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'I take engineering with me': epistemological transitions across an engineering curriculum

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ABSTRACT

In this paper we study epistemological transitions across an intended engineering curriculum and recommend strategies to assist students in attaining the increasingly complex concepts and insights that are necessary for transition to advanced levels of study. We draw on Legitimation Code Theory [Maton, Karl. 2014, *Knowledge and Knowers: Towards a Realist Sociology of Education*. Abingdon: Routledge], in particular the dimensions of sematic gravity and semantic density, to explain these transitions. Data for the study was obtained from a curriculum renewal project that reveals how engineers understand engineering knowledge. We find an interdependent relationship between semantic gravity and semantic density in the intended engineering curriculum. The complexity of the context and the problems that arise from it pose strong cognitive challenges. The semantic gravity wave rises and falls across the engineering curriculum s, enabling both abstraction and a focus on 'real world' problems in specialised knowledge fields. Control of the semantic gravity wave is key to the provision of 'epistemological access' [Morrow, Wally, ed. (2003) 2009. *Bounds of Democracy: Epistemological Access in Higher Education*. Reprint, Pretoria: HSRC Press] to engineering knowledge.

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Introduction: 'engineering is hard'

There is general consensus in the literature that undergraduate engineering programmes pose significant challenges to students and their teachers; many programmes are marred by high attrition rates, poor student success, and a notable lack of diversity (Baillie and Armstrong 2013; Carstensen and Bernhard 2008; Garrison et al. 2007). There is growing recognition worldwide by governments, professional councils and researchers of the need for educational transformation in undergraduate engineering (McKenna et al. 2011). Significant resources have been invested in engineering education in an effort to improve the number, quality and diversity of engineering graduates, but these investments have not resulted in widespread adoption or systemic transformation

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(McKenna, Froyd, and Litzinger 2014). While many agree that engineering is difficult, there is less consensus on what makes engineering programmes so challenging (King 2012; Siddiqui and Adams 2013) – despite 100 years of engineering education (Froyd, Wankat, and Smith 2012).

Many studies in engineering education have focused on pedagogy, student learning, or issues of institutional or departmental cultures, while considerably fewer have interrogated the epistemological base of engineering curricula. The focus on what teachers, students and their departments do (or do not do) has tended to obscure the nature of engineering knowledge itself. This is the issue that we address in this paper. Our focus is the logic of the epistemological shifts across an undergraduate engineering programme, as well as the educational implications for successful passage across these transitions.

The context of this study is the revision of an Electrical and Computer Engineering (ECE) undergraduate degree. Computer engineering integrates principles of electrical engineering and computer science for the purpose of building computer systems and computer-related electronic devices (Shackelford 1997). The degree, BSc (ECE), denotes the engineering specialisation and its scientific base, and emphasises that graduates acquire both electrical and electronic knowledge. ECE is not a widely used term; more common programme names are Computer Engineering or Electronic Engineering – but none of these effectively describes the ECE programme, which combines electrical engineering with electronics and computer engineering. It includes much of the standard electrical engineering degree programme (e.g. building circuits, electricity generation and transfer), but includes a significant focus on computer systems design, at the price of sacrificing some of the depth of knowledge of the standard electrical engineering curriculum (e.g. electrical engineering includes alternative energy and high current transfer; while ECE provides little coverage in these areas).

In this paper we analyse the epistemological basis of the intended ECE curriculum in order to discover its challenges and to motivate for a more systematic and theoretically grounded way to guide curricular selection, sequencing and pacing for the purposes of enhancing students' 'epistemological access' (Morrow 2009) to engineering knowledge.

Engineering knowledge and its selection and sequencing in engineering curricula: a brief overview of the literature

Engineering programmes are based on selections of the pure and applied disciplines that underpin their areas of practice. The pure disciplines, such as Physics and Mathematics, are 'internally oriented' (Bernstein 2000), that is, they have a logic and coherence that is specific to the discipline and have clear boundaries between themselves and other areas of knowledge. The engineering sciences are described by Bernstein (2000) as 'regions' of knowledge that face outwards towards practice. Bernstein explains that in professional programmes, pure disciplines are 'recontextualised', that is, codified into 'larger units' that 'operate both in the intellectual field of disciplines and in the field of external practice' (2000, 52). Beck and Young (2005) argue that professional identity is strongly built into the regions because of the historical linkages between the professions and their specialised knowledge bases. Bernstein (2000) locates the driving force of professional identity in the relationship that practitioners have with knowledge, a relationship he characterises as 'inner dedication'. The interrelationship between 'inner dedication' and the 'field of external practice' is fundamental to professional consciousness, commitment and rigour.

