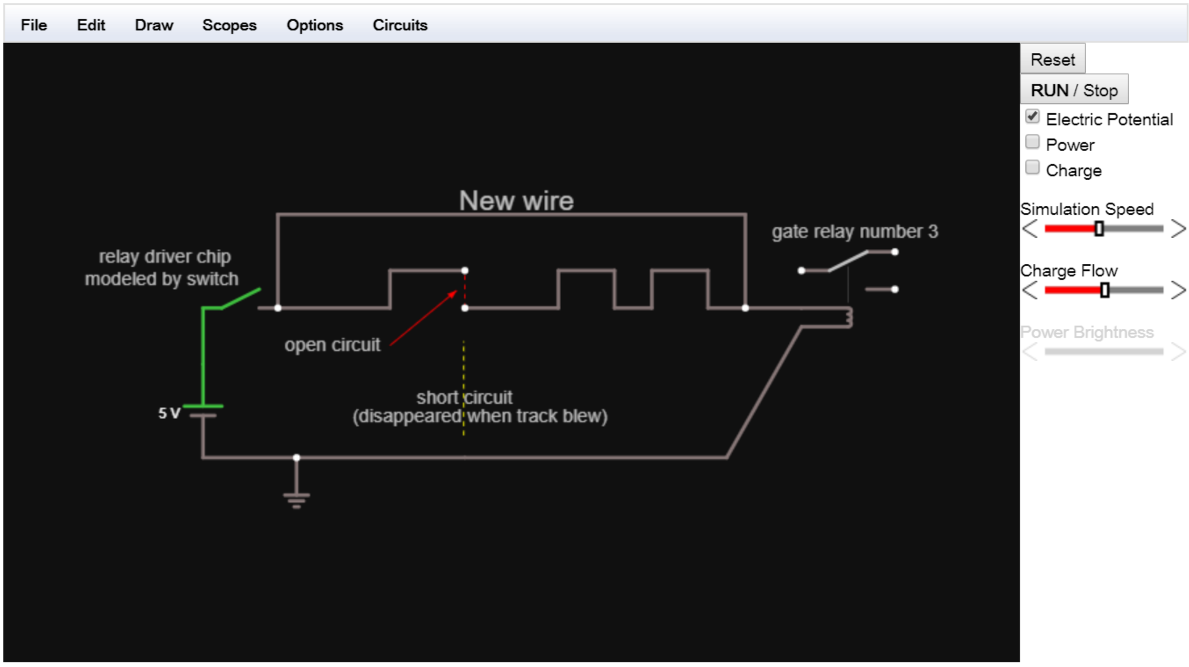
Tracks and vias on circuit boards are really really fine (about 0.5mm wide and 0.05mm thick) and would normally carry only a very small electric current. However if it gets a short circuit to ground then it can suddenly carry a large current and will disappear in a puff of smoke! I think a drop of moisture (or an ant) shorted the electric potential from track to ground (0V electric potential) and that was the end of the via (and the water drop/ant as well). I would have to think about sealing the box better or regularly checking it is dry inside.



Important knowledge point #4: strategic thinking. Here I began thinking abstractly (in general terms) about the issue (the electric potential not getting from the driver chip to the relay) not the actual context of the problem (the burnt out via). I realized all I needed to do was make a connection somewhere along the path that bridged the open circuit. The tracks are so fine you cannot solder to them and I thought it would be easiest to solder a new wire from the pins on the chip to the large pins on the relay. This made it a **closed circuit** again so the electric potential could get from the driver chip to the relay.

Can you complete this sentence about the issue.

I had replaced the [▾] circuit in the track caused by the [▾] circuit (from the drop of moisture or ant) with a new wire in [▾] with the old track making [▾] circuit again.



Save Answer(s)

FCCT question 11

Learning Outcome: Understand fundamental electric circuit concepts as transfer, conversion and control of Energy

Keywords: Energy transfer, conversion and storage, Charge, Electric potential, Potential Difference, Voltage, Charge Flow, Current, polarity

How energy sources are actually drawn in electric circuits

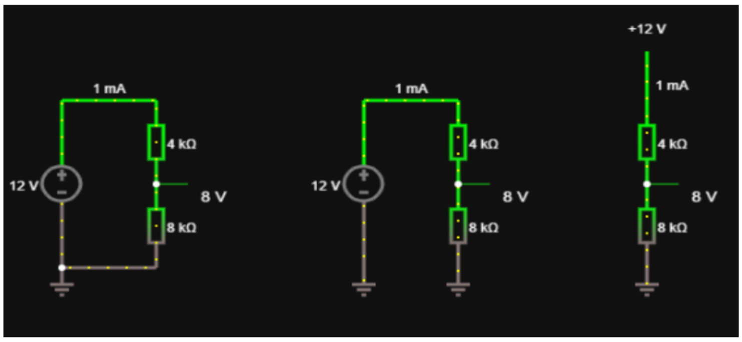
Sometimes in electronics our schematics get very very large!

The first course I ever wrote and taught was for this Marconi 10kW transmitter, it is 2M wide x 2M high x 1M deep.

It had books of schematic diagrams.

In complex pieces of equipment there is a neat trick that engineers use to simplify schematic diagrams.

We often draw voltage sources with a single connection not with two connections. We do this by hiding the ground connection, this is what they llok like.



Each of these three circuits is exactly the same.

1. In the first all the wires are shown - that is ok for small circuits.
2. In the second there is 1 less wire than the first as the ground symbols are used to show the points are electrcially connected together.
3. In the third circuit we just draw the positive potential to use as few wires as possible - this is great for large complex circuits. There is still a loop from ground back to the supply though - we just do not draw it.

You can tell they are all the same, the electric potentials and the resistor values are the sanme so the resultant current are the same.

Here I have put together your growing understandings of Ground and how power supplies are drawn to make **a** silly circuit.

Note:I call it '**a**' circuit as these parts are one circuit, they are not separate circuits. Every voltage that is the same value is connected together, this includes ground (0V)

- +12 is Bright Green
- +5V is green
- 0V is gray
- -5V is light red
- -12V is bright red

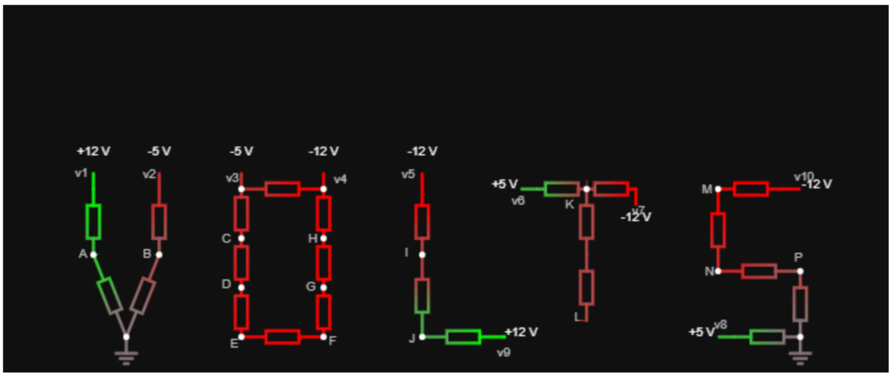
Each of the connections v1 to v10 has been made to one of the four supply voltages <u>and all the resistors are the same values</u>

For example v2 and v3 are connected together and are at -5V. And v4, v5, v7 & v10 are connected together.

This means that it is valid to calculate or take measurements between points such as H and N or between K and A.

- Example: The electric potential (voltage) **at** point B is -2.5V (**at** means the PD from point A to ground) note direction is important and ground is 0 so it is negative. The value is going to be half of v2 because the resistors are all equal values.

1. Point A is [▾] with respect to ground
2. Point H is [▾] with respect to ground
3. What is the voltage at point I? [ ] V
4. What is the voltage at point J? [ ] V
5. What is the electric potential at M [ ] V
6. What is the pd at point K [ ] V
7. What is the voltage at point L [ ] V



FCCT question 12

Learning Outcome: Understand fundamental electric circuit concepts as transfer, conversion and control of Energy

Keywords: Energy transfer, conversion and storage, Charge, Electric potential, Potential Difference, Voltage, Charge Flow, Current, polarity

Describe Ohm's Law as a model for circuit behaviour

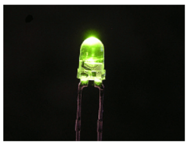
In the early 1800's Georg Ohm found some amazing things about electricity, he found that:

1. electric current passing through a wire is the same at any cross-sectional area of a wire
2. electric current is directly proportional to the potential difference applied to the circuit
3. electric current is directly proportional to the cross-sectional area of a wire
4. electric current is inversely proportional to the length of the wire
5. when the conductor is uniform, the potential falls uniformly from its highest value at the positive pole to its lowest value at the negative pole.

We use Ohm's Law all the time however students often do not know the meanings behind it, here is an example - no calculation but ohm's Law is required

An LED (light emitting diode) such as the one here typically requires about 2V and 20mA to light up brightly.

If too much current is allowed to flow through the LED the it will burn up! We use a resistor in series to limit the electric potential across the LED and hence the current through it.



In the simulation below the two parts of the circuit each with an LED are connected to a 32V power supply

LED D1 has too much current through it because the resistance in series with it is too [▾].

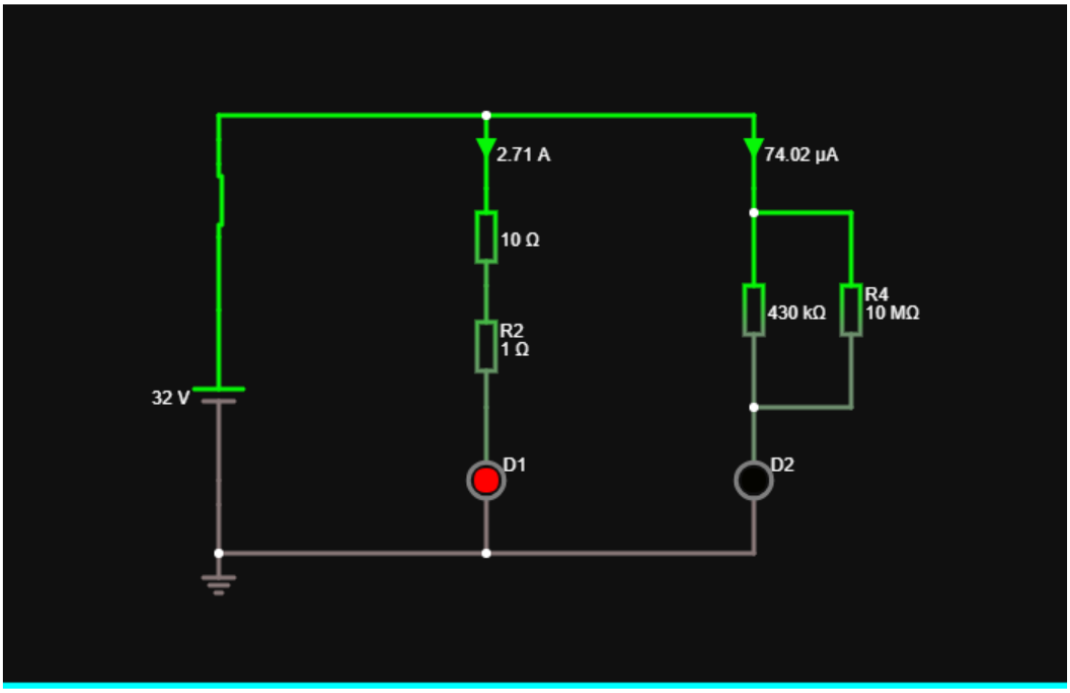
LED D2 has too little current through it because the resistance in series with it is too [▾].

