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A language for the analysis of disciplinary boundary crossing: insights from engineering problem-solving practice

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ABSTRACT

Poor graduate throughput and industry feedback on graduate inability to cope with the complex knowledge practices in twenty-first century engineering 'problem solving' have placed pressure on educators to better conceptualise the theory-practice relationship, particularly in technology-dependent professions. The research draws on the social realist work of Basil Bernstein and uses the Legitimation Code Theory dimension of Specialization to interrogate different disciplinary organising principles and their impact on complex sociocultural practices. Data gathered from 18 engineering case studies situated in three different types of industrial practice sites form the empirical basis of the original study. This paper focuses on the application of a Language of Description to aspects of the problem-solving process which illuminate the nature of disciplinary knowledge in practice. The intention is to provide educators across professions with empirical insights into the theory-practice relationship in a complex problem-solving context, and which might inform their curriculum and pedagogic design thinking.

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Introduction

Professions in the twenty-first century have become increasingly complex in the face of globalisation and technological development. Tertiary education institutions, worldwide, face the unprecedented pressure of training masses of 'professionals [equipped with the] broad problem-solving skills' (Kraak 2000, 11) necessary to function in increasingly complex fields. This challenge extends to the health sciences, accounting and legal professions, and is particularly acute in engineering (the focus of this paper). With a national average dropout rate of 50% on engineering programmes (CHE 2015; Fisher 2011), and employer dissatisfaction with graduate abilities (Griesel and Parker 2009), South African (SA) engineering education institutions simply cannot afford to ignore the crisis (Du Toit and Roodte 2008). The demand 'that graduates can deliver value from their first day in the workplace' (Case 2011, 3) has resulted in widespread curriculum review and redesign processes.

The design of engineering curricula is complicated by the fact that 'the "content" of engineering practice other than basic principles is changing far too rapidly for engineering

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curricula to keep pace with' (Felder 2012, 11). What exactly are the 'basic principles', though? The knowledge profile for all SA Higher Education engineering qualifications lists *natural, mathematical* and *engineering science* knowledge in one competency outcome (ECSA 2012), as though they were comparable. The concatenation of all the relevant sciences into one outcome in service of the overarching goal of the qualification – to enable problem solving – is problematic. It suggests a lack of 'sophisticated understanding' (Shay 2008, 596) of the nature and purpose of the individual disciplines. What exactly is the relationship between these disciplines, or Felder's 'basic principles' (2012) and actual engineering problem-solving? If, as educators, we hope to enable our students and graduates to solve problems in technologically and socially complex twenty-first century contexts, we might benefit from an examination of how graduates actually navigate the theory-practice relationship.

As a continuation of earlier research into the nature of multidisciplinary engineering knowledge (Wolff and Luckett 2013), the PhD study focused on an analysis of mechatronics engineering problem-solving practices observed in three different types of industrial sites. The intention was to better understand how successful practitioners draw on different forms of engineering disciplinary knowledge when solving a particular real-world problem. The research is located in the sociology of education, and draws on the work of Basil Bernstein (2000) and Karl Maton (2014). This paper foregrounds an aspect of the research methodology and presents a 'language' based on the Legitimation Code Theory (LCT) Specialization concept of *epistemic relations* through which to analyse not only the problem-solving practices from a disciplinary perspective, but also the key elements in the problem-solving situation. *Epistemic relations* considers practices in terms of '*what* they relate to and *how* they so relate' (Maton 2014, 175). The research findings, drawn from 18 case studies, suggest there is a generative relationship between the nature of the problem solver, the problem environment and the disciplinary problem structure. Each of these elements may manifest a different orientation to both the *what* and the *how* of the problem. Where there are clashing orientations, a problem-solving process may be impeded.

The paper begins with relevant elements of the theoretical framework and introduces the *epistemic plane* as analytical tool. This is followed by an overview of methodological aspects related to the use of the analytical tool. Following a summary of the key research findings as illuminated by the *epistemic plane*, a single case study is presented in order to demonstrate the application of the *epistemic relations* principles to multiple features of a problem-solving situation. The paper hopes to provide educators who teach in the professions with an operationalised analytical tool which can help to shed light on the nature of curriculum content and pedagogy in relation to twenty-first century professional problem-solving practices.

Conceptual framework

Engineering is classified in Bernsteinian language (2000) as a 'region', which sees 'singulars' (pure disciplines such as Physics and Mathematics) combined into knowledge areas for specific occupational or professional purposes. The focus for this research is one of the most rapidly emerging and expanding engineering sectors – that of controlled electromechanical systems (or Mechatronics engineering). Mechatronics harnesses industrygenerated technological developments in service of more efficient automation. One sees mechatronic systems in factory production lines, medical diagnostic equipment, military surveillance machines, or in fact any process where components and machines are controlled by a computer. The reason for this particular focus is that the core disciplines that constitute the region are significantly different: the *Mathematics* and *Physics* underpinning the mechanical and electrical elements, and what I am terming '*Logic*'[1] as the discipline underpinning control systems and computer programming. Mechatronics curricula are broadly designed around three core subject areas: structures (mechanical engineering), power (electrical engineering) and control (computer and systems engineering). From a knowledge perspective, 'structures' and 'power' draw on Mathematics and Physics, albeit in significantly different ways. 'Control', in this region, is based on the Logic and Mathematics of computer engineering. This combination of disciplines is comparable to the disciplinary differences in a medical qualification between, say, Anatomy (biological sciences), Pharmacology (Chemistry) and diagnostic technologies (computer-based).