In addition to selections from the basic and engineering sciences, engineering curricula include 'design and synthesis' components (Flanagan, Taylor, and Meyer 2010), curricular modalities that are closely associated with the acquisition of knowledge through project-based learning. A number of studies have attempted to describe engineering design processes (e.g. Atman et al. 1999); engineering design occurs in 'object-rich' environments in which artefacts (such as computers and codes) mediate and contribute to knowledge. Computer engineering involves set codes and procedures for working on problems, and the use of these technologies opens up ways for more explorative engineering design as 'resources are re-embedded and recreated when utilized in specific settings' (Nerland and Jensen 2014, 92). The ability to use or reuse engineering artefacts is dependent upon knowledge that develops through practice and which allows engineers to understand the limits and possibilities of different technologies. Another example of the use of complex objects is that of accessing provider websites, software upgrades and question-and-answer forums through computer engineers' membership of extended practice communities (Nerland and Jensen 2014). In this regard, the engineering project is a 'signature pedagogy' of engineering programmes, usually undertaken towards the end of the qualification and involving practical laboratory work and the building of engineering artefacts (Stiwne and Jungert 2010). Most engineering programmes also require students to undertake a practicum. Such work practice or internships have the educational value of providing students with access to and engagement in authentic instances of professional work, and are offered in the expectation that theory and practice will be effectively integrated through practical work (Rooney et al. 2014).

Students' difficulties when encountering engineering knowledge is well documented in the literature on 'threshold concepts' (e.g. Carstensen and Bernhard 2008; Flanagan, Taylor, and Meyer 2010). Much of the knowledge in engineering is conceptually complex and specialised, thus very different from the mathematics or science learned at school. But, conversely, many students become bored with the 'ritual knowledge' of the basic sciences and mathematics, such as the routines and procedures of mathematical algorithms or the 'inert knowledge' of Physics that is seemingly unrelated to the integrative and dynamic nature of engineering (Baillie, Goodhew, and Skrybina 2006). Many difficulties are caused by the technical language of engineering. Discourses have developed within the engineering sciences to represent ways of understanding – and these can be 'troublesome' for the newcomer, particular if the words have a common meaning as well as an engineering-specific meaning (Baillie, Goodhew, and Skrybina 2006). An additional challenge, particularly at the higher levels of project work, is accessing the reservoirs of tacit knowledge that have been developed by engineering communities of practice over many years.

The concept of a 'learning transition' is increasingly being used in higher education to identify key stages in student development, such as the transition from school to university, from introductory to more advanced concepts, and from undergraduate to postgraduate study (Scott et al. 2014). In engineering education there are distinct epistemological transitions, such as the transition from the basic sciences to the engineering sciences, from theory to problem-solving and design, and from the world of the university to that of the profession. Key transitions are associated with 'threshold concepts' (Carstensen and Bernhard 2008) and ‘conceptual gateways’ (Grayson et al. 2013) that open up new ways of thinking, doing, and being in particular disciplines. University teachers have become increasingly aware of these epistemological shifts and understand that successful transfer across stages is important for student success.

Conceptual framework: towards a model engineering knowledge for curricular selection

In this section we propose a model of engineering knowledge to explain epistemological transitions across an intended engineering curriculum – and why they require different curricular logics, pose higher levels of intellectual challenge, require different pedagogies and increasing student independence.

Thus far we have identified a number of knowledge types from which curricular selections can be made: basic sciences, engineering sciences, design and synthesis and practice. In most models of professional knowledge (e.g. Bernstein 2000; Muller 2009) the knowledge types are understood to occupy different points along a continuum, with specialised scientific or theoretical knowledge at the one end and the knowledge developed in practice at the other. This single continuum does not do justice to the variety of engineering knowledge types (see e.g. Hanrahan’s [2014] rich analysis of the layers of engineering knowledge), and for this reason we draw on Maton’s (2014) Legitimation Code Theory (LCT) that extends prior work done in the sociology of knowledge to show that knowledge types can be reconceptualised in a less dichotomous way. LCT builds on Bourdieu’s (1993) field theory (that sees actors positioned in fields of struggle over status and resources) and Bernstein’s (2000) code theory (that conceptualises curricular and pedagogic organising principles in terms of ‘codes’). LCT offers an explanation of the underlying structures of different knowledge forms. By examining the structuring principles of various examples of engineering knowledge, we can make explicit what engineering knowledge is, why it is perceived to be difficult, and how it may be made more accessible.

Maton identifies a range of knowledge dimensions (2014) and within each dimension locates knowledge types along two axes, thus providing a powerful and detailed language of description. We draw on the dimensions of semantic gravity and semantic density, two continua along which the knowledge areas that underpin the curriculum can be plotted. Semantic gravity (SG) refers to:

> … the degree to which meaning relates to its context. Semantic gravity may be relatively stronger (+) or weaker (−) along a continuum of strengths. The stronger the semantic gravity (SG+), the more meaning is dependent on its context; the weaker the gravity (SG−), the less dependent meaning is on its context. (Maton 2014, 129)

Weakening the semantic gravity in a programme or subject involves drawing generalising principles from the particulars of a specific context or case, while strengthening semantic gravity involves application from an abstracted concept to specific cases or problems.