You want to make the current in each LED **less than but as close as possible** to 20mA

You can find details about the values in each E-series of preferred numbers on Wiikipedia (or on many other websites)

1. Change the value of R2 from 1Ω to the best value available from the E12 series.

2. Change the value of R4 from 10MΩ to the best value available from the E12 series.



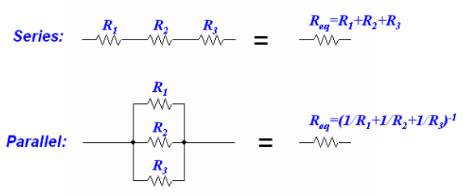
FCCT question 13

Learning Outcome: Understand fundamental electric circuit concepts as transfer, conversion and control of Energy

Keywords: Energy transfer, conversion and storage, Charge, Electric potential, Potential Difference, Voltage, Charge Flow, Current, polarity

Replace simple series or parallel combinations with an equivalent resistance.

You will have most likely done quite a few series and parallel resistor calculations in your time, and become very familiar with these formula.



It is all very well being able to calculate the value of two or more resistors in series or parallel but being able to recognize why, when and what to do with your answer is much more important.

The reason for doing these calculations is so that you can simplify a complex circuit into some equivalent simpler circuit.

Thinking about our learning outcome for understanding about energy in electric circuits. If we replace two series (or parallel) resistors with 1 equivalent resistor it means the single resistor will have the equivalent (same) effect on the energy transfer in the circuit as the two resistors did.

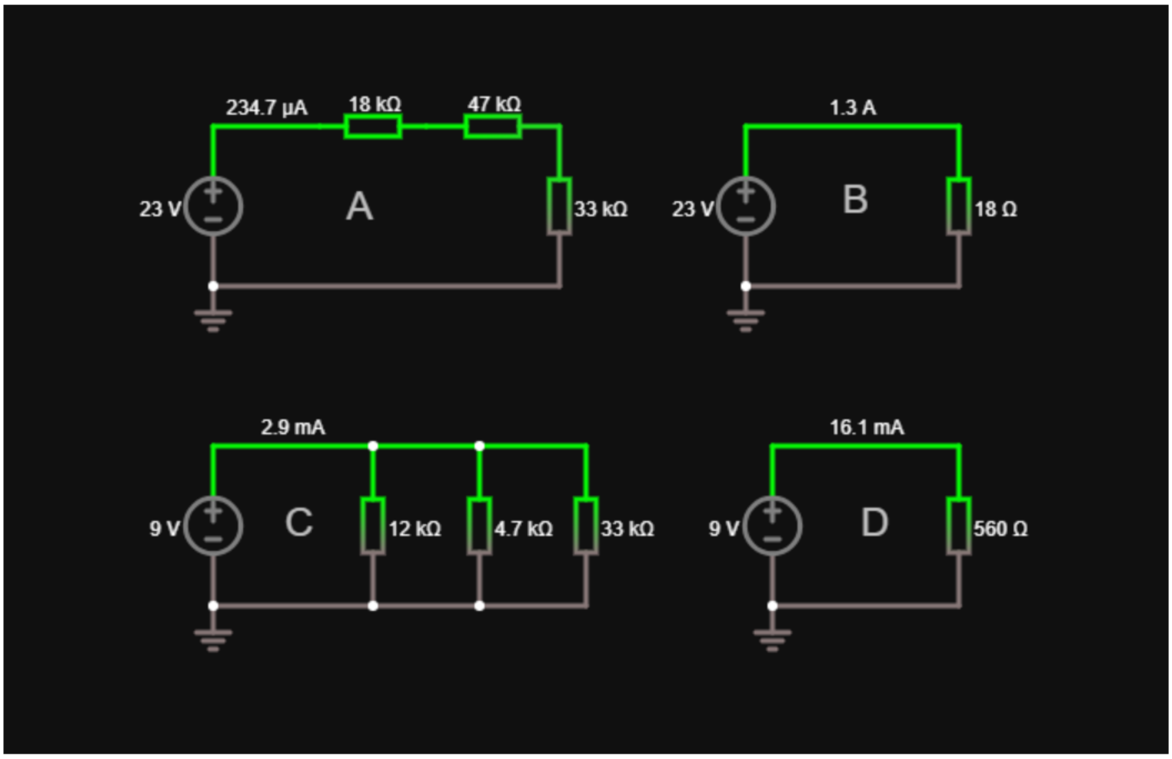
In the simulator there are 4 circuits.

You need to make circuit A and B equivalent, then make circuits C and D equivalent

You can edit the value for R4 and R8 by double clicking on them, then change their values so that:

1. the current in circuit B = the current in circuit A
2. the current in circuit D = the current in circuit C

the currents need to be within 1%



Save Answer(s)

FCCT question 14

Previous Question | ELECTENG 101: Fundamental Circuit Concept Tutorials 2018 - wcol001 - Question:14 of 16 (Value=1) | Front Page | NextQuestion

Learning Outcome: Understand fundamental electric circuit concepts as transfer, conversion and control of Energy

Keywords: Energy transfer, conversion and storage, Charge, Electric potential, Potential Difference, Voltage, Charge Flow, Current, polarity

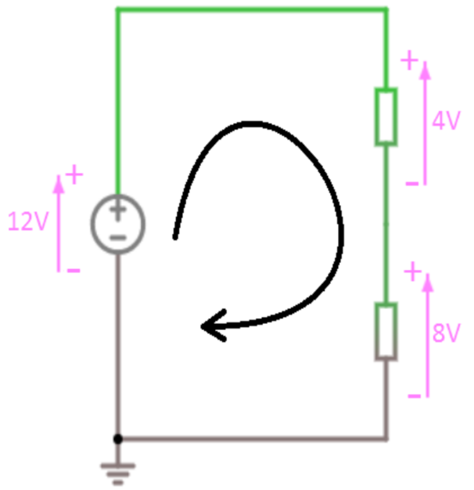
Explain electric circuits in terms of energy conservation using KVL

The law of conservation of energy states that **the total energy of a system remains constant**—it can neither be created nor destroyed.

Gustav Kirchhoff's Voltage Law (KVL) is how we use the energy conservation law with the levels of electrical energy (voltages) around a circuit.

In each loop in a circuit the levels of electric potential across all devices must always sum up to zero.

Here is a really simple one loop circuit. If we move around the loop in the direction of the black arrow we can add the voltages in the loop.



This becomes -12V + 4V + 8V = 0V.

BUT how do we know whether to add or subtract the electric potential across each component?

1. Draw a voltage arrow next to each component that shows which is the most positive end of the component.

In this simple circuit can you see which end of each component is higher in potential than the other? That will be the +

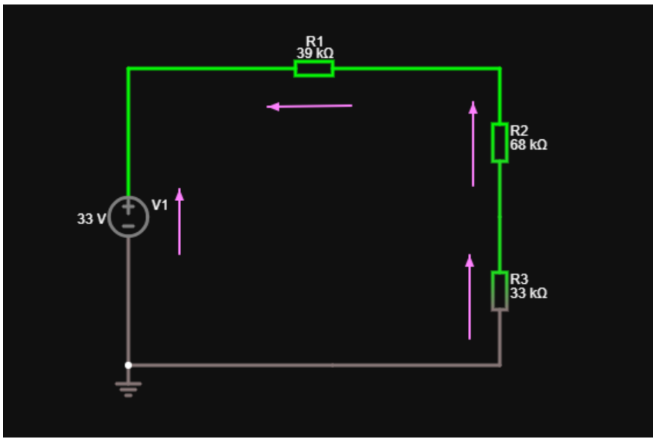
2. Then as we move around the circuit you wil notice that sometimes you come to a + on the component before the -

so we add a voltage if we see the + first and subtract it if we see the - first. In the above diagram the order we see the electric potentials is: -12V then +4V then +8V

in this simulator the + and - are not actually needed as the arrow direction shows which end has the higher potential.

Now write the equation for the circuit in the simulator (hover your mouse pointer over the component to see the potential difference across it)

▾ 33V ▾ 9.19V ▾ 16.03V ▾ 7.78V = 0V



FCCT question 15

Previous Question ELECTENG 101: Fundamental Circuit Concept Tutorials 2018 - wcol001 - Question:15 of 16 (Value=1) Front Page NextQuestion

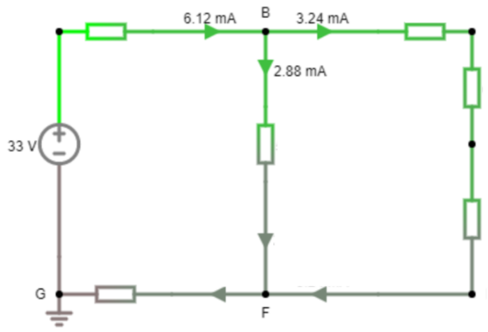
Learning Outcome: Understand fundamental electric circuit concepts as transfer, conversion and control of Energy

Keywords: Energy transfer, conversion and storage, Charge, Electric potential, Potential Difference, Voltage, Charge Flow, Current, polarity

Explain electric circuits in terms of conservation of energy using KCL

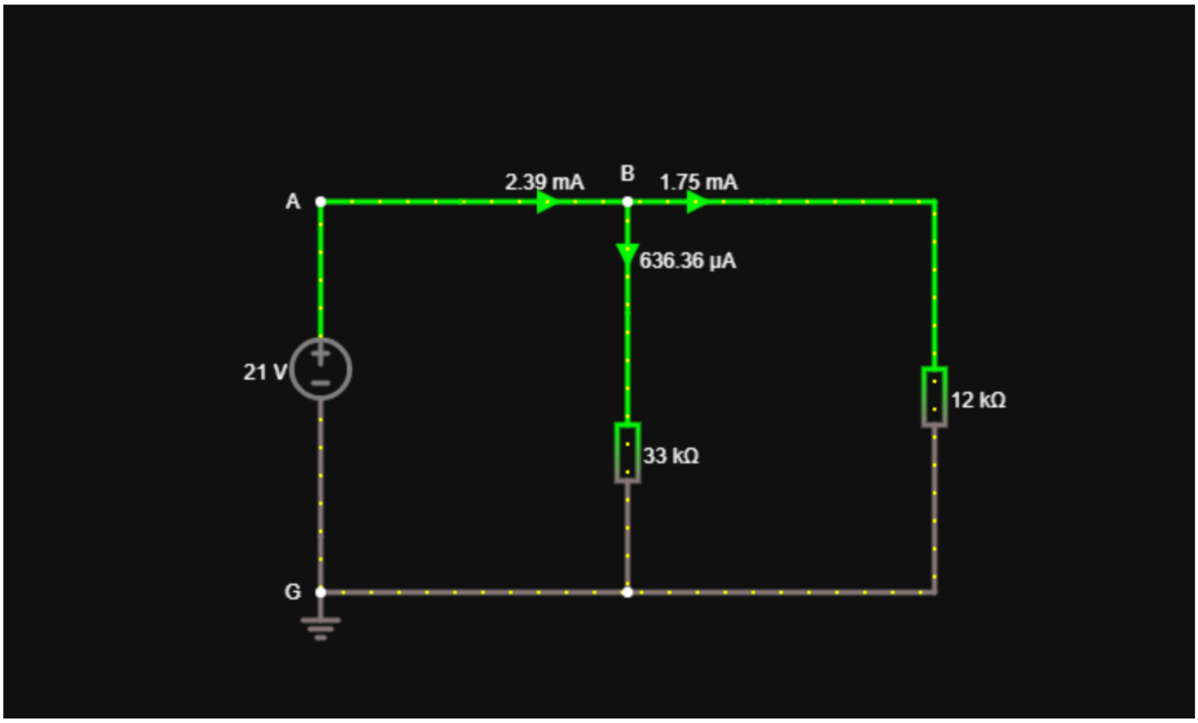
Gustav Kirchhoff's Current law is another rule based upon the conservation of energy, i.e. at any node the sum of all currents entering and leaving will be 0.