The challenge for educators in such regions is twofold: When they lose sight of the disciplinary basis of the region, the curriculum may lack 'conceptual coherence' (Muller 2009) and be experienced as segmental 'pieces of unrelated information' (Allais 2010, 105); When they ignore 'the occupational practices of the profession' (Shay and Steyn 2014, 141), the curriculum and pedagogy may lack 'contextual-coherence' (Muller 2009), and thus not enable the complex forms of problem solving we expect of our graduates. Navigating this distance between the *conceptual* and *contextual* is complex in a region, and implies moving between different forms of theory and different kinds of practices. This paper takes the position that educators can develop a better understanding of what is required of our professional graduates through an examination of *both* the disciplines *and* practices of a particular region.

Knowledge structures and organising principles

We begin our examination with the disciplines. The key Bernsteinian concept is that of the way in which knowledge is structured. Vertical discourse is the formal 'systematically principled' knowledge (Bernstein 2000, 157) one finds in education systems, as opposed to the informal 'everyday knowledge' Bernstein describes as Horizontal discourse. Within formal Vertical discourse, Bernstein differentiates between two primary structures which reflect the way in which knowledge has progressed in the field. Hierarchical knowledge structures, represented by the natural and physical sciences, attempt 'to create very general propositions and theories, which integrate knowledge at lower levels' (Bernstein 2000, 161). Hence, we see a 'subsumptive progression' of knowledge over time, where new concepts extend and integrate earlier ones. The organising principles of Physics (the key hierarchical knowledge structure in Mechatronics engineering) are reflected in strongly sequenced concept chains. For example, Ohm's Law subsumes a number of concepts – electron behaviour, the nature of different conductors, the principles of resistance and so on – and is reduced at its simplest to $V = IR$. Similarly, in Biology, Mendel's Law of Segregation subsumes concepts such as cell structure, DNA, chromosomes, reproduction and so on. The building of this kind of knowledge occurs through the explicit, sequential and relational combination of base concepts over a long period of time, as is evident in the traditional structure of schools' Physics, Chemistry and Biology curricula. The inadequate grasp of a higher order concept often points to a gap in understanding of the base concepts and their relation to others.

In contrast, horizontal knowledge structures 'consist of a series of specialised languages with specialised modes of interrogation and criteria for the construction and circulation of texts' (Bernstein 2000, 161). In other words, there are kinds of knowledge structures where the same type of knowledge has different 'languages'. Where these 'languages' are powerful because they address specific phenomena in specific ways, Bernstein describes them as having 'strong grammars', and offers Economics and Mathematics (the second key discipline in Mechatronics) as examples. The 'explicit conceptual syntax' (Bernstein 2000, 163) in the Pythagoras theorem ($a^2+ b^2=c^2$) clearly announces itself as algebraic Mathematics, and stably identifies the relationship between the lengths of the sides of a right-angled triangle (the geometric version, i.e. another mathematical 'language' with its own conceptual syntax). Each of the languages in this kind of knowledge structure has strong and recognisable organising principles which do not necessarily apply to other languages of the same family. The different 'languages' of Economics, for example – Classical, Marxist, Keynesian to name a few – each have their own 'strong grammar'. Learning these 'languages' may entail similar sequential procedures to the learning of Physics. The difference is that there are *several languages* to draw on to address the same phenomenon.

Then there are horizontal knowledge structures with 'weak' grammaticality, such as those of the Humanities, where the 'capacity of a theory to stably identify empirical correlates' is weaker (Young and Muller 2007, 188). Weak does not mean 'bad'. It means there may be different intended concepts or interpretations. Bernstein establishes that knowledge in such fields progresses by way of proliferation and redundancy. This is particularly evident in Information Communication Technologies (ICTs), a region which is at the heart of twenty-first century computer-based engineering practice, and which represents the third key discipline in Mechatronics engineering: Logic. One sees the 'weak grammaticality' here in the use of everyday words, such as 'function' or 'object' which take on very different, but specific meanings in different programming paradigms. Working with these knowledge structures requires one to constantly refresh one's knowledge base, adapt to new forms, and respond to a different set of organising principles in different contexts. This implies a far greater number of 'particulars' (Muller 2009) that need to be learnt independently, not sequentially as in the case of Physics, and more often than not in specific and multiple contexts. So, the question for the original research project was *what happens when these three significantly different disciplinary structures meet in a problem-solving moment?* We now turn to knowledge *practices*.

Legitimation code theory

The knowledge structure categories are useful characterisations for curriculum analysis and development, or for conceptualising pedagogic approaches to building knowledge in recognisable disciplines. Regions, we have established, are combinations of 'singulars' (Bernstein 2000) which may become obscured in such subject areas as 'computer-aided design' or 'biotechnology'. Real world problem-solving practice is essentially a 'regional' activity and does not map neatly to a particular discipline. A more robust instrument is necessary if we are to understand 'practices'.