Semantic density (SD) refers to:

> … the degree of condensation of meaning within socio-cultural practices (symbols, terms, concepts, phrases, expressions, gestures, actions, clothing, etc.) Semantic density may be relatively stronger (+) or weaker (–) along a continuum of strengths. The stronger the semantic

> density (SD+), the more meanings are condensed within practices; the weaker the semantic density (SD–), the less meanings are condensed. (Maton 2014, 129)

When there is stronger semantic density (SD+), the theoretical, abstract components of the programme are foregrounded. When there is stronger semantic gravity (SG+) the contextual, practical, work- or professionally oriented aspects of the programme are more dominant. A programme that is described as SD−SG+ does not mean that it is devoid of theory or intellectual challenge, it means that the application context is given prominence. Strong semantic gravity can also suggest the complexity of the practice in a particular profession.

Drawing on the insights of LCT, as well as the research literature on engineering knowledge and its selection and sequencing in engineering curricula more broadly, an initial conceptual model of engineering knowledge emerges that is based both on the relative strengths of semantic gravity and semantic density across the engineering transitions, as well as the potential for a variety of different relationships between these two dimensions. We can use this model to distinguish different forms of knowledge within a curriculum, but also to provide some of the detail that is missing from knowledge-based approaches that foreground (and value) disciplinary, conceptual knowledge and relegate contextual knowledge to a minor, supporting role. The shifting relationship between semantic gravity and semantic density is central to understanding the epistemological transitions and their increasing levels of difficulty in engineering programmes.

The emerging model proposes that the underpinning basic sciences of Mathematics and Physics have stronger semantic density (SD+) and weaker sematic gravity (SG−), although shifting towards SG+ on the semantic gravity continuum in the more applied forms of Mathematics for Engineering or Physics for Engineering. The engineering sciences have both stronger semantic gravity (SG+) and stronger semantic density (SD+), thus offering, as many researchers have shown (e.g. Ursani, Memon, and Chowdry 2014) a greater level challenge than the basic sciences. Engineering projects, as suggested by studies (Chandrasekaran et al. 2013), are placed at the highest level of challenge, with both strong semantic gravity (SG+) and strong semantic density (SD+). While most engineering programmes include 'complementary' subjects, such as project management, entrepreneurial abilities, communication skills, and the social contexts of engineering, these subjects tend to have lower semantic gravity (SG−) and semantic density (SD−) because they tend to be shorter 'add on' courses that are not fully integrated within the programme (see e.g. Pulko and Parikh 2003). Many programmes also include generic engineering graduate attributes, the so-called 'soft skills' that tend not to be taken particularly seriously in engineering programmes (Baillie and Armstrong 2013). Finally, the engineering practicum, as preparation for professional practice, while underpinned by the full range of knowledge forms, is characterised by higher semantic gravity (SG+) and lower semantic density (SD−). The usual curricular sequence is from the basic sciences to the engineering sciences, culminating in a major engineering project towards professional practice, but with considerable variation across programmes, particularly those that use problem-based or project-based curricular modalities (Case 2014). Even in non-problem-based curricula there might be earlier and later complementary subjects in introductory or capstone positions, but general trends are as in Figure 1.

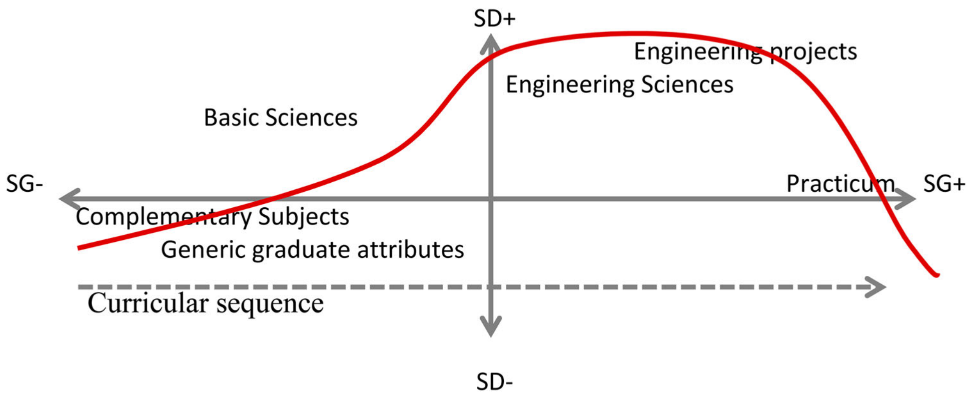

Figure 1. An initial conceptual model of engineering knowledge for curricular selection.

Researching knowledge

In line with a social realist approach, this study understands that knowledge has causal powers and tendencies. As a generative mechanism engineering knowledge cannot be directly accessed, its properties must be inferred from its effects. Data from the level of what realists (e.g. Maxwell 2012) call the level of the 'actual' (such as curriculum documents and assessment tasks) and that of the 'empirical' (how participants understand engineering knowledge, practice or concerns) can elucidate properties of the underlying mechanism. Using a substantive theory, such as LCT, to shape the data collection and analytic tools, makes more visible the causal powers and tendencies of knowledge, its different structures and affordances – and why these 'lend themselves more to certain forms of pedagogy, evaluation, identity, change over time, and so forth, than others' (Maton 2009, 55).