In this circuit, At node B we can form an equation for KCL +6.12mA - 3.24mA - 2.88mA = 0A



For the circuit in the simulator (hover your mouse pointer over the component to see the current through it)

2.39mA 640uA 1.75mA = 0A



FCCT question 16

Previous Question | ELECTENG 101: Fundamental Circuit Concept Tutorials 2018 - wcol001 - Question:16 of 16 (Value=1) | Front Page | NextQuestion

Learning Outcome: Handle metric prefixes correctly

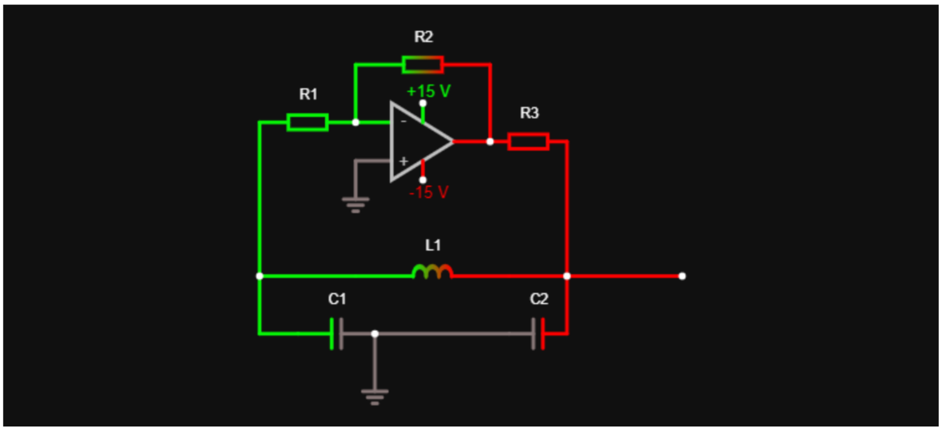
Keywords: units, prefixes

Practice conversions between metric prefixes

Here is an opamp oscillator circuit, don't think about the circuit for now - we just want you to practice prefix conversions with the component values.

In the circuit there are some resistor, inductor and capacitor values and a voltage source V1, convert the values to the required units as per the text boxes below

Component	Value	Conversion 1	Conversion 2
R1 value	= 2200Ω	= kΩ	= MΩ
R2 value	= 10000Ω	= kΩ	= MΩ
L1 value	= 0.68H	= mH	= uH
C1 & C2 values	= 3.3E-06F	= uF	= nF



Appendix 4. **ElectEng101 Learning Objectives**

At the end of electrical energy module lectures, students should be able to understand and/or describe

- Primary sources of energy
- Concepts of electricity generation, transmission, distribution and utilization
- Usefulness of electric circuits and mathematical models during design & implementation
- Direct Current (DC) and Alternating Current (AC) electricity
- Single-phase and 3-phase electricity
- Calculation of electrical power and energy
- Apparent, active and reactive power, and power factor associated with an electric
- circuit
- Faraday's Law and Lenz's Law
- Usefulness and applications of inductors, transformers and electric motors
- Operation and modelling of permanent magnet commutator motors
- Residential wiring and the importance of electrical safety

Number Systems

- Be able to convert numbers between different bases. Including,
    - Decimal - base 2 (binary)
    - Decimal - base 16 (hexadecimal)
    - Binary - hexadecimal
- Logic Gates
- For each of the logic gates (AND, OR, XOR, NOT, NAND, NOR, XNOR) be able to:
    - Draw the circuit symbol.
    - Write the truth table.
    - Define the equivalent Boolean algebraic expression.
- Be able to develop truth tables for combinations of logic gates.

Boolean Algebra

- Be able to develop truth tables for Boolean expressions.
- Be able to write Boolean expressions for logic circuits.
- Be able to convert truth tables to Boolean expressions.
- Be able to explain the operation of
    - A half adder
    - A full adder
    - An N-bit binary adder

Sequential Logic Circuits

- Be able to determine the timing diagrams for simple sequential logic circuits.
- Be able to determine the output of an SR flip-flop.
- Be able to describe the differences between level- and edge-triggered devices.
- Be able to determine the timing diagrams for:
    - A level-triggered SR flip-flop
    - A level-triggered D flip-flop
    - An edge-triggered D flip-flop

Transducers

- Be able to describe the operation of transducers which are based on variations in:
    - Resistance
    - Current
    - Voltage
    - Capacitance
    - Inductance.
- Be able to sketch the architecture and explain the operation of a computer-based

Data Acquisition System

- Be able to specify signal conditioning circuitry appropriately so that it neither too severely loads the input transducer nor presents too high an output resistance to the data acquisition circuitry.

- Be able to calculate the requirements of signal conditioning circuitry, given the characteristics of both the input transducer and the data acquisition circuitry.
- Be able to draw a Thevenin equivalent circuit.
- Explain the extent to which a Thevenin equivalent circuit is equivalent to the original circuit.
- Calculate the Thevenin equivalent voltage.
- Calculate the Thevenin equivalent resistance.

Signal Conditioning

- Be able to sketch a model of a voltage amplifier.
- Be able to use a voltage amplifier model to determine circuit gain and output voltage, and to investigate the conditions for maximum power transfer.
- Be able to sketch the circuit symbol for an OpAmp and an internal model of an OpAmp.
- Be able to state the properties of an ideal OpAmp.
- Be able to use the virtual earth principle to simplify analysis of OpAmp circuits.
- Be able to use basic circuit theory (KCL, KVL, Node Voltage Analysis and
- Superposition) to analyse simple OpAmp topologies including:
    - An inverting amplifier
    - A non-inverting amplifier.
    - An inverting, summing amplifier.
    - A level shifter.
    - Cascaded OpAmp circuits.
    - A differential amplifier

Appendix 5. **Circuit simulator extensions**

Much of the epistemic capabilities of GECKO rely on the circuit simulator, and extensive modifications were needed to create the functionality desired. This involved: adding nomenclature (labels) to each component type (e.g. R for resistors, C, L etc.), writing code to automatically generate sequential component instances (e.g. R1, R2, R3 etc.), writing an API (application programming interface) to allow the simulator to be interrogated and controlled by GECKO, adding new component models and modifying a number of others. Making use of these new features automatically within questions involved developing a simple scripting language and repurposing an open-source tool as an interpreter for it.

Component labels

The original circuit simulation has no facility for identifying components other than their value. Changes to all the existing models in the simulator and the core classes was undertaken to add the ability to give components labels/nomenclature. This was essential so that an API could be written to allow GECKO to control, add, delete, hide, show and change values for individual components.

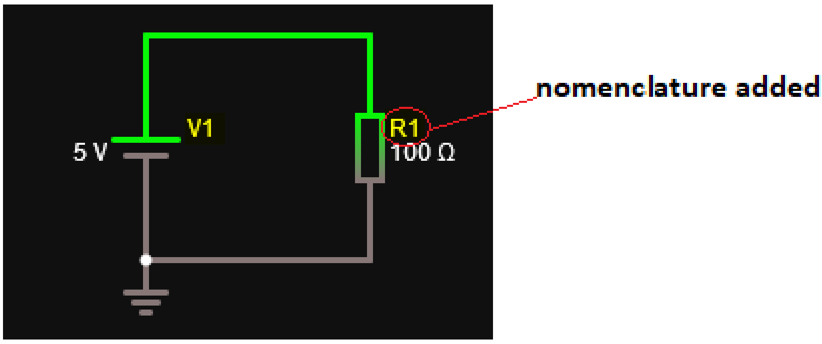


Figure 102: Component labels

OpAmp model

The common OpAmp symbol used in circuit diagrams (Figure 103) shows power supply connections to the power supply. The model for the OpAmp with the circuit simulator (Figure 104) is the same used in the ElectEng101 course notes; it has no power supply connections. This was felt to be an inadequate model for students who have poor understandings of the energy relationships in circuits particularly

Kirchhoff's Current Law. It was felt that a model which had charges flowing out of or into the output and going to or coming from nowhere else in the device (as in Figure 104) would not support their conceptual understanding. A new model was written for the circuit simulator to show the current to and from the power supply (Figure 105).

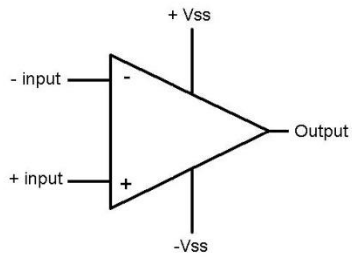


Figure 103 Typical OpAmp symbol with power supply connections

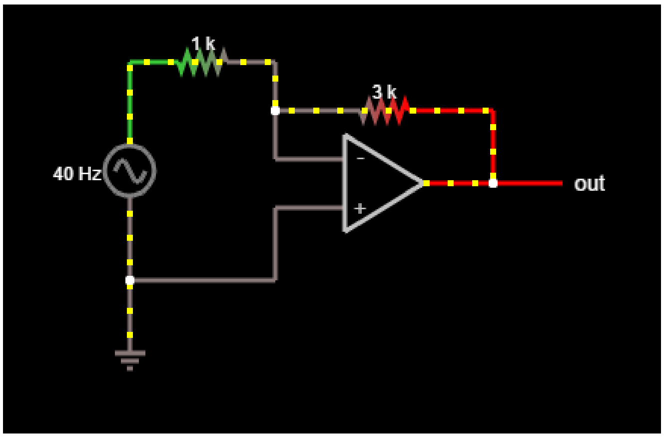


Figure 104 OpAmp model used in the simulator (no power supply connection)

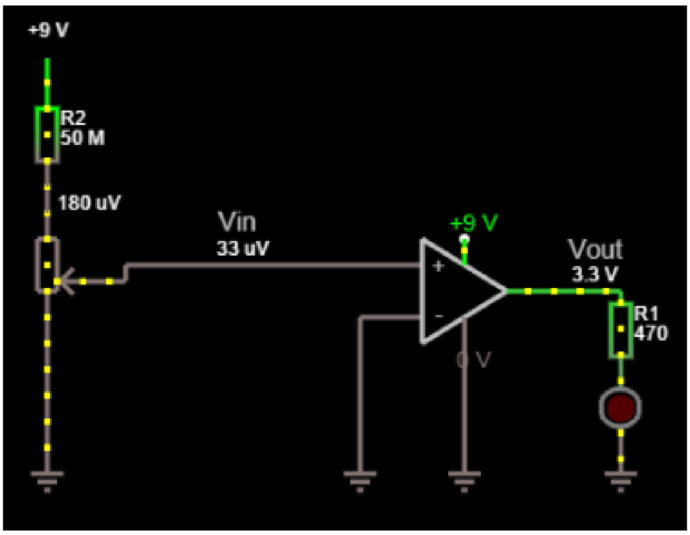


Figure 105 OpAmp model developed for use in the simulator with power supply

Sensor models

Two new sensor models were written to support student understandings of sensor use. An NTC thermistor model with resistance settings for 25 and 50 degrees Celsius (Figure 106) and a strain gauge model with nominal resistance, gauge factor and limits properties (Figure 107).

