Towards an informed course design

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CONTEXT
This research was motivated by a desire to identify barriers to academic success in a first year (concept rich) electrical engineering course. Misconceptions of key concepts of electrical circuit theory are known to be carried from high school into first year university classes. If such misconceptions are not identified and overcome, students will likely lack confidence in this discipline, struggle academically in first year electrical courses and be unlikely to continue with further study in this area. Central to our research methodology has been the desire to properly separate “know that” knowledge from the “know how” knowledge usually tracked in programme and course design via institutional and professional graduate attributes. Thus a question central to our investigation has been how course design and pedagogy can be improved to simultaneously ensure both appropriate conceptual progression and the development of the required “know-how” knowledge.

PURPOSE
The initial questions that motivated this research were to identify whether there were specific barriers to success in a particular course and, if so, to determine the key features that should be considered in making consequent changes to the curriculum design. Early results of our research pointed toward fragmentary learning and haphazard development of conceptual understanding. These early findings encouraged us to focus our investigation on whether there was a better way of systematically approaching the unfolding of key concepts in a course so that student understanding and their ability to generalise (i.e. the so-called far-transfer problem), and then apply that generalised understanding, could be improved.

APPROACH
On-line tutorials were developed to support and further develop conceptual understanding rather than merely giving practice in the development of procedural knowledge. Students were incentivised to complete these tutorials and to complete questionnaires which examined their learning styles and motivation. The quantitative analysis and interpretation of student performance in these tutorials and their responses to the questionnaires was enriched by interviews conducted with students, teaching assistants and lecturers. Student performance in the coursework and the exam was analysed in relation to their survey responses and performance in on-line tutorials.

RESULTS
The principal factors to emerge are that misconceptions and a poor ability to generalise and engage in far-transfer seem to be the consequence of learning circuit understandings as isolated fragments. Such behaviour is exacerbated by an over-reliance on summative assessment practices bound to assessable fragments of understanding and curricular design which permits too much teacher (and student) choice of which topics to cover, thereby fracturing the epistemic foundation leading to a procedural approach which limits students’ ability to generalise to unfamiliar settings.

CONCLUSIONS
This project has identified several of the key barriers to be considered in the development of an engineering course which seeks to embed learning in connections between propositional and procedural knowledge and assist educators in maximising their efforts in creating student learning opportunities.

KEYWORDS
Engineering course design, Conceptual understanding, Epistemic Ascent

Background

This research was motivated by a desire to identify barriers to academic success in a first year electrical engineering course covering circuit theory, instrumentation and electromagnetics. Misconceptions of key concepts of electrical circuit theory are known to be carried from high school into first year university classes (Parker & McGill, 2016; Smaill, Rowe, Godfrey, & Paton, 2012) . If such misconceptions are not identified and overcome, students will likely lack confidence in this discipline, struggle academically in first year electrical courses and be unlikely to continue with further study in this area.

A novel feature of this research is the collaboration that took place between engineering academics and postgraduate (engineering) researchers and colleagues from the Faculty of Education. This served to bring a different lens to bear on this issue, thereby better integrating educational theory and class-room practice for engineering course design and delivery. This cooperation brought into sharp focus a little recognised misinterpretation of Vygotsky (Vygotsky, 1962) that some would argue has bedevilled current education systems – namely the idea that meaning is created in what students do. Central to our research methodology has been the desire to theoretically separate “know that” knowledge from the “know how” knowledge usually tracked in programme and course design via institutional and professional graduate attributes (Winch, 2014). The realist approach we use locates *meaning* in the concept itself and *understanding* of the meaning in the student’s ability to apply the concept (after Vygotsky). By distinguishing between ‘knowledge-that’ (conceptual knowledge) and ‘knowledge-how’ (procedural and practice knowledge) in this way, we want to know how students acquire both conceptual understanding, and in particular how they connect the two forms of knowing which leads to subject mastery.