Legitimation Code Theory (LCT) (Maton 2014) is part of a broad social realist coalition which sees knowledge as both socially constructed and 'real', in the sense of having effects, having organising principles that one needs to recognise. LCT offers a means to overcome dichotomous types by considering knowledge and its practices as *relational*, whether in terms of forms of meaning (more or less 'complex'), temporality (a retrospective versus prospective orientation), or legitimacy in fields. The LCT dimension of *Specialization* 'extends and integrates Bernstein's concepts of "grammars"' (Maton 2014, 95) and is about 'what counts', what is legitimate in a field of practice and to what extent. There are two sets of *Specialization* relations: those concerned with *knowledge (epistemic relations)* and those concerned with *knowers (social relations)*. When these two aspects are considered in combination and illustrated as two axes of a Cartesian plane, the *Specialization plane* enables an analysis of what really counts in different fields. In a qualitative study on design thinking (Carvahlo, Dong, and Maton 2009), for example, researchers found that Architecture lecturers recognise legitimacy through the demonstration of specific forms of *knowledge* expertise and having the attributes of a particular kind of *knower*. In contrast, their Engineering participants foregrounded *knowledge* alone as the basis of legitimacy. This finding may seem to be 'common sense', but the power of the instrument lies in its ability to illustrate differences *relationally*: In a different qualitative study on engineering lecturer assessment practices, the *Specialization plane* demonstrates that (in the study in question) mechanical engineers valued *knowers* more than *knowledge* as a result of the 'absence of specific epistemic expertise' (Wolff and Hoffman 2014, 18) as opposed to their electrical engineering colleagues. The instrument helped to illuminate the fact that the different engineering sub-regions view *knowledge* and *knowers* in different ways.

The research presented in this paper zooms into the *knowledge* quadrant of the *Specialization plane*, which then becomes a Cartesian plane in its own right called the *epistemic plane* (Figure 1). *Epistemic relations* 'highlights that practices may be specialised by both *what* they relate to and *how* they so relate' (Maton 2014, 175). The vertical axis represents the strength of the relationship between a knowledge claim and the empirical data (*ontic relations*), in other words *what* is the focus of the claim/practice and how strong is its 'internal identity'? Is the phenomenon recognised and accepted for what it is irrespective of how it is named or situated? The horizontal axis (*discursive relations*) represents the strength of the relationship between ways of referring to or dealing with (*how*) a particular object of study (the empirical data). At right angles to each other, these continua produce four quadrants representing different *insights*.

It will be observed in the following examples that the concept of *epistemic relations* enables a more nuanced understanding of Bernstein's knowledge structures.

Purist insight: Here we see practice based on strong adherence to both the phenomenon in question and the approach. The concept of structural 'force' in Physics is governed by a commonly agreed set of laws and formulas, which thus dictate particular procedures for determining force at a given moment in a system. In other words, there are both strong *ontic relations* (*what)* as well as *discursive relations (how)*. Many of the hierarchical knowledge structures exhibit this same internal 'strength' and restricted or defined 'grammaticality' – *how* one considers an established and accepted phenomenon. It is worth noting that contested phenomena (such as those within quantum physics or evolutionary biology) may see educators adopting a *purist insight* approach for the sake of simplicity,

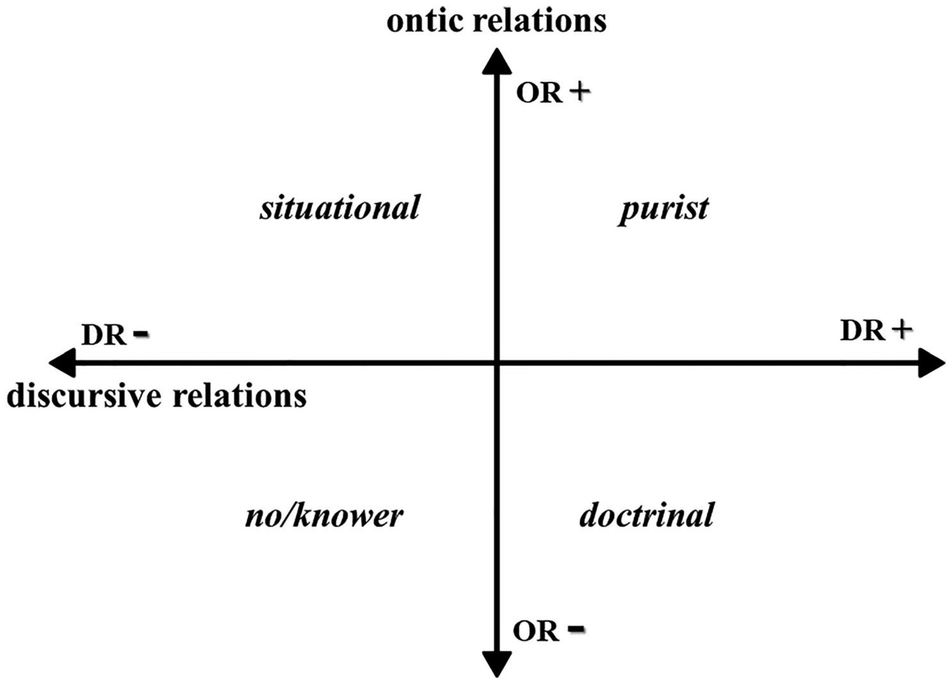

Figure 1. The epistemic plane (Maton 2014).

but which may lead to misconceptions. Using the *epistemic plane*, one could indicate which phenomena and approaches are stronger than others within a particular field.