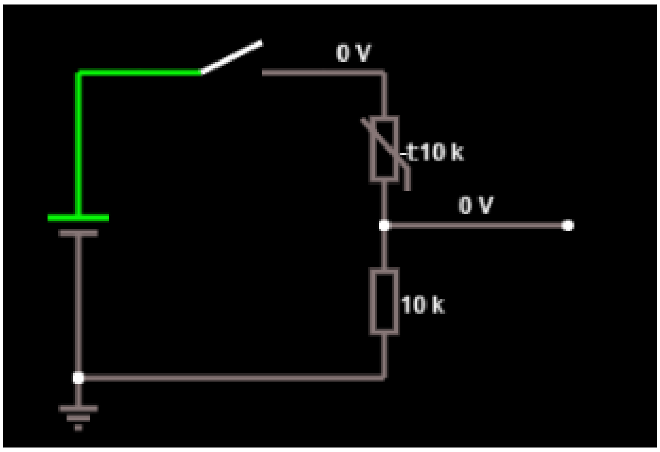


Figure 106 The new thermistor model in a voltage divider circuit

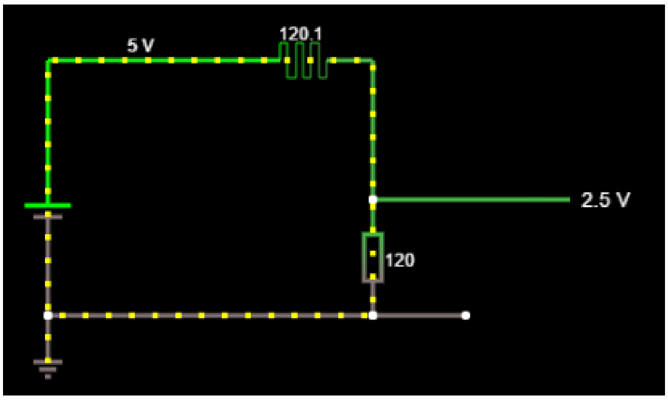


Figure 107 The new strain gauge model in a voltage divider circuit

Amplifier model

Electrical engineering often makes use of models for amplifiers and students in ElectEng101 struggle with foundational systems understandings involving input and output identification between the three subsystems (sensor, amplifier and load). An amplifier model did not exist in the circuit simulator and was developed for use with students (Figure 108) to support these understandings.

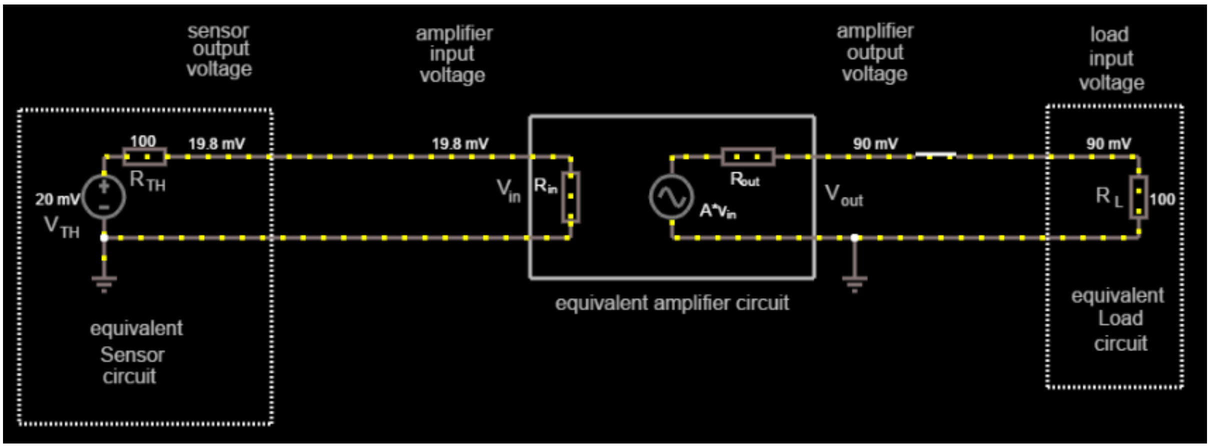


Figure 108 Amplifier model in context

Of note this fundamental systems understandings is one aspect of Technological Knowledge within the New Zealand Technology Curriculum, an area which I have been involved with the assessment of for many years. It is not an easy understanding to develop and was treated lightly in all the courses I observed.

Simulator options

The latest public version of the circuit simulator has options for display of Voltage, Current and a slider to vary 'Current Speed' (Figure 109).

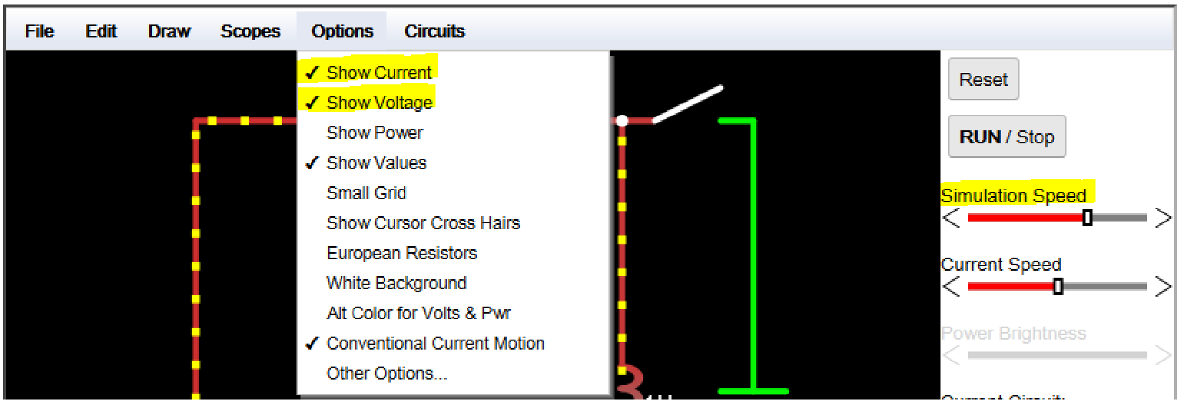


Figure 109: Existing open source simulator controls

For the modified version of the simulator it was felt that students conceptual understanding would benefit from more accurate terms e.g.: Electric Potential, Charge and Charge Flow (Figure 110). These were also moved to make them easier for students to use.

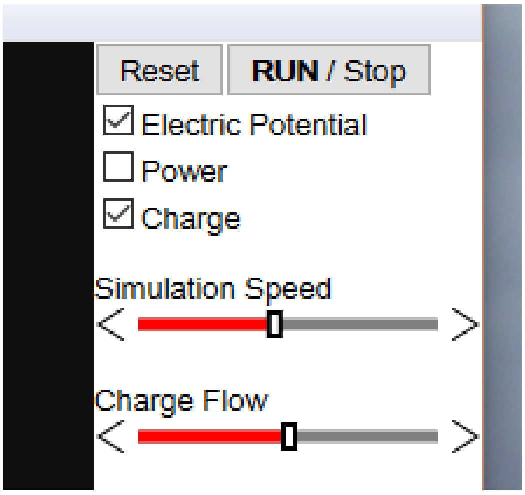


Figure 110: Modified simulator controls

Resistor power ratings

These were added to the resistor model for use with circuits to demonstrate energy related understandings.

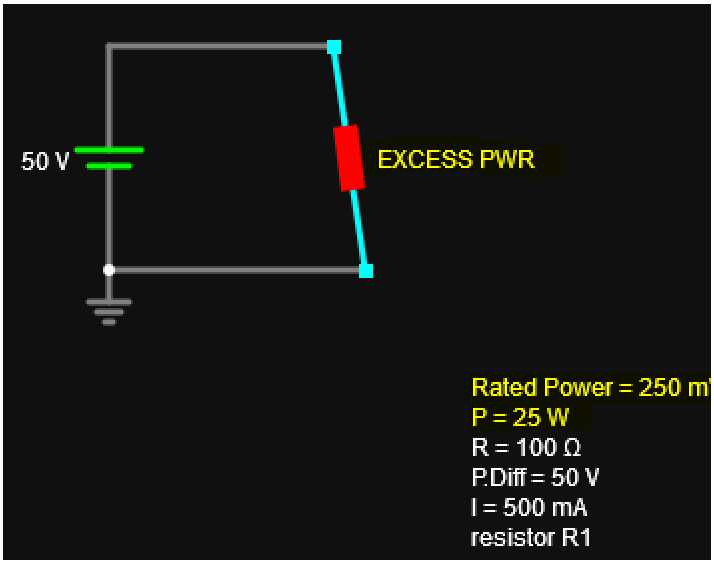


Figure 111: Resistor power ratings

New and modified digital components

Several new digital component models were developed and others modified Figure 112. In addition to these 8 and 16 bit multiplexers were also added

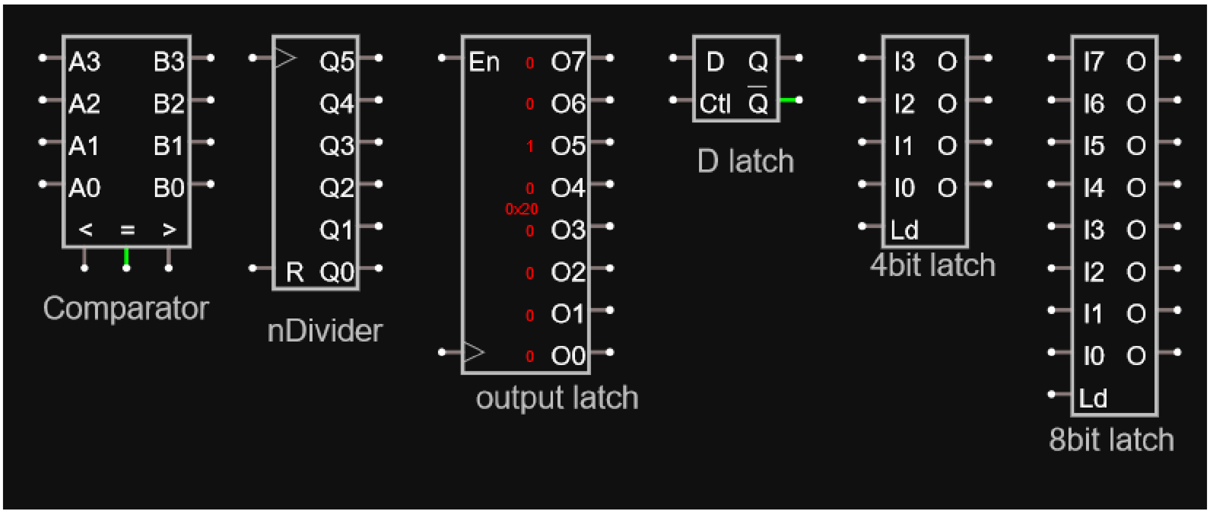


Figure 112: New digital components

Modified voltage sources

The existing voltage source is drawn as a battery symbol, however this is not correct as a battery has internal resistance. So the model was copied and modified so that there are now two dc sources types: an ideal battery and a dc voltage source.