The initial questions that motivated this research were to identify whether there were specific barriers to success in a particular course and, if so, to determine the key features that should be considered in making consequent changes to the curriculum design for this course. The collaboration with colleagues from another disciplinary area brought a different gaze resulting in a broadened focus on the wider question of how best to integrate course design to simultaneously meet the requirements of the three key elements of curriculum, pedagogy and the development of a disciplinary identity.

Methodology

Evidence was collected about:
(i) how the course design of a Year 1 generic engineering course accommodates the needs of students transitioning from secondary school to 1st year studies,
(ii) how the Year 1 course design prepares students to move to their 2nd year studies,
(iii) lecturer and student teaching and learning experiences,
(iv) expert lecturer views on the selection and teaching of Engineering concepts.

The data collection involved quantitative and qualitative methods:
(a) A pre-entry Year 1 Questionnaire (the ‘Ready for First-Year Quiz’ - RFFY),
(b) A questionnaire to Year 2 Electrical Engineering students about their Year 1 experience in Engineering,
(c) Interviews with year one, two and three Electrical Engineering students, and with PhD students who had acted as teaching assistants for the ELECTENG 101 course,
(d) Interviews with past and present teaching and non-teaching staff,
(f) Interviews with secondary school physics teachers;
(g) Application of the Felder-Solomon Index of Learning Styles (ILS) questionnaire.
(h) Application of the MSLQ questionnaire

In addition we developed on-line tutorials to support learning in this first year (concept-rich) electrical engineering course (Collis, Rowe, & Donald, 2016). These tutorials were designed to support and further develop conceptual understanding rather than merely giving practice in the development of procedural knowledge. Students were encouraged, via a small contribution to coursework marks, to complete these tutorials and in addition to complete questionnaires which examined their learning styles (via the Felder-Soloman ILS questionnaire (Felder & Silverman, 1988)) and motivation (via the MSLQ questionnaire (Credé & Phillips, 2011; Pintrich & De Groot, 1990; Pintrich & others, 1991)). The (ethics-approved) quantitative analysis and interpretation of student performance in these tutorials and their responses to the questionnaires was enriched by interviews conducted with students, teaching assistants and lecturers. A thematic analysis was carried out on the interview transcripts. Student performance in coursework and the exam was analysed in relation to their survey responses and performance in on-line tutorials.

Eighteen first-year students, seven second-year students, one third-year student, six PhD students, two secondary school teachers and three lecturers in the department were individually interviewed. The interview questions were tailored to each type of participant and focused on how the design of ELECTENG 101 accommodated the needs of students transitioning from secondary school to first year studies, and from year one to year two engineering studies.

For student participants, the interview questions included background questions, concept understanding questions and learning questions. For example, first-year student interviews started with background questions which focused on their learning experiences of electricity in secondary school. Concept understanding questions were designed to identify what students found difficult during their study. Some electrical circuit exercises were also used to elucidate student's concept understanding levels. Pedagogical questions included probing students' perceptions of learning materials design and lecturer's teaching styles. Second year and third year student interviews also probed student's learning experiences of the ELECTENG 101 course. The PhD student interviews concentrated on identifying techniques which led to successful learning experiences and probing their tutoring experiences in the ELECTENG 101 course.

The interview questions used for lecturers were designed to probe their teaching experiences and identify what were their main concerns about student's electrical conceptual understanding.

Results

Three principal factors have emerged. Firstly, misconceptions and a poor ability to generalise knowledge into new situations - to engage in far-transfer (Perkins & Salomon, 1992). This seems to be the consequence of learning circuit understandings as isolated fragments arising from the focus on learning outcomes disconnected from the central concepts at the root of the discipline. While our analysis has identified that most student knowledge is fragmentary, some interviews revealed sound understandings underpinned by successful pedagogy with the specific teaching of knowledge-that or conceptual understanding, sequentially arranged according to conceptual progression principles (Rata, 2015). In these cases, a well-structured epistemic ascent had connected “knowledge-that” to “knowledge-how” (Winch, 2013, 2014) and led to student ability to generalise.

