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Engineering problem-solving knowledge: the impact of context

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ABSTRACT
Employer complaints of engineering graduate inability to 'apply knowledge' suggests a need to interrogate the complex theory-practice relationship in twenty-first century real world contexts. Focussing specifically on the application of mathematics, physics and logic-based disciplinary knowledge, the research examines engineering problem-solving processes as enacted by recent graduates in a range of industrial settings. Theoretically situated in the sociology of education, the Bernsteinian concept of knowledge structures and Legitimation Code Theory *epistemic relations* are utilised to surface the disciplinary basis of problem solving in different sociotechnical contexts. It is argued that the relationship between the 'what' and the 'how' of the problem gives rise to significantly different practice 'codes' between which successful engineering problem-solvers are required to shift. This paper presents two contrasting case studies which demonstrate the impact of the environment on code-shifting practices. Findings suggest that engineering curricula need to facilitate a more conceptual grasp of contextual complexities.

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Engineering problem solving; disciplinary codes; Legitimation Code Theory; sociology of education

Introduction

Engineers are problem solvers. And the world in which they are expected to solve problems has become increasingly complex. Globalisation, social justice ideals, economic competitiveness, sustainability and technological advancement are just a few of the factors which shape an engineer's practices in the twenty-first century. Engineering education is under pressure to deliver work-ready graduates (Case 2011), which means the traditional, academy-based engineering curriculum – rooted in the disciplinary bases of mathematical, natural and engineering sciences – has seen the addition of elements such as ethics, team work, impact awareness and a range of 'professional competencies' (www.ieagreements.org). The twenty-first century engineering curriculum has developed considerable breadth, while attempting to retain its disciplinary depth. The curriculum shifts significantly 'from one kind of know-that and know-how of the basic sciences to another of the applied sciences to yet another of the design disciplines' (Shay, Wolff, and Clarence-Fincham 2016, 78). The diploma[1] curriculum has the addition of a greater focus on technical application. In order to facilitate the bridging of theory to practice along the expanding conceptual-contextual continuum (Muller 2009), engineering education has also seen a shift towards a range of work-related pedagogies. Work-integrated learning (WIL) modalities are essentially designed to integrate 'classroom theory with industrial practice' (Mutereko and Wedekind 2015, 5).

Despite the stretching of the curricular continuum and the explicit introduction of work-related problems, not only do engineering retention and graduation rates in South Africa (the research site) remain problematic (Fisher 2011), but there are widespread employer complaints of engineering graduate

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abilities. A key complaint is the inability to 'apply knowledge' (Griesel and Parker 2009). In other words, engineering graduates are not bridging the theory-practice divide effectively enough to be able to engage in the kind of problem-solving activity required by the profession.

The contention in the research on which this paper is based is that we do not have an adequate understanding of the theory-practice relationship in engineering problem solving relevant to the twenty-first century. As regards 'theory', the UNESCO (2010) report on engineering appears to argue that the engineering curriculum needs to rid itself of its traditional disciplinary shackles and allow students to focus on 'problem solving'. This, I argue, is to perpetuate a view of knowledge-based practices as constructivist processes of 'knowing' (Maton 2014). Such 'knowledge-blindness' ignores the fact that 'though made by us, knowledge has properties and tendencies of which we may be unaware' (Maton 2014, 13). On the 'practice' side of the equation, there are several challenges with the vocationally-orientated training initiatives encouraged through WIL approaches. Problem- and project-based learning within the curriculum can only remain idealised, decontextualized learning opportunities. Invaluable though these may be, they do not approximate the 'messiness' of real world problems, where 'context plays an important role … and can only be taught by experience' (Brezillon 1999, 25). Secondly, the work-based WPL experiences for diploma students are not homogenous, are poorly resourced from an educational perspective and are not available to all students (Mutereko and Wedekind 2015). Given the rapid technological developments and increasing complexity in engineering workplaces, training that is either decontextualized or locked into a particular context denies students the opportunity to develop relational, causal and more conceptually holistic ways of thinking (Wheelahan 2007). The impetus for the research reported in this paper was a desire to better understand the relationship between engineering theory and practice in real world contexts under everyday industrial conditions.