Doctrinal insight: Here we find practices governed by methodological dogmatism, such as the way in which students are taught to apply Mathematics. Mathematical models and methods are followed rigorously, implying stronger *discursive relations* irrespective of the phenomenon (weak *ontic relations*). One sees practices based on *doctrinal insight* wherever the method is more important than the phenomenon in question, such as 'The Scientific Method'. There is a link here to 'strong' horizontal knowledge structures: When addressing a particular phenomenon with any of the different 'languages' of a particular knowledge type (say, for example, different Economics paradigms), the focus is first and foremost the rules of that particular language – its own strong *discursive relations*.

Situational insight: 'Knowledge practices are … specialised by their problem-situations' (Maton 2014, 176), which means a greater degree of methodological freedom. In other words, there are more ways to accomplish the same thing. Any number of programming languages or technologies, for example, can be used to fulfil the same objective. Businesses which specialise in custom-made machines display a *situational insight*. The focus of the potential solution is strongly bound (strong *ontic relations*) by a particular customer need (*what*), but the means to accomplish this (*how*) may vary. This quadrant is interesting from a knowledge structures perspective: It offers a space for considering different approaches to contested phenomena in hierarchical knowledge structures; it also represents the basis of practices in strong or weak horizontal knowledge structures (such as Economics and Art, respectively) where there is consensus as to the phenomena in question, but the range of approaches is variable (for example, Social Welfare grant distribution methods or an artistic tribute to a national hero).

Knower/no insight: The weakest point of the *epistemic relations*, practices here are either characterised by an 'anything goes' philosophy or the practice is legitimated through the 'attributes of the subject' (Maton 2014, 176) – a *knower* code. The *knower insight* is dominant when an action is based on the nature of stakeholders and not a particular phenomenon or method. I suggest that the *no insight* characterisation may represent weak horizontal knowledge structures where the phenomenon in question is contested or ambiguous, and the *discursive relations* draw on multiple, competing or proliferating 'languages'.

Where the *epistemic plane* offers more than Bernstein's knowledge structures is in the fact that *any* knowledge practice – irrespective of its disciplinary organising principles – may demonstrate *any* of the *insight* orientations. Thus, one may see teachers starting their Biology classes in the *knower* quadrant, for example, by drawing on their pupils' experiences of gender differences prior to crossing the *insight* boundary into a *purist* explanation of human reproduction from a cellular perspective. Similarly, in constructivist pedagogy, 1st year engineering students are routinely given everyday items – such as spaghetti – with which to build a bridge or tower. Each group of students will invariably approach the problem from a *situational insight* perspective, as opposed to the *purist insight* required when deducing the structural concept of 'force' or *doctrinal insight* when completing practice sheets for force calculations. In this example, each of these *insights* has its place in the learning process, but the core disciplinary concept of 'force' – as part of the hierarchical knowledge structure of Physics – requires a *purist insight* for effective conceptual grasp.

In this paper, the *epistemic plane* is used to analyse Mechatronics engineering practice which entails Physics, Mathematics, Logic and other contextual knowledge. Each knowledge structure type and each *insight* represents a kind of 'code' or way of thinking which is significantly different. In a multidisciplinary region, the practitioner is required to shift his/her way of thinking at different times and to cross boundaries between different forms of knowledge in order to effectively solve problems. The *epistemic plane* helps us to map this shifting and to see what people are actually doing with the knowledge we teach in practice. As educators, we may have strong conceptions of how our own discipline works, but in a professional 'regional' qualification we need to see our own discipline in relation to other disciplines in order to have a better understanding of what happens in real world contexts.

Methodology

Fifty mechatronics technicians/technologists employed in the SA Western Cape province volunteered over the period of 2012–2014 to participate in the research project. 27 completed a first phase questionnaire to determine contextual information and a brief technical description of any recent problem-solving process. The responses gave rise to the classification of three types of Knowledge-Practice Environment (KPE) contexts based on scale and the nature of particular sectors:

- KPE A: Contained Systems – Small businesses with a focus on the design (R&D), manufacturing, distribution and maintenance of tailor-made standalone devices (such as medical equipment).

- KPE B: Modular Systems – Small to medium businesses where large manufacturing machines comprised of several 'modules' are designed, built and installed; or businesses who integrate existing modules via a computer system and program actual production processes.
- KPE C: Distributed Systems – Medium to large manufacturing industries where the focus is managing the efficient (semi-) automated production of goods, such as raw materials, beverages or food.

18 case studies were selected across the three KPE categories for phase two of the study, where participants were interviewed at the actual site of practice in relation to the problem artefacts (machines or devices). This protocol has been termed a 're-enactment interview', and these were video/audio recorded. Each case study took into account four components* of the problem-solving situation: the nature of the problem-solver (*1) in a particular environment (*2) who undertakes a problem-solving process (*3) in relation to a particular artefact, at the heart of which is the actual problem structure (*4) characterised by a relationship between Mathematics, Physics and Logic. A range of mixed methods was utilised to enable the most rigorous possible research process, but, for the purpose of this paper, the LCT *epistemic plane* is the key analytical tool applied to each of the aforementioned KPE components. The following section demonstrates this application and summarises key findings.