Secondly, and not surprisingly, student agency and engagement is a major determinant of first-year academic success. The primary driving factor associated with student motivations is the summative assessment practices which are unavoidably bound to assessable fragments of understanding. Learning linked to epistemic principles was avoided in favour of what is to be examined. While all students suffer from this those from backgrounds where pedagogy was underpinned by epistemic principles had come to realise the benefits to their understanding and had altered motivations to learning in summative laden environments.

The third factor is a local one and relates to the majority of the first-year students who have studied under a high-school qualification which is heavily constructivist in its design. A formally prescribed curriculum has been replaced by teacher (and student) choice of which topics within physics will be covered and examined. This fractures the epistemic foundation at the root of a discipline, and consequently the student has only a procedural approach to rely upon. While local in nature this was of concern to academics as there is an increasing trend toward earlier and earlier contextualised problem-based learning course design within engineering education. This social-constructivist, teacher-facilitator and student-led model of pedagogy focusses on the student, rather than the epistemic knowledge of the discipline. Introducing this type of learning too early to engineering students who do not have the epistemic foundation gives them nothing to generalise their work from or towards.

Main findings

Ready for First Year Quiz Results

Prior to beginning their studies all students are encouraged to complete a Ready for First-Year (RFFY) Quiz , the results of which inform both the lecturers and the students themselves about the student's prior preparation. This RFFY quiz comprises multi-choice questions based on years 12 and 13 of the 13-year schooling system operated in New Zealand. It has been run each year since 2011 with the results consistently showing that the students are least well prepared for the electrical subject at first year. The results obtained in 2016 and 2017 are presented in Table 1. In 2016, 511 out of a possible 892 students completed the quiz. In 2017 there was a substantial increase in the size of the first year intake (and a corresponding reduction in average entry GPA) with 588 out of 1016 students completing the quiz. The reduction in average entry GPA is clearly evident in the reduced subject averages obtained in 2017, however the relative preparedness for each of the subjects has not changed – with Electrical preparedness being by far the worst in both years.

Subject	Maximum Mark	Average Mark 2016	Average Mark 2017	Std Dev. 2016	Std Dev. 2017
Mechanics	10	6.41	6.05	2.11	2.19
Electrical	10	4.61	4.35	2.18	2.12
Biology & Chemistry	10	5.95	5.45	2.41	2.58
Maths	10	7.48	6.82	2.11	2.41
Software	10	6.68	6.31	2.11	2.31
Overall	50	27.78	25.83	6.99	7.49

Table 1 RFFY Quiz results for 2016 and 2017

In the case of the electrical questions, students were proficient on questions which tested just a single concept but struggled with any questions that required the use of multiple concepts. The conclusion we drew from these results was that such students would benefit from a first year curriculum which supported epistemic ascent with appropriately scaffolded learning activities targeting multi-concept problems.

Motivated Strategies for Learning Questionnaire (MSLQ)

In order to explore the relationship between engineering student's self-regulated learning (SRL) abilities and their academic performance, we used an online questionnaire (the Motivated Strategies for Learning Questionnaire (MSLQ)) to collect data from first-year students enrolled in ELECTENG 101. All 866 students enrolled in ELECTENG 101 in 2016 were incentivised to complete the MSLQ via a small contribution to course-work marks and the return to each student of an individual report summarising their own strategies. A total of 738 valid questionnaires were ultimately analysed. The MSLQ probes eleven SRL abilities, namely: motivation (interest), motivation (expectancy for success), confidence over taking exams, cognitive strategy (rehearsal), cognitive strategy (elaboration), cognitive strategy (organisation), metacognition, resource management (time and study space), resource management (self-effort), peer learning, and help-seeking. We performed an ANOVA test to identify the major characteristics of the students' SRL abilities, with results tagged for gender, first language, entry qualifications and future study plans. We also performed a regression analysis to find the influence (if any) of student's self-regulated learning skills on their academic performance, and it is this second analysis that has the most relevance to the theme of this paper. We found statistically significant evidence (Table 2) of impact for four SRL categories with expectancy for success, self-effort and metacognition all showing a positive impact and, surprisingly, rehearsal ability showing a negative impact. The latter result has a clear implication for curriculum design – specifically suggesting an improvement is needed in the clarity of the learning objectives and learning activities conveyed to the students.