The translation of science-based 'theory' into real world practice and vice versa is complex. Problem-solving studies to date have tended to produce descriptive typologies of types of problems, activities and environments or generic methodologies. These approaches ignore the nature of disciplinary knowledge and the potential implications for practice. This paper presents an approach to the study of problem solving which foregrounds disciplinary knowledge. Focussing specifically on the application of mathematics, physics and logic-based knowledge in the multidisciplinary field of mechatronics engineering, the research entailed the analysis of engineering problem-solving processes as described and re-enacted by recent diploma graduates in a range of industrial settings in South Africa, from small prototype developers to large manufacturers. Using a novel, theoretically-informed problem-solving framework, the practitioner's sequential process was graphically mapped so as to illuminate how he/she navigated between different forms of disciplinary knowledge in different contexts. The analysis draws on the Bernsteinian (2000) concept of knowledge structures and the analytical instrument is that of the Legitimation Code Theory (LCT) concept of Specialisation, specifically *epistemic relations* (Maton 2014). It is suggested that understanding the 'ways of thinking' underpinning the different engineering disciplinary structures contributes significantly to dealing with different kinds of real world complexity.

The research demonstrates that there are different moments in the problem-solving process when, for example, analytical depth is required, or sequential, procedural rigour. Some of the contextual variables are dictated by commonly accepted principles or procedures, both of which may differ in different types of engineering environments. This paper demonstrates two significantly different kinds of environments in which comparable discipline-based engineering problems were solved in very different ways as a result of the environment. These examples intend to highlight what may be missing in engineering curricula, and it is suggested that there are techniques through which we can explicitly teach our undergraduates how to become more effective engineering problem solvers.

Theoretical framework

Theoretically, the research is situated in the sociology of education, drawing on the work of Basil Bernstein (1975, 2000) and Karl Maton (2014). Bernstein provided an initial conceptualisation of forms of knowledge which could be described in terms of how concepts are related to each other as they emerge in the field of production. Concepts with strongly sequenced and subsumptive elements, such as those in the natural sciences, are described as a hierarchical knowledge structure (Bernstein 2000). These forms of knowledge (specifically physics in the case of engineering) are acquired over long periods of time through the systematic building of lower- to higher-order concepts. In contrast, there are disciplinary fields in which a range of 'languages' has emerged, each with its own strong internal relations and conceptual rules. These 'strong' horizontal knowledge structures are disciplines such as mathematics or economics (ibid.). Each mathematical language, for example, has features which clearly identify that specific language, and which are, therefore, acquired independently. Unlike physics, these concepts do not build cumulatively. A third type of knowledge structure represents those fields in which disciplines develop by way of proliferation and redundancy, developing multiple 'languages' and borrowing concepts across families of the same disciplinary type, such as art or sociology. This 'weak' horizontal knowledge structure also describes the disciplinary basis of Information Communication Technologies, in this research given the disciplinary term of 'logic'. The fact that these have 'weak' internal and external conceptual and discursive rules simply means that there are far more rules (as there are far more 'languages') which are context-dependent, and which require the acquisition of 'masses of particulars' (Muller 2009, 212). The 'organising principles' (Maton 2014) of the different knowledge structure types imply different ways of thinking and learning. Together, these three types represent the knowledge forms underpinning the core disciplines in science and technology-based professions, such as engineering or medicine.

Bernstein's early characterisations are a useful starting point to address complex multidisciplinary problem solving. The twenty-first century has seen the rapid emergence of what Bernstein terms 'regions' – combinations of disciplinary types, particularly in the professions. The dilemma with regions is that one may lose sight of the disciplinary foundations to such an extent that they are no longer evident. The contention in this research is that not only is the kind of thinking implied in the different core disciplines essential for complex practice, but there also needs to be a means to 'see' the different knowledge types in relation to each other.

The past decade in the sociology of education has given researchers increasingly refined sets of tools through which to consider the question of knowledge and its associated practices. LCT – which extends Bernstein's original knowledge conceptualisation – moves beyond dichotomous types and offers a range of practical, conceptual devices through which to analyse knowledge practices. One such device is the LCT Specialisation *epistemic relations* concept which 'highlights that practices may be specialised by both *what* they relate to and *how* they so relate' (Maton 2014, 175). This relationship is captured on a Cartesian plane.

The vertical axis on the *epistemic plane* (Figure 1) is about the phenomenon in question – how strongly it is bounded by recognisable and 'legitimate' principles. These are called *ontic relations*. The horizontal axis is about ways of approaching the phenomenon. The stronger the rules, the stronger the so-called *discursive relations*. The epistemic plane gives us four *insights* ('codes') – or ways of thinking. The *purist insight* demonstrates knowledge practices or claims based on recognised, strongly bounded principles *and* associated procedures, such as the concept of Ohm's Law: No matter your culture or language or location, the relationship between voltage, current and resistance is commonly understood and captured in a specific formulaic expression. Physics knowledge (Bernstein's hierarchical knowledge structure) as traditionally taught in the curriculum is at home in this *purist* quadrant. The bottom right *insight (doctrinal)* describes a knowledge practice based on recognised methodologies, where it does not matter what the phenomenon is – the methods are fixed. This is like following a formula for the structure of an experiment, or applying a particular business methodology, or the way mathematics works – in this case an example of Bernstein's 'strong' horizontal knowledge structure. The top left quadrant is called *situational insight*. Here, there are many possibilities for addressing the same phenomenon. What is desired is fixed, but how it is done is variable. The discipline of 'logic' as evident in ICTs (and characterised as an example of Bernstein's 'weak' horizontal knowledge structures) would initially require a *situational* insight. The lower left quadrant is where there is not a strongly bounded phenomenon or any fixed ways to do things. This could either be because the focus is not on *epistemic*