Applying the language of description

To recap, LCT *epistemic relations* demonstrates the relationship between the *what* and *how* of a knowledge practice, which provides a framework for four distinct *insight* orientations. All the research participants are working within the same, relatively narrow confines of applying Mathematics, Physics and Logic-based thinking (whether explicitly or tacitly) to a mechatronics engineering problem. From a Bernsteinian knowledge structure perspective, the educator might assume that these disciplinary forms are at home (as has been suggested) in particular *insight* quadrants, and that solving the problem means crossing neat disciplinary boundaries. The purpose of the following analysis, however, is to demonstrate that different contexts and stakeholders have an impact on the problem-solving process, as well as how practitioners employ disciplinary forms of thinking. There are complexities in problem-solving contexts that educators seldom take into account, but which can usefully be illuminated through the use of the *epistemic plane* as a 'translation device' (Maton, Hood, and Shay 2015).

Problem environment

The research found that different industrial sites focus on different aspects of automation (and the underpinning knowledge) in different ways. The environments themselves sometimes explicitly indicate a certain 'way', which can be read as what the company values and how it operates. In each case study, an analysis of the websites, premises, and interview texts revealed a dominant *insight* orientation.

Generally, the custom-made industries focussing on tailored, technically-sound solutions (KPE B) demonstrate a *situational insight* orientation – foregrounding customer needs and economic viability, as opposed to the more *purist* approach of R&D-based companies (KPE A). In the latter, the typically small project teams focus on the science and technologies in ways similar to student design project work. There is time in such environments for analytical thinking and experimentation, but only the highest academic achievers tend to gain access to R&D work in SA. Most graduates are more likely to work in medium to large-scale manufacturing environments (KPE C) where a distinct *doctrinal insight* orientation is evident. Here the allegiance is to certain established business process methodologies (irrespective of their product), as suggested by the home page of one manufacturing company website:

> *"XYZ is … dedicated to lean manufacturing and Total Quality Management. Continuous improvement has been intrinsic to the company's philosophy since … "*

In contrast, a number of KPE C websites and industry premises reveal a recent shift to an espoused '*knower insight*' orientation, showcasing their personnel, and using 1st and 2nd person discursive references, such as:

> *"We believe that people who have time to create, think, and discover … build great companies!".*

This shift emerged in environments which are struggling to run efficiently, and where employee morale is visibly low. I suggest that this shift may be an attempt to pay lip-service to a 'people, planet and profits' (Slaper and Hall 2011) philosophy, but is unsuccessful when business processes are dominated by *doctrinal* procedures and human beings are expected to behave in *doctrinal* ways. Such environments seldom afford practitioners the luxury of engaging in analytical, time-consuming root-cause-analysis processes driven by the science itself (*purist*) since the 'time is money' ethic dictates cost-effective, regulated production (*doctrinal*). This, in turn, manifests as compliance-orientated, procedures-driven practices in hierarchical organisational structures. These environmental differences have implications for problem solving which are seldom considered in education.

Problem-solver

A full problem-solver profile was constructed based on cognitive, experiential and mood factors in order to establish any factors that might impact on the problem-solving process. One aspect of the problem-solver analysis was to determine their natural *insight* orientation. While this was evident from the re-enactment interviews, it was also clear from their questionnaire submissions. The following are extracts of how different participants described the most recent technical problem encountered:.

Situational practitioner:

> *… Once I was happy with the layout, I checked the circuit layout multiple times … Then slowly populated the strip board with components … Just then I smelt that tell-tale electronic burning smell. Straight away, I unplugged the USB … (B3).*

Purist practitioner:

> *Solving this problem requires some background information: XX has a clever addressing system which allows all entities on the system … to be identified by using the node ID of*

each device. It works by adding the node ID to a known constant so when connected to the bus, one does not attempt to communicate with a device but rather with the communication object directly (B4).

Doctrinal practitioner:

1.Define: Loss of production due to high failure rate on product height measurement.
2.Measure: Data collection, conducted a gage study.
3.Analyze: Design of experiments (DOE); Replace 1 LVDT probes & redo study;
Change cable to shielded for less interference & redo study; Hard wire probe directly to Analogue card, bypassing the connector island & redo study on one probe … (C1).

'Knower'-orientated practitioner:

We are trying to implement a standard operating procedure (SOP). But … [*this*] *requires a lot of time and adapting for individuals. Due to the work load some instructions have to be skipped … there are unrealistic deadlines from project managers and clients (A5).*

These dominant *insight* orientations either reflect the impact of the environment (such as the *doctrinal* example from KPE C) or they may be an indication of how a particular practitioner goes about working irrespective of the environment (such as the narrative, chronological explanation in the *situational* example). Highly *purist* or *doctrinal* environments tend to value depersonalised, methodologically rigorous work. In the examples provided, we see 3rd person, passive references from B4 and C1. These practitioners are more comfortable with stronger *discursive relations*, in other words on the right-hand side of the plane. The findings demonstrated that *situational* or *knower* orientated practitioners (left-hand quadrants) experienced a 'code-clash' (Maton 2014) in *doctrinal* environments. Similarly, *purist* and *doctrinal* practitioners struggled when there were multiple ways to approach a problem (weaker *discursive relations*). This is not to suggest that certain types of practitioners can only function in certain environments. Rather, it opens a discussion for educators on ways to better prepare students with differing *insight* orientations for the range of possible contexts. Local industry feedback suggests engineering education seldom adequately prepares students for the *doctrinal* realities of KPE C, or for the multiple possible approaches (*situational insight*) to concepts traditionally taught in *purist* fashion.