Attribute	Coefficient	Std. Error	t-Stat	p-Value
Expectancy for Success	4.613	0.943	4.893	0.000
Self-Effort	3.178	0.794	4.003	0.000
Rehearsal	-1.820	0.671	-2.711	0.007
Metacognition	3.305	1.333	2.479	0.014
(Intercept)	32.223	5.016	6.424	0.000

Table 2 – Regression analysis of students' academic performance and SRL skills

Final examination and coursework performance

The coursework included invigilated MCQ tests and the final examination included a mixture of MCQ and long answer calculation questions. Students demonstrated proficiency on activities for which they had been trained, but struggled with far-transfer type questions and with questions that involved more than one concept. These conclusions are consistent with those found for the RFFY and suggest that improvements to the course design should probably target epistemic ascent and scaffolding of complex problems.

Felder-Solomon Index of Learning Styles (ILS) questionnaire

The Felder-Soloman ILS results were unsurprising with a significant portion of the cohort showing learning preferences for active and visual presentations. A much smaller percentage of the cohort identified with strong global learning preferences. Such students are known to be disadvantaged in many first-year engineering courses as these are often taught in a serial de-contextualised manner. The inferences we drew were to take care to always paint the big picture via literacy statements for the course overall and the major sub-sections.

Interviews and Questionnaires

Thematic analysis of the results led to the establishment of a framework of themes that included :

- Context and abstraction
- Electrical engineering knowledge

- Material object and abstract concept differentiation
- Specialised language
- Student cognitive processes
- Student agency
- Educators subject knowledge
- Educators agency and the development of their pedagogical practice

Context and abstraction

This category explored how outside prompts assist with understanding. The main prompts identified in the interview data came from three sources: experiments or practical tasks, real life examples and teacher's demonstrations. Unsurprisingly, students benefited from learning concepts by doing. Practical experiences enhanced learner understandings of concepts. Making connections between abstract concepts and concrete instances bridges the gap between learner's new and existing knowledge.

Electrical engineering knowledge

Electrical engineering knowledge is comprised of large systems of meaning made up of inferential relations between abstractions. The knowledge structure is complex and concepts are connected tightly. Specific issues identified in the interviews related to disjointed presentation of concepts, issues arising from the compartmentalised nature of the major high school qualification (NCEA), the impact on Physics of students limited numeracy skills (the ability to use Mathematics to solve problems) and the desirability of teachers building understandings using the historical background of major Physics discoveries.

Material object and abstract concept differentiation

Students reflected that if they cannot make connections of abstract concepts with physical material, it was hard for them to understand. Some teachers used vivid demonstrations to help students make the connections happen, whilst others used experiments to help students get visual and practical experiences of the concepts they studied.

Specialised language

Teachers must condense each concept using words. Words serve as signals for the concept (its symbol) and for its place in the complex system of meaning. A simple word teachers use to explain a concept can significantly influence students' understanding. One secondary teacher mentioned in his interview about the importance of consistently reinforcing correct terminology for example using the term 'electric potential' rather than the more confusing term 'voltage' just as we would not use the term 'centimeterage' instead of height.

Student cognitive processes

Meaning or know-that, is constructed via building inferential relationships between abstract concepts. Student interviews provided some specific and living examples to show when the turning point happened and students felt they truly understood a concept. Such turning points were developed by educators assisted by well-structured learning materials, which can include textbooks, lecture notes, videos, visualisations and exercises.