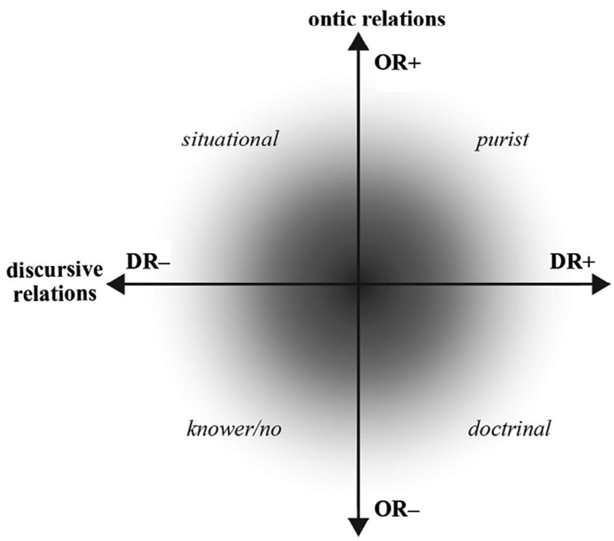

Figure 1. The epistemic plane – insights (Maton 2014, 171).

relations, rather on *social relations* (where other things count) or because there is no legitimate or recognisable phenomenon and associated practices. The epistemic plane thus offers a means to combine Bernstein's concept of knowledge structures (as may be evident in curriculum analysis) with an analysis of actual knowledge-based practices where practitioners may have different approaches to the 'what' and 'how' of a problem in different sociotechnical contexts.

It is worth pointing out that there is a difference between the *focus* and the *basis* of practices (Maton 2014, 31). *Focus* is 'what' is being referred to, while *basis* is from what perspective. A practitioner may talk about the physics concept of 'force', for example, without focussing on the *purist* equation or the physics laws themselves. He/she may simply be talking about different kinds of forces and the possibilities of their interaction. The statements may then be regarded as demonstrating *situational* insight. This is common in school curricula where students may be encouraged to 'discover' the laws through trial-and-error. By the same token, completing practice sheets for the calculation of force equations would see a shift to the *doctrinal* perspective. The focus for this research is from what *basis* do practitioners actually work with the different disciplinary forms? There are distinctly different focal points during a problem-solving process, and these may reveal different bases of practice or *insight* phases:

- 'how' the practitioners approach the overall problem itself
- 'how' they determine the cause (analysis)
- 'how' they implement a solution (synthesis)

Not only do we need to consider the *insight* orientation of the problem solver and his/her problem-solving process, but the problem environment also suggests a particularly dominant 'basis' for practices in general. *Insights*, in other words, demonstrate the *basis* from which a practitioner views a particular situation or activity, or the *basis* of procedures in an organisation. These are forms of 'code' which could be dictated by the practitioner, the problem or the environment.

Summary of the contextual framework and methodology

Mechatronics engineering entails the design, implementation and maintenance of computer-controlled electromechanical systems. Essentially, mechatronics practitioners are responsible for automation processes in industries like mining, manufacturing, and food and beverage processing. This is a field in which the rapid evolution of complex technologies plays a fundamental role, similar to that experienced in the medical field. In South Africa, three internationally-aligned engineering qualification levels are offered by higher education institutions in relation to three professional designations: a 3-year diploma (technician), a follow-up 1-year advanced diploma (technologist), and a 4-year professional bachelor's degree (engineer).

The research study on which this paper is based was conducted among diploma graduates from one of only two institutions in the country that offer a Diploma in Mechatronics Engineering. Researcher access to multiple industrial sites and involvement on a range of engineering education research projects (CHE 2013) had highlighted the failure of higher education in South Africa to both retain students and adequately prepare them for the workplace (CHE 2015).

Industry complaints of graduate inabilities across engineering sectors suggested the need for a better understanding of the relationship between theory and practice in twenty-first century professional engineering contexts, particularly given that these challenges are increasingly emerging on a global scale.