Problem-solving process

The *epistemic plane* analysis of the problem-solving process focussed on three stages:

- 'how' the practitioners approach the problem itself (from what *insight* basis)
- 'how' they determine the cause (analysis)
- 'how' they implement a solution (synthesis)

The interview transcriptions were captured in sets of discrete statements on a spreadsheet, and references to disciplinary knowledge as well as processes and actions were analysed using the rubric in Figure 2.

The broad problem-solving process was mapped onto the *epistemic plane* to capture the problem-solving trajectory across different *insights* – in other words, the 'basis' of their thinking and action at each of the three stages. Explicit or implicit references to

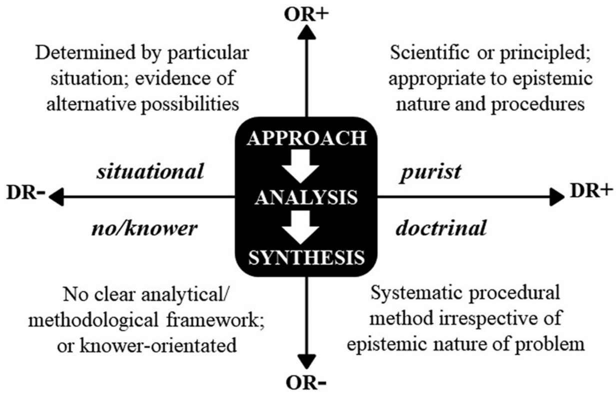

Figure 2. External language of description for *insights* analysis.

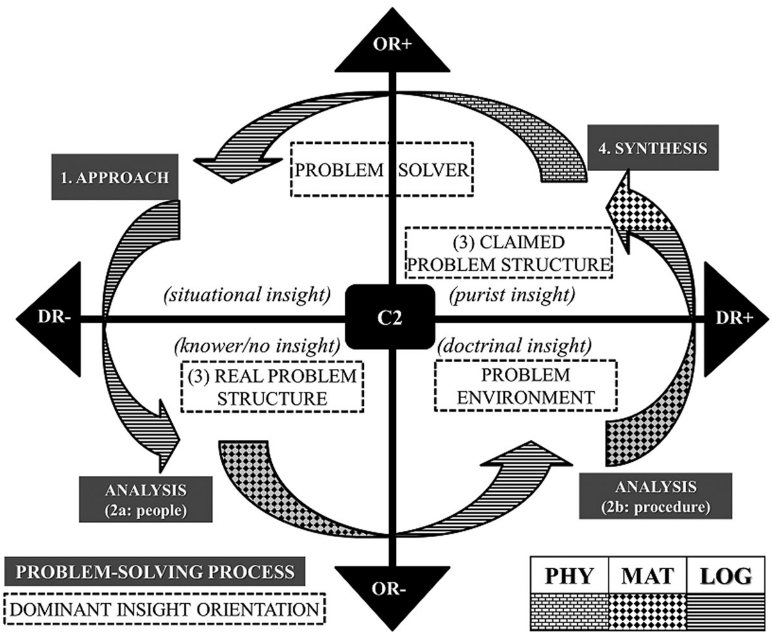

Figure 3. C2 Case study analysis.

Mathematics, Physics and Logic-based knowledge were colour-coded on the original problem-solving maps so as to enable a visual depiction of both the knowledge as well as the dominant *insight* at each stage. The *epistemic plane* maps served to illustrate both disciplinary boundary crossing as well as *insight* shifting in different real world problem-solving contexts. This is best illustrated through a discussion of the sample case study depicted in Figure 3.

Case study analysis

A case study from KPE C (Distributed Systems) presents a very interesting problem. At the time of the interview, participant C2[2] worked in the maintenance department of a large manufacturing company and was responsible for various optimisation processes identified by technicians or engineers in the plant. The problem he describes concerned a certain component the company manufactures for an external client and which is continuously being rejected by the client's scanning equipment. The client's scanner reads a barcode to verify that this particular component 'belongs to' a sub-assembly they are producing. The client realises that the barcode label itself is the problem as their scanner cannot differentiate between the black and white barcode lines and the label text.

C2 describes the cause of the problem as follows:

> *The label printer runs out of stickers and the operator does not follow the correct procedure for replacing the roll.* [*The*] *printer is then misaligned and maintenance technician then compensate* [*for the*] *error by editing label on the PC. (sic).*

What happens is that because the printer is not calibrated properly, when the new label roll is inserted, the stickers (labels) start coming out with 'chopped off' bits of label data. So the maintenance technicians 'edit' the label content on the computer, bringing the label information too close to the barcode. When the client's scanner tries to 'read' the barcode, it gives an error reading because it cannot distinguish between the black text and the black lines of the barcode.