The study drew on two main sources of data: (1) curriculum documents and (2) interviews. The curriculum documents studied included the university prospectus, official curriculum documents (with approved credit values for subjects), minutes of curriculum committee meetings, syllabus outlines and assessment tasks. The study of these documents was the starting point; after an analysis of the documents an initial value of SG+/− and SD+/− was given to each subject. These values were adjusted, following the interviews.

University staff (both the academic engineers and teachers of the 'complementary subjects'), external moderators, programme accreditation teams, expert professional engineers and recent graduates of the programme were interviewed. The selection of the participants was based on existing, mainly research-related, collaborations that had been in place for many years. Thus most interviewees were familiar with the existing ECE curriculum, and several participants had employed graduates of the programme. Interview schedules were developed from the initial model of engineering knowledge to probe more deeply into the properties of the different knowledge areas – both to enable the participants to identify their knowledge forms, as well as to enable comparison across participants. The interviews were conducted face-to-face, telephonically, or via Skype; in some cases the interview questions were sent via email. These data (with the exception of the email archive) were transcribed and checked for accuracy by the researchers and relevant participants. Two researchers coded each transcript separately, using *in* *vivo* coding processes. The research team subsequently refined the categories in alignment with the conceptual framework. The data produced by the interviews were used to further describe the properties of engineering knowledge and their emergent effects across the ECE programme. The richer data enabled a more detailed curricular mapping of subjects in the existing ECE curriculum in terms of their semantic gravity and semantic density (see Winberg et al. 2014) and further development of the initial model of engineering knowledge for curricular selection in the intended curriculum revision.

The participants were able to explain engineering knowledge, although not in the specific terms of the conceptual framework developed for this study. They discussed desired engineering abilities, the techniques that students should learn, the application contexts and problems that they should experience and the types of systems and projects that students should be exposed to. Maxwell (2012) contends that what matters in the data is the nature of the understanding produced by each participant and how the researchers 'abduct' inference of the real.

This research study developed from a curriculum renewal project in ECE, the main objective of which was to ensure that up-to-date tools and technologies were incorporated into the ECE programme, with a view to preparing graduates for twenty-first-century computer engineering (Winberg 2014). Ethical clearance to use the data for scholarly publication was obtained from the institution concerned; neither the research participants nor their institutions or companies were identified. Our findings from the research study are discussed below.

Findings: semantic gravity and semantic density in the ECE curriculum

In this section we discuss new graduates', academic, professional and research engineers' understanding of the engineering knowledge forms underpinning the existing ECE curriculum, as well as their proposals for curriculum renewal.

Semantic density: the fundamental core of professional expertise and identity

We start with semantic density, as ECE is characterised by rising levels of challenge across the programme. In many engineering programmes there is not an absolute distinction between pure and applied knowledge because the pure sciences – Mathematics and Physics – are selected and sequenced in the intended curriculum for the engineering practice. Thus subjects such as Engineering Mathematics, Statistics in Engineering, Vector Calculus for Engineering, Linear Algebra for Engineers and Engineering Physics combine elements of pure and applied disciplinary knowledge. In this regard, participants spoke in terms of 'the fundamental core' and 'essential professional expertise'. All participants felt that the 'fundamental knowledge core' of ECE needed to be 'protected' because Mathematics, Physics and the engineering sciences – subjects with stronger semantic density – would always underpin engineering practice, regardless of the type of career or application context in which graduates might practice engineering:

> … the fundamentals: mathematics, physics, basic computing are non-negotiable … . (Academic Engineer 1)

> I have interviewed … candidates for [engineering] positions in both South Africa and the United States … candidates are chosen not for experience in any single [engineering] technology or environment, but for a strong grounding in the fundamental concepts. (Professional Engineer 1)

> With an understanding of programming fundamentals, they will be able to go into more detail with it if and when needed. (Professional Engineer 1)

The general consensus was that a core of semantically dense knowledge underpins engineering practice, and needed to be protected in the curriculum renewal project. The most valued requirement in terms of graduate qualities was that of 'professional expertise' in terms of the underpinning knowledge and the professional values derived from this disciplinary base. This was emphasised by both industry and research collaborators.