New test point

A new test point model was written so that when students are asked to create circuits their models can be interrogated by the software to see if they conform to specifications given.

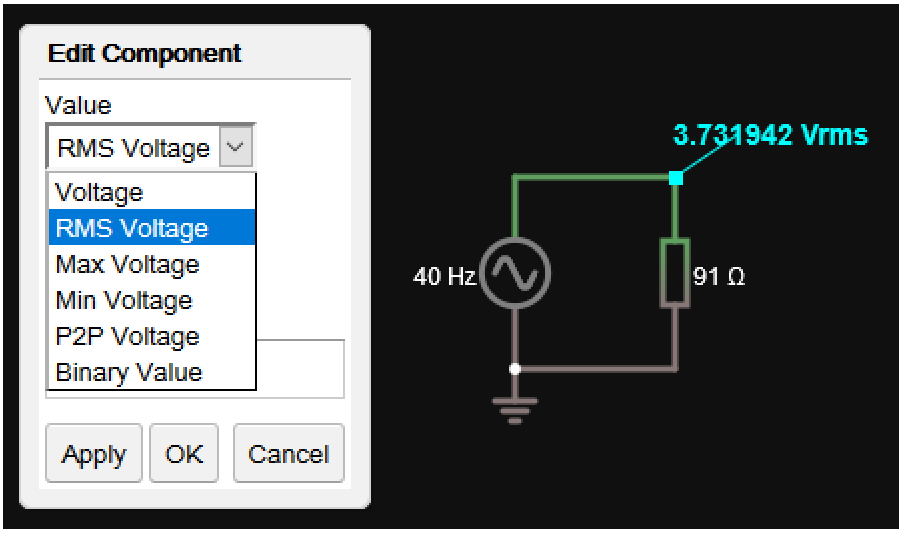


Figure 113: Test point model

The API developed for the open-source circuit simulator

Command	Comment
set(R1, value, R1val)	set the value of R1 in the simulator to the value stored in R1val
set(R1, value, 12)	set R1 value to 12 ohms
set(Sw1, value , 0)	0= closed 1 = open
set(R1, highlight, warning)	colour options are: false, warning, info, success, danger
set(R1, displaylabeloverride, true)	Toggle display state of label
set(R1, displayvalueoverride, true)	Toggle display state of value
set (R1, tempr, 99)	set temperature of a thermistor component, you can also set r25, r50, mintempr, maxtempr values
set(R2, pos, 0.3)	set position of a potentiometer 0 to 1 range, take careful note of the orientation of your pot when you add it to the simulator
set(Text1, text, Hi how are you)	change the text in a text element
VText = concat(Vval,\u2220,0,\u2218) set(Text1, text, VText) set(Text3, -junittext, XCval, \u03A9) set(Text4, unittext, Rval, \u03A9) set(Text5, junittext, XLval, \u03A9)	use symbols, j, -j within text in the simulator

set(Text1, size, 10)	font size
set(Text1, visible, true/false)	Change text visibility
set(Text1, bar, on/off)	bar over text (as used for logic not)
set(scope N maxscale)	Scopes are numbered 0 to N-1, options are maxscale, scale, speedup, slowdown, reset, showCurrent(T/F), showVoltage(T/F) showMax(T/F), showMin(T/F), showFreq(T/F)
set(Line1, width, 4.4) set(Line1, R, 50) set(Line1, G, 150) set(Line1, B, 0) set(Line1, visible, true)	There are 3 types of lines (line, dashed line, dotted line) By default lines are white in colour, but can be changed Width is a double - (3 is the width of wires and components) Visible (true/false)
set (R1, swap R2)	swaps the components in the circuit
deleteComp (R1)	delete a component
hideComp (R1)	hide a component e.g., hideComp(Sw1,Sw2,Sw3,Sw4)
show Comp (r1)	show a hidden component
set(V1, rotate180, 1)	1 = rotate V1 180 degrees, 0= no rotation
set (option, fastsimulaton, 50)	makes the simulation carry out multiple iterations rapidly so that new settings, or scope measurements can quickly settle to new values

set (option ... true/false)	Can be used with any of these commands • ShowCurrent e.g. set (option showcurrent true) • ShowVoltage • ShowPower • EnablePowerRatings • ShowValues • ShowLabels • WhiteBackground • ShowInfo • ShowMenus • ShowControls • AllowInputs • AllowComponentEdit • AllowComponentMove • LargeDot • Stopped • ShowScopes • Euro • ConvCurrent • ShowSimTime • ComponentValueScroll

Appendix 6. **CompSys201**

GECKO front page for CompSys201 Assignment

COMPSYS201 AVR assignment

This assignment involves answering technical and programming questions about the AVR uC, many involve use of the circuit and AVR simulators. The assignment is designed to engage you with the course content and to assist you in your learning of the technical aspects of uC's within ES's. All answers will be submitted online.

This assignment is worth 10% of your course grade, this is a significant amount of marks and so will require a significant amount of work.

Aim to spend at least 3 hours per week for the next 3 weeks working on it, start this week, as the questions follow along with the work in the lecture.

- Some questions are worth more marks than others.
- Some questions must be answered multiple times to get full marks to encourage you to ground your understandings
- You can attempt a question multiple times until you get it correct.
- For many questions once you save an answer you will see if you got it correct or not.
- Some questions will be marked by the course staff after the assignment due date
- You can close and reopen the assignment once you have started it and your answers and marks will be saved,
- A grade summary is visible further down the page
- To **navigate** click on a question number or click on the previous/next question buttons
- **These questions work on Firefox or Chrome on a PC**
- You may ask general non-specific, questions on Piazza about a question to gain support, assistance will also be available in the Friday clinic/tutorial
- To avoid losing your work, once you begin your answer you are advised to finish and save it; as you may be logged out after a certain period of inactivity.
- The assignment is due at **~~midnight on Friday June 2 (week 11)~~**,6AM Monday morning June 5th. At that time I will stop access to the assignment for several days for final marking to take place. The assignment will then be available again in time for you to revise for the exam, however any answers entered after that will not count toward the assignment grade.
- No assistance for assignment questions will be available after the end of the tutorial on Friday June 2.
- If you have a **technical issue** save a **screen shot** of the problem. The last page in the assignment has an email form for you to fill in and send, I will get it straight away. Otherwise you can directly email me bill.collis@auckland.ac.nz, do not put it on Piazza as there is often a delay in reading Piazza posts.

Academic Integrity

Are you familiar with the universities policies on your academic work? They exist for a good reason. When you shortcut your learning by using other peoples work you are the one who ultimately loses, it is useful to think of the saying "there are no shortcuts to any place worth going to". The University of Auckland does not tolerate cheating, or assisting others to cheat, and views cheating in coursework as a serious offence. The work that you submit must be your own. Some of the work you submit will be compared to other peoples submissions to check it authenticity. Refer to the University of Auckland Student Academic Conduct Statute and the guidance on Third Party Assistance if you have any questions.

Questions display from the assignment editor, showing question setup options

#	Question	Title	Value	Times it must be answered	is formative	is research
1	AVR Concepts #1	Identify program commands that control uC outputs	1	1	1	0
2	AVR Concepts #1C	Write program commands that control uC outputs	1	1	1	0
3	AVR Concepts #1D	Debug commands that control hardware	3	1	1	1
4	AVR Concepts #1CA	ES state concept	2	1	0	0
5	C Programming #1	Decimal conversions - easy	0.5	2	1	0
6	C Programming #2	Decimal conversions - upto 16 bits	0.5	2	1	0
7	C Programming #3	Binary conversions - easy	0.5	2	1	0
8	C Programming #4	Binary conversions - upto 32 bits	0.5	2	1	0
9	C Programming #5	Best variable type	0.5	4	1	0
10	C Programming #6	variable addition	0.5	2	1	0
11	C Programming #7	subtraction of variables	0.5	2	1	0
12	C Programming #8	multiplication of variables	0.5	2	1	0
13	C Programming #9	division of variables	0.5	2	1	0
14	C Programming #10	modulus	0.5	2	1	0
15	C Programming #11	left shift	0.5	2	1	0
16	C Programming #12	Setting and clearing register bits	0.5	2	1	0
17	C Programming #13	Arrays	0.5	2	1	0
18	C Programming #14	Arrays counting down	0.5	2	1	0
19	AVR Concepts #1E	Registers	1	2	1	1
20	AVR Concepts #1F	Write code that manipulates/checks single bits in registers***UPDATE***	1	2	1	0
21	AVR Concepts #2	Write commands that read and write external hardware in a die program	4	1	1	0
22	AVR Concepts #2A	Die - if in countdown - A	1	1	1	0
23	AVR Concepts #1G	switches with pullup resistors	1	1	1	0
24	AVR Concepts #1H	setting and clearing register bits	1	1	1	0
25	AVR Concepts #1J	Pullup to pull down	1	1	1	0
26	AVR Concepts	Anatomy of an input decision	3	1	0	0

#	Question	Title	Value	Times it must be answered	is formative	is research
	#1K					
27	AVR Concepts #2D	Pedestrian Crossing exercise	2	1	1	0
28	AVR Concepts #3	Quiz Game Controller	1	1	1	1
29	AVR Concepts #3D	1x 7segment -blocking problem	1	1	1	0
30	AVR Concepts #3E	Integer Division & Pointer use	1	1	1	0
31	AVR Concepts #30	Counter/Divider	1	1	1	0
32	AVR Concepts #30A	AVR Prescaler	1	1	1	0
33	AVR Concepts #31	Prescaler and counter	1	1	1	0
34	AVR Concepts #33	Timer0 Normal Mode	1	1	1	0
35	AVR Concepts #32	Timer0 CTC Mode	1	1	1	0
36	AVR Concepts #35	Timer0 setup	1	1	1	0
37	AVR Concepts #36	Timer1 setup	1	1	1	0
38	AVR Concepts #37	OCR1A OCR1B setup	1	1	1	0
39	AVR Concepts #20b	Voltage Divider solving for each value	1	1	1	0
40	AVR Concepts #20a	Voltage Divider ratios	1	2	1	0
41	AVR Concepts #22	ADC intro	1	2	1	0
42	AVR Concepts #22a	ADC - potentiometer angles	2	1	1	0
43	AVR Concepts #22b	ADC - potentiometer angles	2	1	1	0
44	AVR Concepts #22c	ADC - thermistor	2	1	1	0
45	AVR Concepts #26B	LM35 Temperature conversion	2	1	0	0
46	AVR Concepts #27	Keypad Voltage Divider to ADC	3	1	1	1
47	AVR Concepts #27A	Keypad Program	2	1	1	1
48	AVR Concepts #4D	Interrupt option setup	1	2	1	0
49	AVR Concepts #4	Polling to Interrupt based code	2	1	0	1
50	AVR Concepts #4C	Interrupts, variables and Volatile	2	1	1	0
51	AVR Concepts #100	3LED_DISPLAY	3	1	0	0
52	AVR Concepts #38	WDT	3	1	0	0