Student Agency

Students showed awareness of their diverse learning styles. They realized some specific kinds of learning activities, or presentation modes were particularly effective for assisting their conceptual understanding. However their response to learning situations is always mitigated by their agency - their conscious decisions about their learning behaviours. Student's responses were diverse but could be generalised into a number of approaches. Some students expressed an overt preference for shallow understanding focussed only on passing tests and exams. Some students exhibited a naïve 'espoused theory' about a preference for understanding but demonstrated a 'theory-in-use' (Argyris & Schon, 1974) which was actually focussed on passing. Some demonstrated this real preference by blaming high workloads and ever looming assessment tasks for their approach to learning and criticising lecturers when they did not teach to the test. A number of students though expressed a desire to deeply understand material and while recognising the work load issue did not let it interfere with their learning. One group of students conflate their mastery of know-how (using formula) with know-that (understanding), and, as identified by Case and Marshall (2004), this type of understanding lacks the depth of real understanding.

Teacher subject knowledge

Students talked about having physics teachers who were not trained in Physics or had insufficient subject knowledge in electricity or had knowledge that was not relevant to real world applications. While lecturers and graduate teaching assistants were seen as highly knowledgeable, lecturers were criticised by students for not making their expert knowledge comprehensible to students – significantly, this is the definition of pedagogical content knowledge.

Educators pedagogical expertise

Lecturer's teaching strategies of engaging, demonstrating, sequencing, pacing and evaluating were analyzed based on our interview and observation data. Student's levels of conceptual understanding were found to depend on lecturer's overt focus on assessment, and the clarity and logic of their explanations in relation to developing conceptual progression. Deficiencies in these areas were found to have a significant impact upon student understanding. Students made a number of references to how their school physics teachers had worked primarily to either develop understanding or to prepare students for assessment.

A problem in electrical engineering instruction identified via our interviews was a gap between the evaluation techniques used and their measure of student's actual conceptual understanding levels. Several students mentioned that even though they didn't truly understand the concepts, they still managed to solve the problems correctly. This observation is consistent with Winch's (2013) concerns about the need to embrace epistemic ascent when designing courses, to start from a sound understanding of 'first principles' and to be particularly vigilant that we don't streamline complex tasks into algorithmic procedures (Case & Gunstone, 2002).

Discussion

In order to explain the findings we theorised the thematically organised findings using a model of the knowledge-pedagogy relationship (McPhail & Rata, 2015). The purpose of the model is to show the connections between these categories:

1. The epistemic nature of electrical engineering knowledge;
2. Teacher's subject knowledge;
3. Teacher's pedagogical knowledge,
4. Specialised language; and
5. Student's epistemic identity

The application of the knowledge-pedagogy relationship model to the data from the engineering study enabled us to explore how the problem in teaching complex abstract knowledge presented itself in a particular case. Our understanding was further informed by applying the model to a second year course (Collis, Rowe, & Donald, 2017) which directly builds on this first year course. However, it is possible to generalise from this case study to a range of subjects such as technology, biochemistry, calculus in the STEM areas, but also to other non-STEM academic subjects, including music, languages, and history. The findings have sufficient generic principles concerning how curriculum and pedagogy are integrated to provide teachers with the means to select, organise, and deliver content specific to their courses in ways that will lead to student conceptual understanding. In this way, the findings can be used both for course design and for the analysis of that design.

Our data analysis re-affirms Hattie's (2012, 2014) conclusion of the importance of making the learning process visible to students. Furthermore our analysis has led us toward a course which begins with the identification of student identity – and the development of new lenses through which we want a student to view our domain. This is then expressed in learning outcomes centred on abstract understandings rather than content. Through a well-planned epistemic ascent that is rooted in first principles, these are unfolded into specific success criteria and learning activities. Ultimately these return to the overarching identity and course goal that expresses the new lens through which we want a student to view our domain

A complicating feature related to development of know-that knowledge is just how one should best scaffold this process to minimize cognitive overload. In this regard we are informed by the process of scaffolding where relational complexity is reduced by progressively chunking concepts into more and more semantically dense concepts (McCredden, O'Shea, Terrill, & Reidsema, 2016).