Epistemological transitions in the intended ECE curriculum, shown in Figure 2, are characterised by rises in semantic density across core areas of the programme. Selections from the basic sciences, Mathematics, Physics and Computer Science, build the engineering base. There is an implied epistemological transition from the more general forms of science learned at school, to a more specific focus on engineering (i.e. from General Mathematics to Engineering Mathematics). The next transition occurs in the shift from the

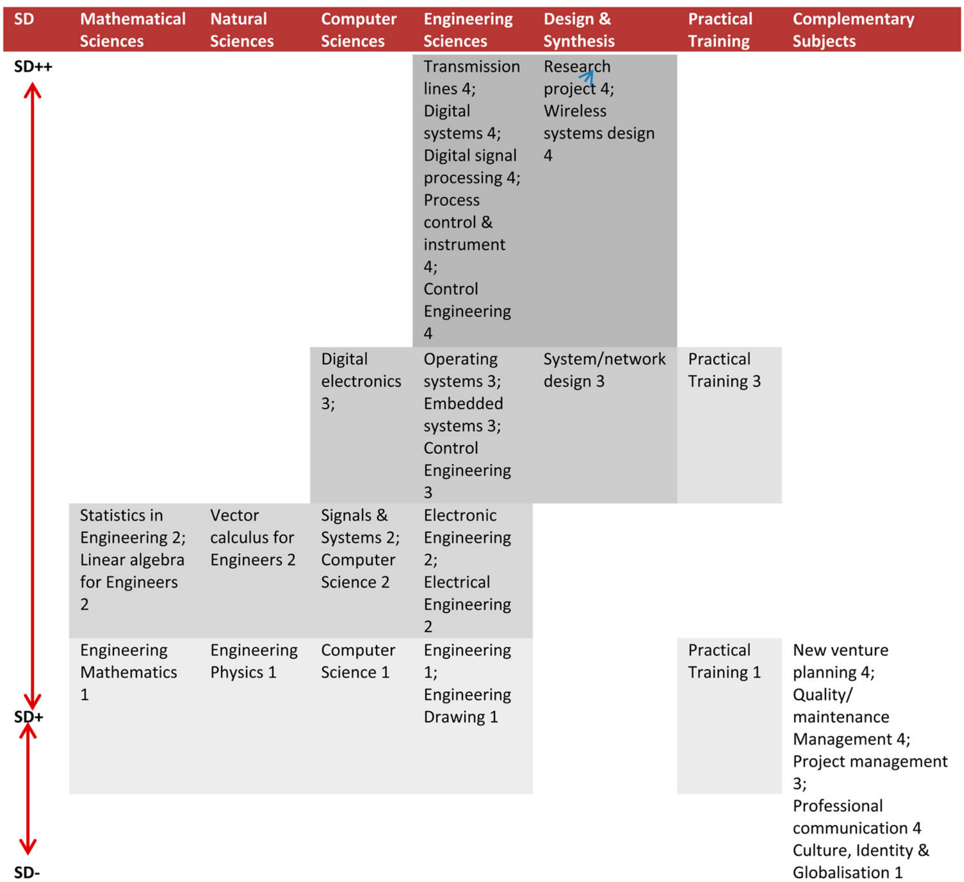

Figure 2. The semantic density range in the intended ECE curriculum.

basic sciences to the engineering sciences, which involves greater specialisation and a sharper focus on the world of computers and electronics. At the higher levels some engineering sciences would be offered as elective subjects, enabling even greater specialisation and focus. Beginning in the third, and especially in the fourth (final) year, students make another significant epistemological transition to problem-solving and design. The insights that students have gained and the principles they have learned build the symbolic language with which they will solve engineering problems, develop designs and build systems and machines. The increasing semantic density in engineering is accompanied by a narrowing of the focus across each transition to achieve greater levels of specialisation.

As a counterbalance to this tendency, and in order to ensure that students understand engineering in its wider contexts, a number of 'complementary studies' are offered (e.g. Culture, Identity and Globalisation, Project Management). These are the only subjects with a lower semantic density range (SD−) in the engineering curriculum, as they do not take the subject content to a very high level (those offered in the final year are offered as short 'capstone' courses with low credit values). The Engineering Council of South Africa requires all engineering students to undertake a practicum at a basic and more advanced level, which brings us to the matter of semantic gravity in the engineering curriculum.

Semantic gravity: 'leaky abstractions' and complex contexts

The engineering context is implied not only by the practicum requirement but the in specificity of techniques and tools and in problem-solving in context. The research participants understood that the ECE requires an understanding of application contexts together with the tools and technologies needed to solve problems within these contexts. A cluster of specific tools and techniques were identified as being important by the research participants, although neither the new graduates, nor the professional engineers advocated training on specific tools, and often qualified their comments by emphasising the importance of understanding how to use tools effectively, such as the engineer who commented that Linux scripting '… is an extremely useful tool if you know how to use it … ', or highlighted the importance of transfer across technologies: 'a good candidate who knows C# can become productive in Java in a matter of weeks … ' (Professional Engineer 1).