C2's approach to the problem-solving process begins in the *situational insight* quadrant, detailing the problem in this situation as entailing a number of variables that could mean a number of solutions: the printer calibration, the operator behaviour, the technician intervention. He has already determined the cause, so the analysis stage (2a and 2b) is retrospective. C2 proceeds into the *knower* quadrant to describe operator behaviour:

> *It is their job to call a maintenance operator and tell them to calibrate the printer first – I don't know if they weren't sure about the calibration, but they actually got the maintenance technician to change the label itself.*

He proceeds with a *doctrinal* description of the result of this action:

> *This then brings other elements of the label closer to the bar code and the vision sensor at the client sees the element as part of the bar code and gives an error …*

C2's instruction (from management) is to integrate a (costly) vision sensor sub-system into the manufacturing system to ensure that the barcode meets specifications: a camera system which has been programmed to measure the spaces around the barcode label and between the barcode and text on the label. This solution synthesis phase is detailed in *purist* fashion, with the technical specifications of the camera system and the particular challenges of the controller programme. C2 is confident when he shifts into the comfortable language of Logic (supported by the principles of Physics):

> *The original PLC program was never received from the machine builders, so the only way to edit the program was to upload it from the PLC and use the HMI program to cross reference … the different variable blocks.* […] *The software on the camera … sends a normal signal like any other sensor. In the program software – ladder logic – you tell it if the distance is correct – you can choose either 24V or 0V for true or false.*

An analysis of the problem structure depends on the problem definition. If the problem is (as originally stated) operator behaviour, then it could be described in terms of human

'Logic' in a particular context with respect to the relationship between the different component production and labelling stages, and the implications of incorrect product delivery for the business as a whole. This would suggest predominantly weak horizontal forms of knowledge, with weak *discursive relations*. Secondly, the label issue is underpinned by Mathematics: the precise geometric and relational arrangement of black text and lines within a defined space. These two features (human 'Logic' and Mathematics) would see the practitioner working with knowledge in the bottom two *insight* quadrants, moving between weak and strong horizontal knowledge structures.

However, C2 describes the problem solution in terms of the Physics underpinning light sensors to detect the black and white edges on the label, the Mathematics of label element proportions, and the Logic of the control system into which the camera system is being integrated. This view of the problem structure suggests a movement between hierarchical Physics knowledge from a *purist insight* perspective to strong horizontal knowledge (Mathematics) to weak horizontal knowledge (Logic). These three knowledge structures each have at least one strong set of relations: the allegiance to the phenomenon *(ontic relations)* or the method *(discursive relations)*. In other words, this solution sees *insight* activity higher up on the *epistemic plane*.

C2's profile analysis reveals he is more comfortable working from a '*situational/purist*' *insight* orientation. In other words, he needs to work in the strong *ontic relations* space with clearly established phenomena. His questionnaire text and interview demonstrate no indication of the dominant *doctrinal* methodology preferred at this company. He is a high academic achiever and equally comfortable in both Mathematics and Logic (strong and weak horizontal knowledge structures). As a researcher, this case study marked a turning point for me. I could not understand why this previously confident student was so uncomfortable during his re-enactment interview. It was the analysis of his problem-solving process *in context* that revealed what I believe to be a distinct diametrical code-clash, and which led to his subsequent resignation from the company.[3]

C2's description of the solution synthesis is *not* a solution to the original stated problem: operators not aligning the printer roll correctly and maintenance technicians 'editing' the label. During the interview, when asked if they had considered operator training, he answered, uncomfortably:

> *We could have put more effort into the operators understanding … but, if it doesn't directly influence them, it's as if they don't care …*

I would like to suggest that the solution in this case study (the integration of a policing camera system) represents a deliberate attempt to artificially strengthen both the *ontic relations* and *discursive relations* in a climate of ever-increasing sociotechnical complexity. The *doctrinal* orientation of such manufacturing environments requires that practitioners apply strong *discursive relations* (fixed methods). If these are to be weakened, then there need to be strong *ontic relations* (consensus as to the phenomenon in question). But there is no apparent consensus in this case as to the phenomenon in question: is the problem 'operator behaviour' or is it 'technical improvement'? When there is a concomitant loss of clarity as to *what* is being addressed, as well as *how* to do so, the associated knowledge practices shift to the lower left quadrant and manifest either as '*no insight*' or require a different set of principles and procedures if the practices are dictated by a '*knower insight*'. Such *doctrinal* manufacturing environments do not appear to have measures in place to deal with weak *ontic* and *discursive relations*. I suggest that C2 recognised this lack of allegiance to a clearly defined phenomenon and experienced the situation as a code clash. This dilemma emerged in several case studies.

Insights for educators

This paper has demonstrated the development and application of a language of description to better understand the problem-solving process entailed in engineering practice. Although focussing on one particular case study, it is important to highlight that no two problem-solving maps across the 18 case studies were the same. However, a number of patterns emerged which suggest the following may be useful recommendations for educators:

- Encouraging disciplinary code shifting
- Rethinking computational Mathematics teaching
- Theoretically-informed engagement with professional contexts

As a general rule, participant references to Physics are almost always located in the *purist insight* quadrant, accompanied by appropriate epistemic language that closely approximates the language in the curriculum. Explicit Physics references are also more common in the smaller R&D KPE A category, in which, however, a minority of graduates is employed. Logic references tend, as expected, to occur in all KPEs in the *situational* and *doctrinal* quadrants. KPE B, in particular, sees successful problem-solving patterns as an iterative movement between the *situational* and *doctrinal insight* quadrants. This requires diametrical code-shifting expertise: the ability to keep a particular phenomenon in sight, consider multiple approaches, and then apply the rules of a particular approach. This marks the first recommendation for educators: consider the multiple 'languages' of a particular 'engineering science' and encourage students to shift between these 'languages' and associated protocols without losing sight of the phenomenon in question.