#	Question	Title	Value	Times it must be answered	is formative	is research
53	AVR Concepts #1L	The logic behind the internal pull-up	2	1	0	0
54	AVR Concepts #3F	Commenting Code	3	1	0	0
55	AVR Concepts #5B	Electronic Safe	3	1	0	0
56	AVR Concepts #5	StateMachine - Interrupt	4	1	0	0
57	AVR Concepts #5A	Traffic lights and Timers	4	1	0	0
58	AVR Concepts #50	Single LED Interface	1	1	0	0
59	AVR Concepts #51	Another LED Interface question	1	1	0	0
60	AVR Concepts #52	Interface multiple LEDs	1	1	0	0
61	AVR Concepts #53	Multiple LEDs on a single pin	1	1	0	0
62	AVR Concepts #102	Blank Circuit Simulator - not a question	0	1	0	0
63	AVR Concepts #103	Blank AVR simulator - not a question	0	0	1	0
64	AVR Concepts #104	Technical feedback on the question tool	0	0	1	0
65	AVR Concepts #105	Survey on the assignment and my teaching	0	0	1	0

Note that there were 61 marked questions in the assignment; the last four questions (62-65) were unmarked. Two of these were simply blank simulators for students to experiment with and the others were feedback forms

Student summative assessment feedback.

Samples of summative assessment feedback given to students in 2017

<u>Qu 45 LM35 temperature program –</u>

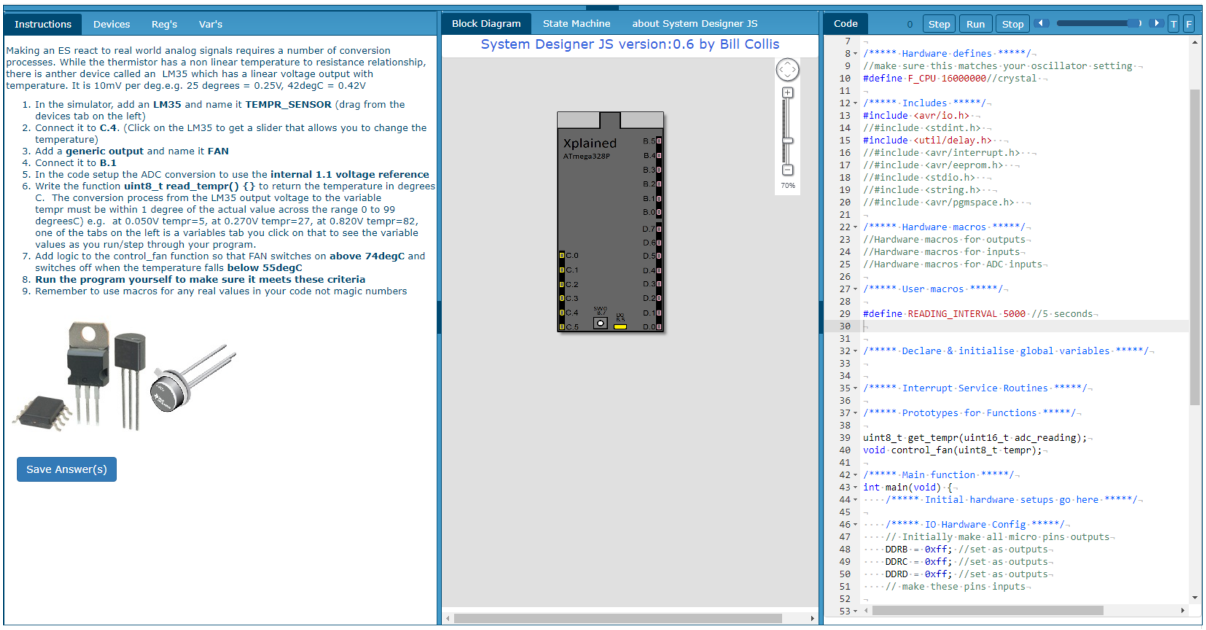


Figure 114: CompSys201 LM35 question

You were required to add the LM35 and a 'Fan' output to the microcontroller and then write the function to convert temperature to a value and have the fan automatically turn on at one temperature and off at a different one. Each student got random pin connections and random temperature values.

<u>34 students</u> were marked correct by the auto-checker, it picked up the following errors:

- *not setting 1.1V ref*
- *trying to do decimal calculations with integer variables*
- *passing/returning different sized variables into/from functions*
- *code that did not track correctly over the full range of 0-99 degrees*

Important point about the last error

Because we use integers and not floating point numbers there are two conversion processes from the voltage out of the LM35 to the variable temperature over the range 0 to 99. The first is from voltage from the LM35 to an ADC integer value and the second from the ADC integer value to an integer representing temperature in degrees C. Because each integer conversion process involves <u>truncation you cannot combine them into one</u>

formula. If you put the values into a spread sheet, you will see there are two 'corrections' caused by this truncation process in the transform around 30 and 60 degrees C.

What I wanted was for students who used a single conversion process (as you would for two sequential linear expressions of the form y=mx+c) to see something that didn't seem to make sense however most students appeared to submit code that they hadn't tested thoroughly as it did not work, so when setting the LM35 to 30.0 degrees C the value in the variable tempr was 31 and not 30.

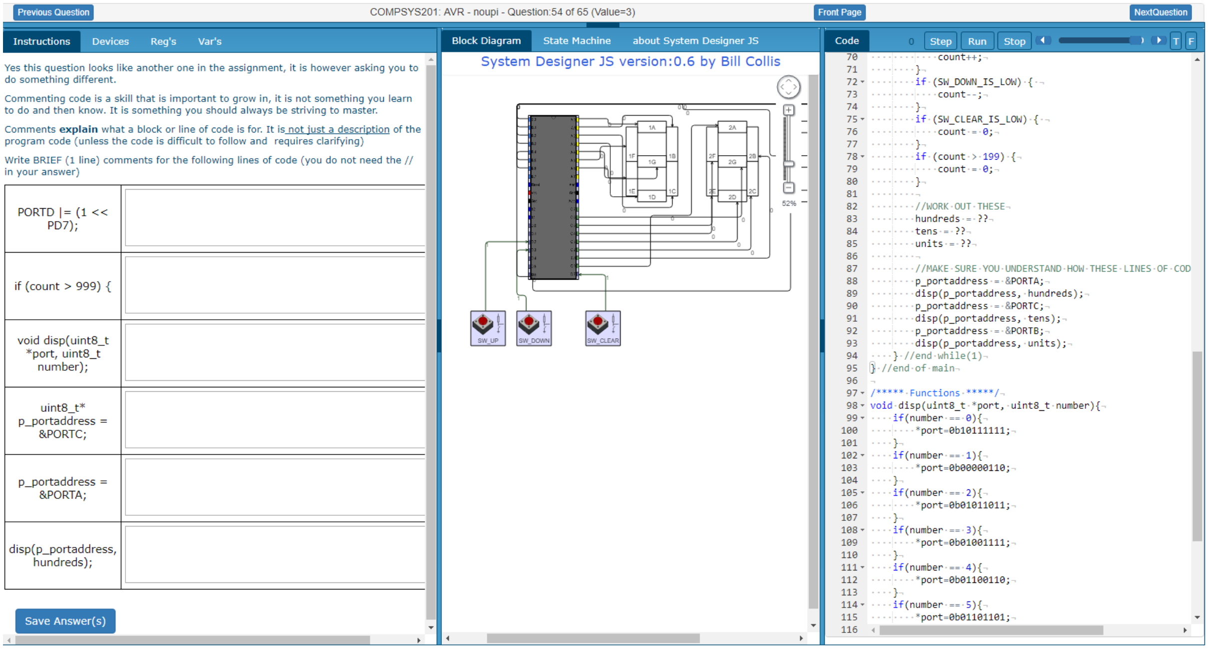
specifically look at these values

LM35 setting	*Pin Voltage (x0.01)*	*ADC conversion hardware x 1.1/1023 then truncated*	*Value in uint8_t tempr Adc_value / 9 then truncated*
28	*0.28*	*260*	*28*
29	*0.29*	*290*	*29*
30	*0.30*	*279*	*31*

The really important take away point here is that ADCs actually are not as straight forward to work with as we might think. For those in ElectEng209 next semester when you use them read the Atmel application note on ADCs and see the real issues of non-linearity and other problems that can occur.

Question 54 - commenting code

<u>This was not well done overall</u>



You needed to write succinct explanatory comments about the <u>function, purpose or role</u> of the line of code within the context of the program (not general descriptive explanations about syntax/ports /registers), examples include:

- *activate/enable <u>internal pullup resister</u> for the CLEAR_SW*
- *Checks if count exceeds maximum number that should be <u>displayed</u>*
- *<u>display</u> a digit on a 7 segment on a port- or display the particular digit on the display by turn on the LEDs.*
- *puts the address of PORTA in the pointer p_portaddress so that the next write to the pointer <u>sends the data to PORTA</u> - or Declare a pointer with the address PORTC, the seven segment <u>display that represents the tens</u> - sets the variable p_portaddress to the <u>tens display</u>*
- *point to <u>hundreds/left/first</u> digit of the display –*
- *<u>display</u> hundreds value in l<u>eft/first</u> 7-segment display/digit/LEDs*

The underlined words relate to the purpose, role or function

What you write should add something to the code.

Appendix 7. **GECKO**

GECKO is a web application developed in Visual Studio. It consists of a suite of tools for editing and presenting, both individual questions and assignments. It also includes tools for presenting data analytics. A simple overview is shown in Figure 115.