Professional engineers use a wide variety of implementation tools and programming languages in their workplaces, each of which is appropriate for solving different kinds of engineering problems. In describing the tools, the engineers speak a contextually embedded language of practice:

> Our products are built with Java and … a tomcat server. We use mysql … and hibernate to communicate between Java and the databases … . (Professional Engineer 4)

> … I am currently working on developing Firmware … only VHDL and a little C code … for radars … we deal primarily in coding with Aldech Active-HDL for block diagram implementation and simulation of VHDL code … [we] use Altera Quartus for synthesis … . (Industry Collaborator 3)

Participants found it difficult to explain the qualities associated with contextual knowledge as knowledge that develops through experience or in innovation is often tacit. The engineers agreed that there should be a broad variety of problem-solving opportunities for students or, in terms of the conceptual framework, a wide semantic gravity range. While there was consensus about the need for students to accumulate problem-solving experiences for complex applications, there was not consensus on specific contexts, although the importance of contexts and of 'real time' was always present. Achieving a high quality of design (or design artefacts) must take the context into account. In this regard 'testing' was felt to be important because through testing one can control the level of contextual complexity: from virtual testing, to controlled laboratory testing, to 'real-time' testing *in situ*:

> Not enough emphasis is on testing and frameworks associated with testing … using an existing framework … or setting up … testing frameworks … . (Industry Collaborator 4)

Graduates of the ECE programme practise engineering in wide variety of contexts: power systems, electronics, telecommunications, embedded hardware and software engineering, radar systems, high performance computing, computer design, automobile, avionics, astronautics and marine engineering, control systems engineering (e.g. robotics, factory line conveyor control, etc.), instrumentation, design, quality control and certification, systems design, field engineering (installing and repairing) and sales and marketing. Rather than focusing on a specific application context, research participants recommended extending the semantic gravity range, as the comment below recommends:

> … I would strongly encourage any curriculum change to focus on providing a diverse range of ideas and experience rather than knowledge of any particular technology. (Professional Engineer 2)

Participants agreed that a wider semantic gravity range, a diverse range of ideas and experiences, was preferable to a narrower semantic gravity range – or a focus on particular technologies. Exposure to technologies within courses should be appropriately focused on the principles of practice, as many technologies have a short 'shelf-life':

> The lifecycle of technologies like these have proven to be short. While exposing students to some of the ideas in these languages is important (LINQ, for example, is a fascinating technology) learning the details should not be the focus. (Research Collaborator 2)

Due to the increasing importance of application contexts across the engineering curriculum, much engineering knowledge is characterised by relatively strong semantic gravity (SG+). In other words the engineering sciences and engineering design have a greater context-dependency than the basic sciences. Thus there is an interdepend relationship between semantic gravity and semantic density in engineering knowledge. It is often thought that when meanings are contextually embedded (SG+), they are likely to be less condensed (SD−), but this is not the case in engineering. In engineering, the relationship between semantic gravity and semantic density is not converse. In his analysis of 'phases' in secondary school lessons, Maton (2013) shows how knowledge can be transformed from a relatively decontextualised abstract state in which meanings are condensed (SG− SD+) through context-dependent exemplification to a more simplified state (SG+ SD−); repeated patterns of higher semantic density/lower semantic gravity and lower semantic density/higher semantic gravity create a 'semantic wave'. In engineering, abstract knowledge is generally not made simpler through contextualisation, it is made more complex. The mutually reinforcing relationship between semantic gravity and semantic density in engineering is one in which stronger semantic gravity pushes the semantic density up. This is because engineering contexts are not 'everyday', they are complex. The complexity of the context and the problems that arise from it pose strong cognitive challenges. Contextually embedded engineering knowledge can vary in semantic density (i.e. in levels of condensation of meaning). In engineering, semantic gravity describes the external relations of knowledge, it does not imply common sense or everyday knowledge; thus is it not equivalent to Bernstein's (1999) 'horizontal discourse'. On the contrary, engineering application contexts and engineering problems require highly specialised knowledge.

Computer engineers talk of 'high level' and 'low level' computing; 'high level' engineering approximates to semantic density as it involves decontextualised abstractions; 'low-level' engineering approximates to semantic gravity as it refers to the application context, or to specific types of hardware or software, as in the quotation below:

> I would very much like to see embedded-systems and lower level courses remain a big part of the ECE curriculum … While virtualization, virtual machines and dynamic languages are a big part of the industry landscape, a solid grounding in bits-and-bytes and the low-level functioning of a computer is still extremely important. All the abstractions we have built are leaky, and when those abstractions leak, a knowledge of low-level computing topics is indispensable. (Professional Engineer 3)

'Leaky abstraction' is a term used in software engineering to describe the 'simplification of something much more complicated than is going on under the covers' (Spolsky 2002). High-level engineering concepts express general principles, but when contextual details (e.g. in the underlying hardware or software) are ignored, inaccuracies 'leak' out of the abstraction into the software that has used it. The term alerts software engineers that they cannot rely on an abstraction's infallibility. Abstractions are 'leaky' because they are 'imperfect'; they might over-simplify the context to the extent that they cannot support engineering design.