The second recommendation concerns the predominant computational (*doctrinal*) teaching of Mathematics, the single largest contributor to engineering programme attrition (Bernold, Spurlin, and Anson 2007). Mathematics references occurred in all *insight* quadrants. This means participants refer to mathematical properties of the problem situation in multiple ways, from inaccurate production line speeds (*doctrinal*) to dimension modifications for a particular short-term problem (*situational*) and algorithmic programming of a microcontroller (*purist*). Rather than focussing on endless computational examples, educators could consider enabling students to 'think mathematically' by considering the different phenomena to which a single mathematical approach can be applied, and similarly, considering different mathematical approaches to a single phenomenon.

A final recommendation concerns the significantly different external contexts in which professional graduates work. Educators across professions would be well served to develop a better understanding of knowledge practices in real world sites. These are accessible through engagement with graduates, industry professionals, or examination of company websites. The *epistemic plane* and the language of description applied in this paper are applicable to any curriculum characterised by 'principles' and 'procedures'. The analytical instrument offers a means to reveal *insight* orientations not accounted for in the curriculum. The dilemma in dynamic regions is that the 'how' is becoming increasingly unfamiliar, both with regard to new technologies and complex human interactions. Our curricula may not sufficiently introduce the range of weaker discursive practices – in the context of both *knowledge* and *knowers* – required in real world problem situations. This may well be an opportunity for educators to rethink the assumption that disciplinary *concepts* and practice *contexts* are separable.

Notes

1. The study of (deductive) 'inferences that depend on concepts that are expressed by the 'logical constants' such as and, not, or, if … then' (Wolff and Luckett 2013).
2. Participants are identified alphanumerically by KPE category and interviewee number.
3. It is important to mention that other participants at this research site, with different *insight* orientations were better suited and very successful here.

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References

Allais, Stephanie. 2010. *The Implementation and Impact of National Qualification Frameworks: Report of a Study in 16 Countries*. Geneva: International Labour Office.

Bernold, Leonhard, Joni Spurlin, and Chris Anson. 2007. "Understanding Our Students: A Longitudinal Study of Success and Failure in Engineering with Implications for Increased Retention." *Journal of Engineering Education* 96 (3): 263–274.

Bernstein, B. 2000. *Pedagogy, Symbolic Control and Identity: Theory, Research, Critique*. Rev. edn. London: Rowman & Littlefield.

Carvahlo, Lucila, Andy Dong, and Karl Maton. 2009. "Legitimating Design: A Sociology of Knowledge Account of the Field." *Design Studies* 30 (5): 483–502.

Case, Jenni. 2011. "Knowledge Matters: Interrogating the Curriculum Debate in Engineering Using the Sociology of Knowledge." *Journal of Education* 51 (2): 1–20.

CHE. 2015. *Vital Stats Public Higher Education 2013*. Pretoria: Council on Higher Education.

Du Toit, Renette, and Joan Roodte. 2008. *Engineering Professionals: Crucial Key to Development and Growth in South Africa*. Pretoria: HSRC.

ECSA. 2012. *5 New Engineering Technology Qualification Standards*. Johannesburg: Engineering Council of South Africa.

Felder, Richard. 2012. "Engineering Education: A Tale of Two Paradigms." In *Shaking the Foundations of Geo-engineering Education*, edited by B. McCabe, M. Pantazidou and D. Phillips, 9–14. Leiden: CRC Press.

Fisher, Glen. 2011. *Improving Throughput in the Engineering Bachelors Degree*. Johannesburg: Engineering Council of South Africa.

Griesel, Hanlie, and Ben Parker. 2009. *Graduate Attributes: A Baseline Study on South African Graduates from the Perspective on Employers*. Pretoria: HESA & SAQA.

Kraak, Andre. 2000. *Changing Modes: New Knowledge Production and its Implications for Higher Education in South Africa*. Edited by Andre Kraak. Pretoria: HSRC.

Maton, Karl. 2014. *Knowledge and Knowers: Towards a Realist Sociology of Education*. London: Routledge.
Maton, Karl, Sue Hood, and Suellen Shay. 2015. *Knowledge-building: Educational Studies in Legitimation Code Theory*. London: Routledge.
Muller, Johan. 2009. "Forms of Knowledge and Curriculum Coherence." *Journal of Education and Work* 22 (3): 205–226.
Shay, Suellen. 2008. "Beyond Social Constructivist Perspectives on Assessment: The Centring of Knowledge." *Teaching in Higher Education* 13 (5): 595–605.
Shay, Suellen, and Diane Steyn. 2014. "Enabling Knowledge Progression in Vocational Curricula: Design As a Case Study." In *Knowledge-building*, edited by K. Maton, S. Hood, and S. Shay, 138–157. London: Routledge.
Slaper, Timothy, and Tanya Hall. 2011. "The Triple Bottom Line: What is it and How Does it Work?" *Indiana Business Review*. Spring.
Wolff, Karin, and Francois Hoffman. 2014. "Knowledge and Knowers in Engineering Assessment." *Cristal* 2 (1): 74–95.
Wolff, Karin, and Kathy Luckett. 2013. "Integrating Multidisciplinary Engineering Knowledge." *Teaching in Higher Education* 18 (1): 78–92.
Young, Michael, and Johan Muller. 2007. "Truth and Truthfulness in the Sociology of Education." *Theory and Research in Education* (SAGE Publications) 5 (2): 173–201.