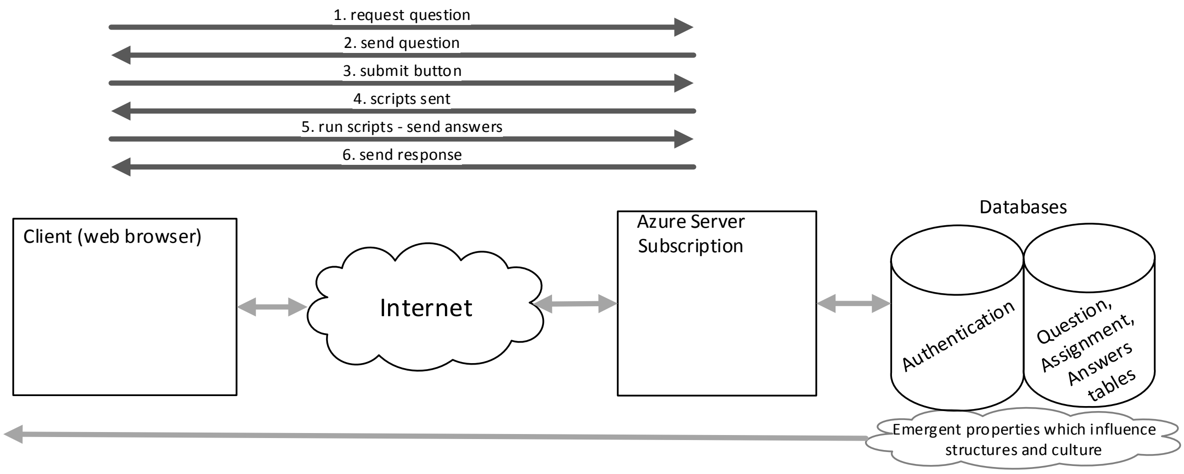


Figure 115: GECKO web application overview

Using their web browser a student requests a question from the server (Figure 115 #1). The server retrieves the question from a database of questions generating and manipulating values in the question and sends them to the web browser (#2), where these are injected into the simulator. The student enters their answer and/or modifies the simulation, then presses a submit button (#3). At this stage scripts are fetched from the server (#4) and run in the simulator to capture values from it, these are then sent along with any answers from multi-choice or text box type questions back to the server (#5) where they are marked. Feedback or feed-forward are sent back to the student (#6) depending on whether their answer was correct or not.

GECKO is an MVC ASP.NET web app written in C#, Razor and JavaScript. The web service is a subscription service from Microsoft called Azure; and the questions, answers and other data are stored using Microsoft Azure Table Storage. Azure tables have a flat (non-relational) structure, where storage and retrieval of data is based upon partition keys and row keys. The decision to use a flat rather than relational database storage system was made early in the design as it was unknown how the structure of the data would need to grow. Authentication for administration is handled using a second SQL relational database, this was chosen to be separate to the data and to be relational as authentication is a general problem which has been solved already and does not have the same unknown nature as big data. Azure is a subscription service and the initial level of service for prototype development was chosen as the lowest cost service available, though this can be dynamically changed as required. Figure 116 is a more detailed overview of communication between the various GECKO applications and the tables in the database. The main tools with GECKO are:

- Circuit question editor
- Circuit question presenter
- AVR question editor
- AVR question presenter
- Assignment editor
- Assignment presenter
- Analytics application
- User manager
- Short answer grader
- AVR answer checker
- User results
- Assignment results

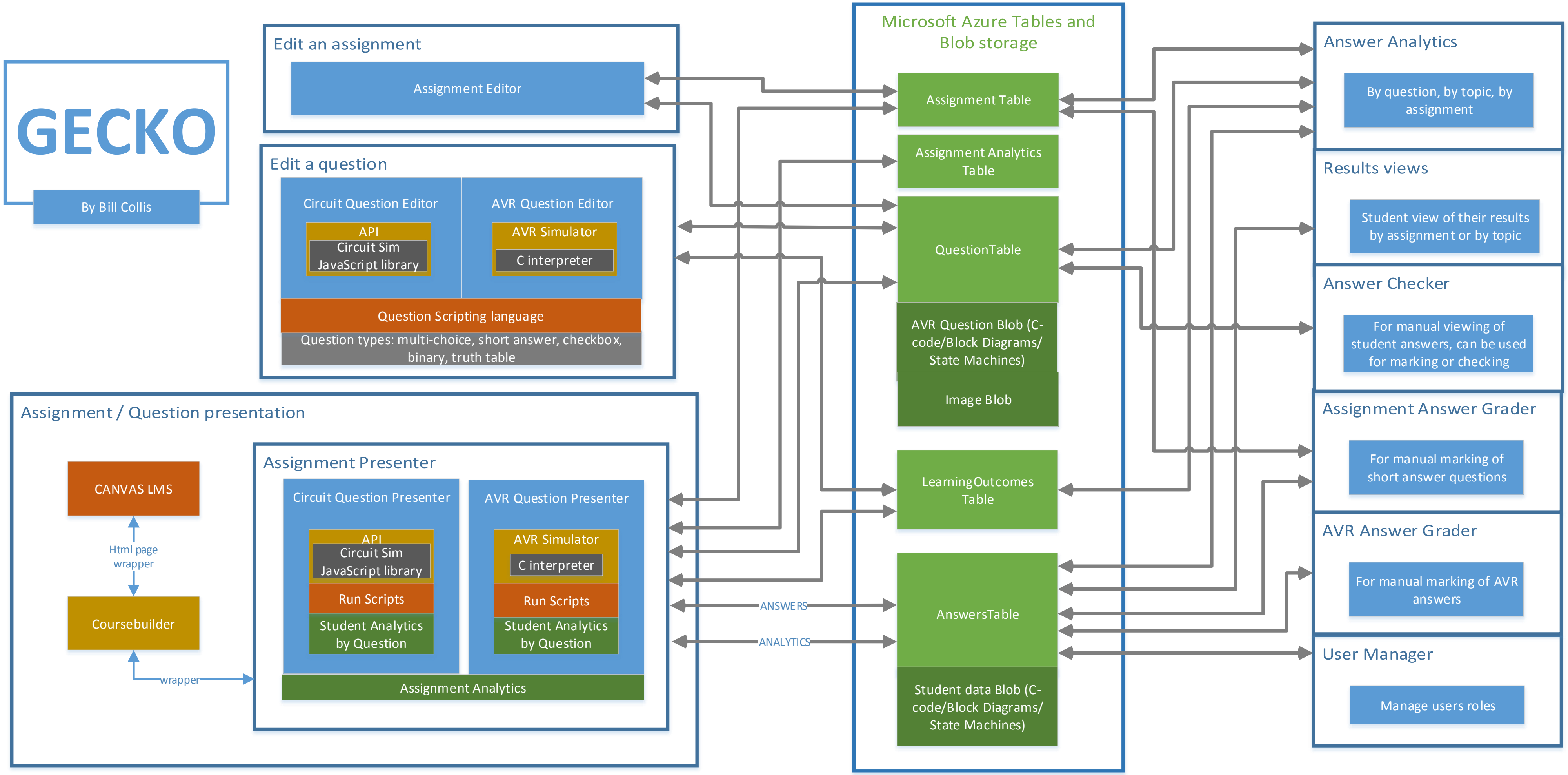


Figure 116: GECKO tools overview

Answer Grader Tool.

A speed grader tool for short answer assignment questions (Figure 117), though it can be used to change the grade of any question for any user.

The drop down indicates score range, the scale is automatically generated in ½ marks up to the full value of the question – in this case the question is worth 2, so the range of marks in the dropdown is 0,0.5,1,1.5,2

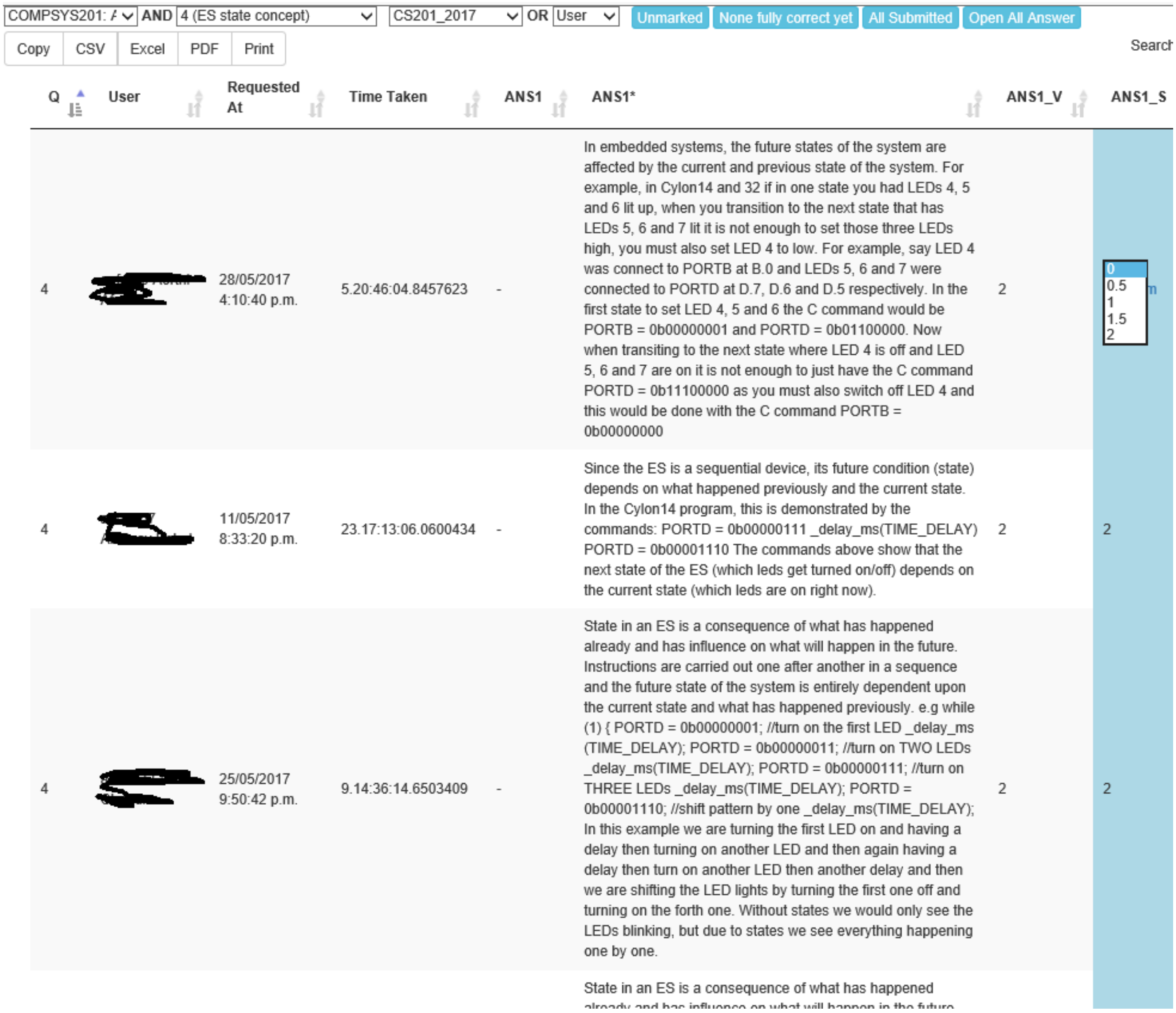


Figure 117: GECKO speed grader tool

AVR Answer Checker

Any student answer for an AVR simulator question can be opened for checking (Figure 118). The choices are selected by drop downs and buttons in the top line of the tool. In this case the CompSys201 assignment has been opened for the CS201_2017 group, and question 55 is selected. The buttons are used to decide what data is populated into the last dropdown, in this case all answers were selected (there were 308 answers submitted by the 215 students). Once a line is selected in the last drop down the student answer is loaded into the simulator and can be manually run, reviewed and marked - the mark being entered into the textbox on the top right and the Save Score button pressed. In this case the student achieved 3 out of the 3 possible marks for this question.