On the other hand being 'too specific' is equally undesirable as engineering knowledge must be transferrable to a range of contexts. The participants were, for example, concerned that students' learning experiences should not be limited 'to the techniques and tools that the industry partners use' (Professional Engineer 1). It is for these reasons that the engineering curriculum incorporates a 'gravity wave' that allows for abstractions, but ensures that they are tested in the application context. The gravity wave weaves in and out of phase with the rising semantic density across the programme, increasing and reducing the levels of difficulty. In studies that draw on LCT, and the semantic wave in particular, high semantic gravity is represented as a negative value on the continuum (e.g. Maton 2013). Because the gravity wave is not a simplification device in engineering, we chose (for mathematical and symbolic reasons) to represent it as a positive value, as in Figure 3:

Figure 3 is a schematic representation of the strengthening and weakening of the semantic gravity wave across the ECE curriculum. More detailed plotting of the data shows more variation across and within subject areas, although similar trends can be identified (see Winberg et al. 2014). Semantic gravity enables the ECE curriculum to focus on 'real-world' problems and the specificity that this entails. Without semantic gravity, engineering would revert to science (and ECE would revert to Computer

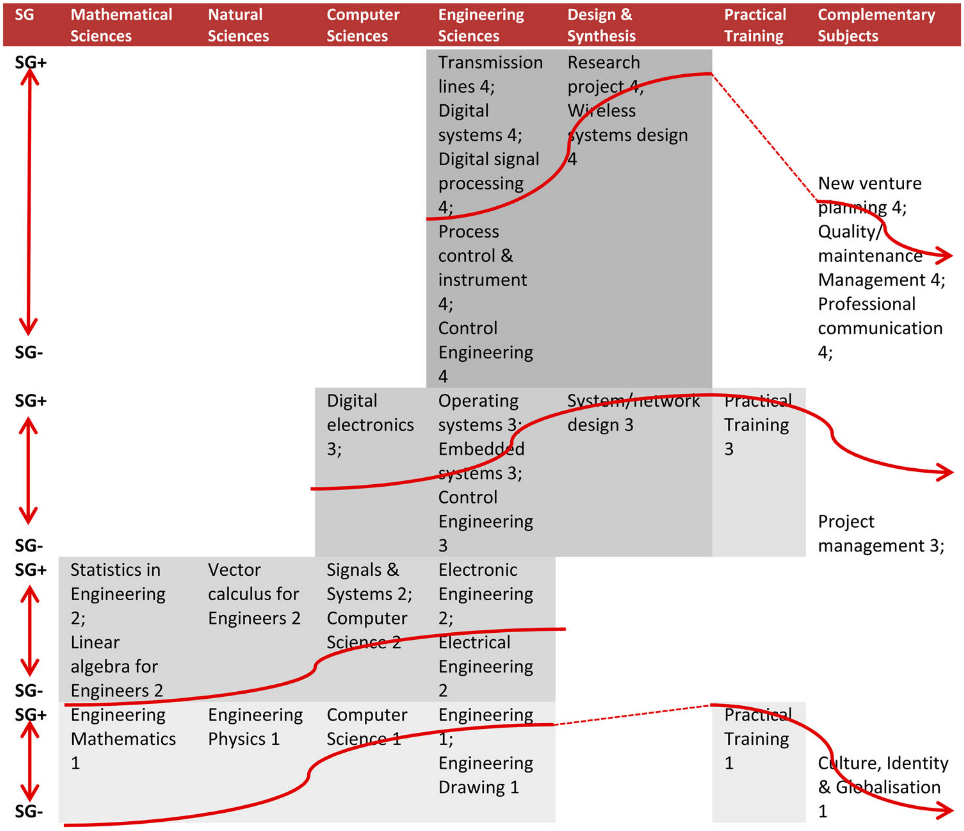

Figure 3. Semantic gravity waves across the intended ECE curriculum.

Science). The ECE curriculum focuses on 'real-world' problems via a semantic gravity wave that enables travel between and across increasingly complex contexts. The gravity wave increases and decreases complexity in engineering. Semantic gravity 'powers' the engineering curriculum as it expands the semantic gravity range across the engineering curriculum.

Reflections on the relationship between sematic gravity and semantic density

The engineering transitions give evidence of the rise in semantic density across the engineering curriculum, giving it its characteristic transitions with concomitant rises in levels of difficulty (see Figure 4).

The epistemological transitions across the engineering curriculum are characterised by changing relationships between semantic gravity and semantic density. When the semantic gravity is significantly reduced, it enables high semantic density (abstraction and condensation of meaning). Everyday contexts are not generally useful in engineering as they would excessively reduce the semantic density towards over-simplification. Simple and more complex application contexts need to be balanced to achieve an appropriate level

Progression	Epistemological transitions in Computer Engineering	Curricular weighting*
SD++	Design and Synthesis	17.0%
	Engineering Sciences	48.4%
SD+	Basic sciences	23.1%
SD-	Complementary Studies	11.5%

Figure 4. Semantic density increases progressively across the epistemological transitions.

of semantic density, more simple application contexts will reduce the semantic density, while more complex contexts will increase it (Figure 5).