The key aspects we have identified from the data can be broken down into three groups. The first two (1-2 below) relate to the establishment of conceptual knowledge (i.e. knowledge "that") while the next two (3-4 below) relate to procedural knowledge (i.e. knowledge "how"). The final aspect (5 below) relates to "choreographing" an appropriate flow between development of meaning via conceptual knowledge and development of skill via contextually-based procedural knowledge to ensure the primacy of the epistemic ascent (through a hierarchy of inferentially related concepts).

1. An overarching goal relating to student identity for the course, or for each major section.
2. Clear identification of:
    a. The first principles /core concepts of the domain which must be understood
    b. The relationship (i.e. linkages) between these concepts
    c. The subset of all the concepts which experts want novice learners to understand and which will form the learning objectives for the course.
    d. An appropriate hierarchy for these concepts which would facilitate epistemic ascent
    e. The development of a concept map of the key concepts and their linkages may prove useful to use with students in this process.
3. For each concept related learning objective, establish a set of contextualised learning activities by which the students may measure the success of the learning (and ideally compare their level of success and their learning progress with that of their peers).
4. For each learning activity identify the scaffolding that will be needed to achieve manageable levels of relational complexity, ideally ensuring students hold no more than four concepts in working memory at any one time. These activities should be

small and frequent to encourage students to study for mastery rather than study for the test/exam. Prompt marking and formative feedback which offers strategies for improved learning are essential.

5. Establish a plan to use direct instruction to flow between the development of conceptual and procedural knowledge, ensuring the primacy of the conceptual development so that learners emerge with “generalisable” integrated conceptual understanding permitting “far transfer” rather than just fragmentary procedural knowledge limited to familiar contexts.

It is traditional to train high school teachers in educational theory to assist them in developing pedagogical content knowledge (PCK) - “the ways of representing and formulating the subject that make it comprehensible to others”‘ (Shulman, 1986, p. 9). It is thus accepted at school level that curriculum and pedagogy are inextricably linked, so that it would be inappropriate to consider one without the other. However, that linkage isn’t so well known amongst all tertiary lecturers and examples abound of curriculum designs focussed solely on content, with learning outcomes written in terms of simple algorithmic procedures amenable to drill and practice and easy assessment, rather than complex tasks developing integrated conceptual understanding. Thus the first original contribution of our research is to look at course design in such a way that the basics of PCK are automatically addressed.

However we aim for substantially more than that. It is already known that concept maps prepared for the same subject by expert scientists and by teachers of science (trained in PCK) differ substantially, with those of the scientists reported to be more flexible and those of the teacher more rigid – allegedly because of high school curricular constraints. This has implications for tertiary teaching in that a straight PCK approach may be too limited. For this reason our analysis gives primacy to facilitating epistemic ascent and encourages that by direct instruction which appropriately guides the flow of instruction from abstract conceptual understanding, moves to authentic contextual activities and returns ultimately to wrap up the learning experiences in terms of enhanced abstract understandings.

Conclusions

While the project is still a work in progress we have identified several key features to be considered in the development of an engineering course which is embedded in a deeper understanding of the inferential connections between propositional and procedural knowledge (Wheelahan, 2010). Of most significance is the requirement for course designers to begin earlier than they begin now with a “first principles” interrogation of the key concepts (McPhail & Rata, 2015). Our insights on course design to date are built around three key mantras:

(1) What you teach must be ordered by first principles

(2) What you teach must be consistently linked back to first principles

(3) When connecting ideas to examples, reinforce general principles not contextual ones.

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