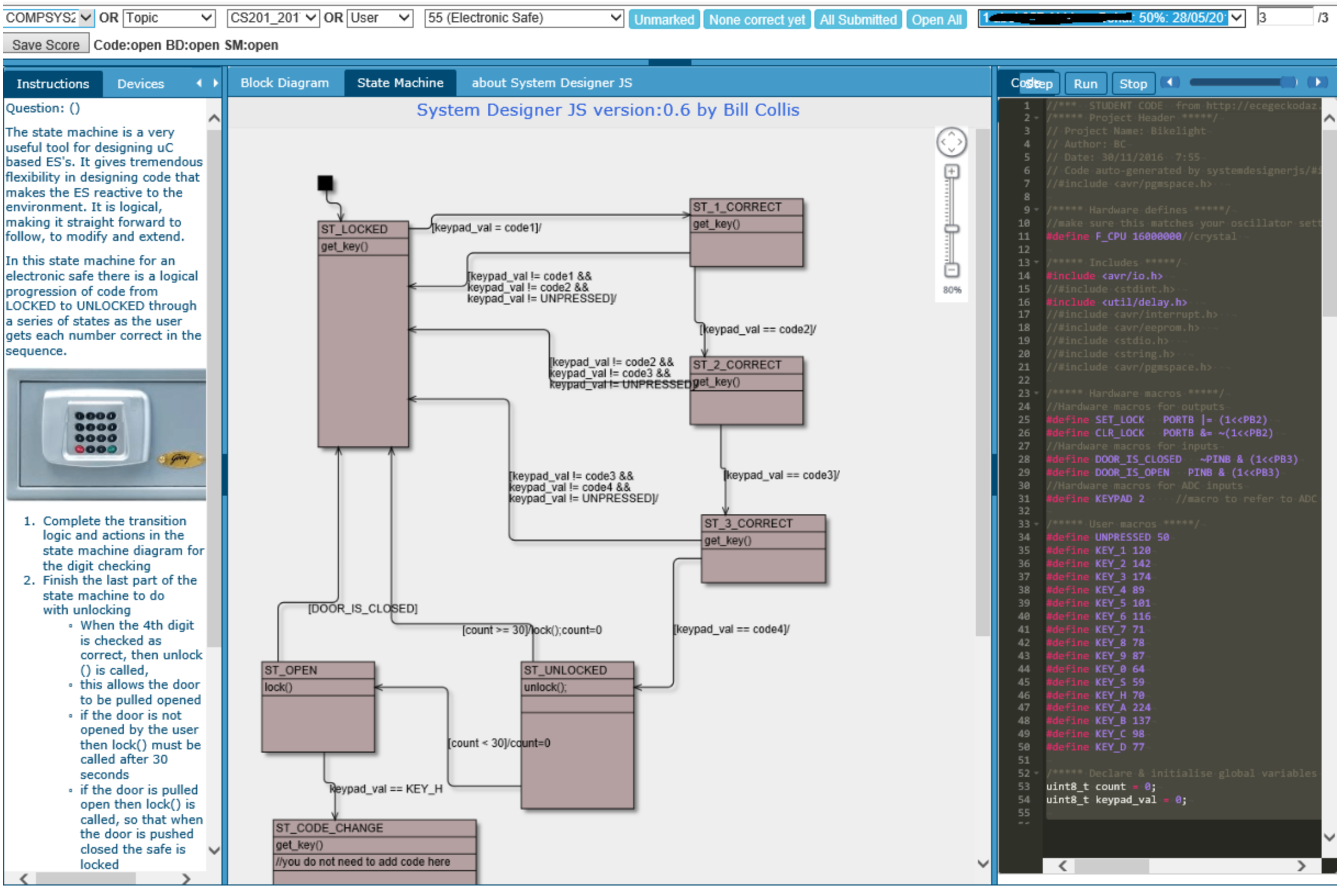


Figure 118: AVR answer checker and grader

Appendix 8. **Ethics Documents**

This research was carried out under four research ethics approvals from the University of Auckland Ethics committee. These are 10032 (2 June 2016), 14647 (30 June 2015), 14122 (27 May 2015) and 17198 (12 July 2016).

The approvals cover the use of surveys, quizzes, online tutorials, interviews, observations, monitoring of online forums, analysis of course work results, and the testing of software. Letters of consent were gained by course coordinators for ElectEng101, ElectEng201, ElectEng202, ElectEng209, ElectEng303, CompSys201, CompSys 301 and the Head of Department for Electrical, Computer, and Software Engineering. Two sample documents for 14647 follow.

Participant Information Sheet

Project Title**: Improving students' qualitative understandings of electric circuits.**

Participation in this research is entirely voluntary

Researcher introduction

My name is Bill Collis, and I am a PhD candidate within the Department of Electrical and Computer Engineering. My Research supervisor is Dr Gerard Rowe who is the Associate Dean (Teaching and Learning) in the Faculty of Engineering and one of the lecturers in the course. We both have a keen interest in engineering education and are investigating first and second year students' conceptual understandings of electric circuits.

Project description

The purpose of this research is to find helpful ways of supporting students in the first and second years of study in electric circuits. You have been asked to participate in this study as you have used the online resources to support your learning. Your participation is entirely voluntary; however we would appreciate you letting us know how they benefited you so that we can more fully understand the support you need during the course. Your participation will also help us support future students.

In the questionnaire you are asked to rate the usefulness of the online quiz and tutorials. You will also be asked to fill in another questionnaire at the end of the course about the overall usefulness of the online quiz and tutorials. During the course we would like to track your use of the resources along with your course results to see if there is a correlation between their use and learning outcomes.

Some students may be contacted and asked to partake in interviews as part of the research. Participation in these will be entirely voluntary; any student who feels they would like to be interviewed is also welcome to approach one of the researchers directly. Through these interviews we hope to gain a deeper understanding of the learning needs of students in specific areas of the course. Interviews will be carried out by the researcher in an office in the department, the will take approximately 50 minutes, and consist of several questions about specific electric circuit concepts. The interview will be recorded (audio only) and then transcribed into a written document. Participants are welcome to review the written document and have any comments they want removed from it. Interviews will generally be carried out individually; if participants wish they are welcome to bring a friend with them.

Confidentiality:

The results collected from the online questionnaire, quiz and tutorials, as well as observations made by the researchers and any comments you make during lectures, face-to-face tutorials or interviews will have all identification removed from them by someone separate to your course to keep them private. Assurances from the Head of Department and the course director have been given that your participation or non-participation, your data and any comments you make will have no influence on your grades for the course. While your results will be stored confidentially and not released to anyone else the nature of using online systems does mean that anonymity cannot be completely guaranteed.

The analysis of the results may be published in the future and it is possible that this may include comments made by you however this will be done in a way that does not identify you as the source. After the conclusion of the study your data will be deleted from the website and your email address will not be stored. The questionnaires and transcribed interviews will be stored in electronic form securely in a locked filing cabinet on university premises for six years after the study is completed, at which point they will be destroyed. Interview recordings will not be kept. You may request a copy of your individual data by contacting the researcher or the supervisors at any time during or after the study is complete.

Your participation in this research is voluntary. You will also be able to withdraw your data at any time up to two weeks from the date of your last participation.

Taking part in the study allows you to contribute to how learners begin to understand electrical circuits. We hope that this research will uncover ways in which learning for first and second year students can be enhanced and lead to better understanding of electrical circuits.

Contact details

Researcher: Bill Collis, bill.collis@auckland.ac.nz

Supervisor: Dr Gerard Rowe, 923-2009, gb.rowe@auckland.ac.nz

Head of Department: Professor Zoran Salcic, 923 7802, z.salcic@auckland.ac.nz

For any queries regarding ethical concerns you may contact the Chair, The University of Auckland Human Participants Ethics Committee, The University of Auckland, Research Office, Private Bag 92019, Auckland 1142. Telephone 09 373-7599 ext. 83711. Email: ro-ethics@auckland.ac.nz

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE ON 30 June 2015 for (3) years, Reference Number 014647

<u>CONSENT FORM</u>

THIS FORM WILL BE HELD FOR A PERIOD OF 6 YEARS.

Project title: Improving students' qualitative understandings of electric circuits

Researchers: Bill Collis, Dr Gerard Rowe

I have read and understood the Participant Information Sheet. I understand the nature of the research and why I have been selected to participate in this research. I have had the opportunity to ask questions and have them answered.

- I agree to take part in this research
- My participation is voluntary
- I understand that my results from the online, quiz, questionnaire and tutorials will be tracked and compared to my course work results this semester.
- I understand that this data will be coded in a way that does not identify me directly.
- I understand that this will be done by someone not directly involved in my course work.
- I understand that I am free to withdraw participation at any time, and to withdraw any data traceable to me for up to two weeks after taking part in this research.
- I understand that the data may be used in publications about the course and its content
- I understand that data will be kept for 6 years, after which they will be destroyed.
- I understand that the Head of Department and the course coordinator have given assurance that my participation or non-participation will not affect my grades or relationships within the University, and that I can contact the head of department, Professor Zoran Salcic (Room 303.244, ext. 87802), if I wish to make a complaint about this assurance not being upheld.
- I do / do not wish to receive a summary of results.

My email address is ___________________________________

Name: _________________ Signature: _________________ Date: _______________

For any queries regarding ethical concerns you may contact the Chair, The University of Auckland Human Participants Ethics Committee, The University of Auckland, Research Office, Private Bag 92019, Auckland 1142. Telephone 09 373-7599 ext. 83711. Email: ro-ethics@auckland.ac.nz)

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE ON 30 June 2015 for 3 years, Reference Number 014647

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THE UNIVERSITY OF AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
NEW ZEALAND

School of Graduate Studies
AskAuckland Central
Alfred Nathan House
The University of Auckland
Tel: +64 9 373 7599 ext 81321
Email: postgradinfo@auckland.ac.nz

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Thesis Chapter 5

Development of electric circuit understanding through fundamental concept tutorials - AAEE 2016 conference paper

Nature of contribution by PhD candidate	Investigation, developing and writing of the tutorials, data collection, analysis of data, writing the article
Extent of contribution by PhD candidate (%)	95

CO-AUTHORS

Name	Nature of Contribution
Gerard Rowe	Technical review and critical feedback of paper
Claire Donald	Technical review and critical feedback of paper

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and
- that the candidate wrote all or the majority of the text.

Name	Signature	Date
Gerard Rowe	Gerard B Rowe	18/2/19
Claire Donald	CDonald	20.2.19

THE UNIVERSITY OF AUCKLAND
Te Whare Wananga o Tamaki Makaurau
NEW ZEALAND

School of Graduate Studies
AskAuckland Central
Alfred Nathan House
The University of Auckland
Tel: +64 9 373 7599 ext 81321
Email: postgradinfo@auckland.ac.nz

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Thesis Chapter 7

Redeveloping an introductory course in microcontrollers through the lens of educational theory

Nature of contribution by PhD candidate	Investigation, developing and writing of the course materials, and the software used in the course, data collection, analysis of data, writing the article
Extent of contribution by PhD candidate (%)	95

CO-AUTHORS

Name	Nature of Contribution
Gerard Rowe	Technical review and critical feedback of paper
Claire Donald	Technical review and critical feedback of paper

Certification by Co-Authors

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- that the candidate wrote all or the majority of the text.

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Gerard Rowe	Gerard B Rowe	18/2/19
Claire Donald	CDonald	20.2.19