The increasing semantic density, together with the range of the semantic gravity wave gives the engineering curriculum its characteristic epistemological transitions. The gravity wave increases and decreases contextual complexity, lessening or increasing the cognitive challenge, but also creating engineering meaning, while the base anchors engineering knowledge to its underpinning disciplines, provides structural stability and builds the engineering identity across the curriculum. It is the semantic gravity wave that enables engineering to travel across a range of more or less semantically dense subject areas, appropriating them for the purposes of solving 'real-world' problems. Engineering is thus, paradoxically, deeply contextualised, but is not specific to a single context:

> Computer engineering is not context-specific … whether I'm working for a software development company in the States or creating a production line inspection device for a factory in South Africa or a monitoring system for a New Zealand farmer … I take engineering with me. (Academic Engineer 2)

Engineering knowledge is dependent on context, but is not reducible to context.

Epistemological access: controlling the gravity wave

While the epistemological transitions in the engineering curriculum are characterised by increasing semantic density, a semantic gravity wave travels across the transitions, reducing the contextual complexity to enable a focus on 'high level' abstractions in parts, but increasing the complexity and level of cognitive challenge in others. Stronger semantic gravity will entail a concomitant rise in semantic density, while weaker semantic gravity

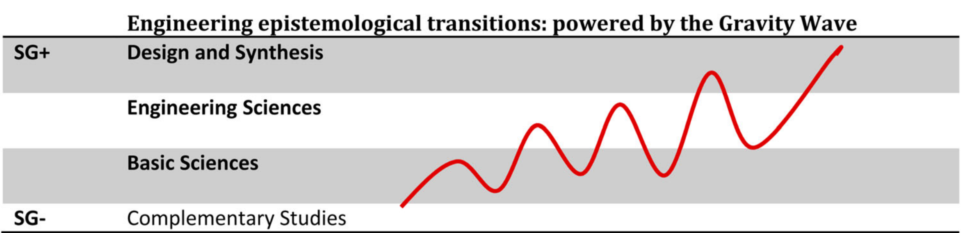

Figure 5. The gravity wave increases its range across the epistemological transitions, increasing and decreasing levels of academic challenge.

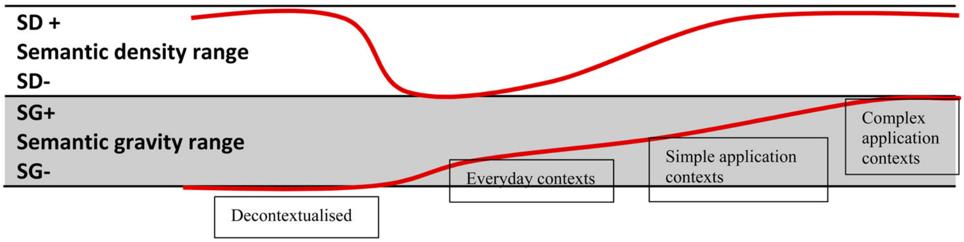

Figure 6. The relationship between semantic density and semantic gravity in engineering.

is, in engineering, a means of simplification through abstraction – of holding the full complexities of the context at bay in order to reduce the cognitive load for the purpose of enabling conceptual development.

Increasing or decreasing contextual complexity is central to supporting students' acquisition of engineering knowledge. Engineering problems must be of a sufficiently complex nature; in other words they must contain an appropriate semantic gravity range. A participant in this study explains, for example, that '… simple PWM … and squeaking speakers are way too simple for third years' (Professional Engineer 4) – in other words, the semantic gravity should be stronger at more senior levels. Another participant suggests that students 'should have exposure to signal processing techniques and [come] up with their own algorithms' (Professional Engineer 3) – this description suggests that both stronger gravity ('processing techniques') and stronger semantic gravity (developing 'the own algorithms') is an appropriate level of difficulty. Contexts and problems can be controlled to achieve an appropriate level of cognitive challenge, for example, a participant suggested '… simple radar receiver processing using simulated data … '. When real data related to complex application contexts are too challenging, data can be 'simulated' in order to reduce its semantic gravity.

Semantic density, represented by the pure and engineering sciences, progressively increases across the engineering transitions. The semantic gravity wave rises and falls across the engineering curriculum, alternatively increasing and decreasing curricular complexity. In engineering there are few 'everyday' contexts, the use of such very simple context (as Maton [2013] shows) will reduce the semantic density, but as the application contexts increase in semantic gravity, they cause a corresponding rise in semantic density (see Figure 6). This is what makes engineering difficult.

Enabling passage across the epistemological transitions is central to a transformative approach to curriculum; it requires pedagogies that are inclusive and that can engage students in the full professional knowledge system. Expanding or reducing the semantic gravity range across the engineering transitions is necessary to achieve an appropriate level of academic challenge an engineering curriculum. Key to the provision of epistemological access is control of the semantic gravity wave.

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