The complexity entailed in solving a problem in an engineering industrial context necessitated the use of several simultaneous methodological approaches. As such, a novel problem-solving model (synthesised from fields such as the cognitive sciences, artificial intelligence and problem-solving literature) provided an organising framework for the methodologically pluralist analysis of 18 research case studies, conducted between 2013 and 2014. The research design mimicked the research focus: a complex integrated system comprised of different sub-systems and components. Four key problem-solving components were considered: the problem environment, the problem solver, the problem structure (disciplinary) and the actual problem-solving process. Each sub-system or component entailed a research strategy drawn from an appropriate field. For example, in considering the 'problem solver', cognitive psychology provided useful categories for the relation to task and environment (Funke and Frensch 1995). Similarly, the difference between the inner and outer environments of a particular artefact (Simon 1996) – the focus of the problem to be solved – provided a key research design distinction. The inner environment is the problem structure itself, comprised of a relationship between different disciplines. Here, Bernstein's knowledge structures provided the theoretical tools for analysis. The 'outer environment' entails context and people. The different practitioners in their different contexts engage in the 'what' and 'how' of the problem-solving process in different ways. The intention was to understand these different problem-solving patterns and their relationship to the disciplinary knowledge of the curriculum. The complexity in engineering practice is similar to that in the health sciences, where a medical practitioner needs to diagnose a physiological condition (underpinned by the medical science disciplines) with respect to a particular patient in a particular context (psychology and sociology) while using a particular set of tools (technology). Medical education, similarly, is facing increasing challenges as a result of the dynamic shifts in technology and social complexity (Gorman et al. 2000). The key challenge in the research design (which is not further elaborated in this paper) was to identify an overarching theoretical and analytical instrument through which to better understand the theory-practice relationship in a science-based, multidisciplinary field. LCT Specialisation provided just the kind of tools that enabled an explicit focus on problem-solving practices while helping to illuminate disciplinary knowledge.

Initially, 50 volunteers working as mechatronics technicians or technologists in three different types of automation environments[2] in the Western Cape, South Africa, were approached to participate on the project. 27 practitioners completed an online questionnaire describing their context, the most recent problem faced, and a technical description of how they solved the problem. Of these submissions, 18 were selected for a semi-structured, re-enactment interview. This meant they were interviewed on site in relation to the actual artefacts, prompted by a reminder (where necessary) of their initial description of the problem-solving process. These interviews were video recorded. The questionnaire and interview texts were transcribed and broken into discrete statement sections. The texts were analysed for types of explicit and implied disciplinary references across the problem-solving process. The references were coded according to the particular *insight* evident in the statement. The epistemic plane was then used to 'map' their approach to and analysis of the problem, and the subsequent synthesis of a solution from the perspective of disciplinary knowledge. In other words, the intention was to 'surface' the disciplinary basis of the problem-solving process *and* the problem solver's shifting *insights*.

Research findings

The analysis of the 18 case studies revealed a number of problem-solving patterns in relation to the different components of the problem-solving system. The following are a few significant findings:

- The scale of the environment (Figure 2) dictated a preferred *insight* (way of thinking). The larger the company, the more *doctrinal* the *insight* orientation.
- Each of the environmental types revealed a different problem-solving process pattern.
- In all cases, there was a multi-layered cause-effect relationship between the disciplines in the actual problem structure in relation to a particular context.

The key finding of the study was that all four *insight* quadrants are relevant in most engineering problem-solving contexts (Wolff 2015), and the successful problem solver recognises and realises the legitimate *basis* of practice at any particular *focus* stage in the problem-solving cycle, where the *basis* is held to be legitimate in relation to the problem and/or the environment. This key finding is significant in that engineering higher education in the South African context sees a predominant focus on theoretical and procedural fundamentals which require a recognisable *purist* or *doctrinal insight* orientation (the right-hand side of the graphic in Figure 2). This is borne out by the fact that the most challenging shift for the case study participants – and indeed cause of delays or failure – was that which entailed multiple possibilities or complex human factors (the left-hand side of the graphic in Figure 2).

The relationship and movement between the different *insights*, however, is not generic, and cannot be formalised as a 'methodology' irrespective of context. Common practice in engineering education is to create an artificial 'project' context (usually design in nature) which is intended to encourage students to work with 'possibilities' and in a team. In other words, the 'design project' is the space in the curriculum where students engage on the left-hand side of the epistemic plane. The purpose of this paper is to demonstrate the impact of a real world context on the problem-solving process and to illuminate how disciplinary forms of thinking may affect the process or be affected by the context. Two

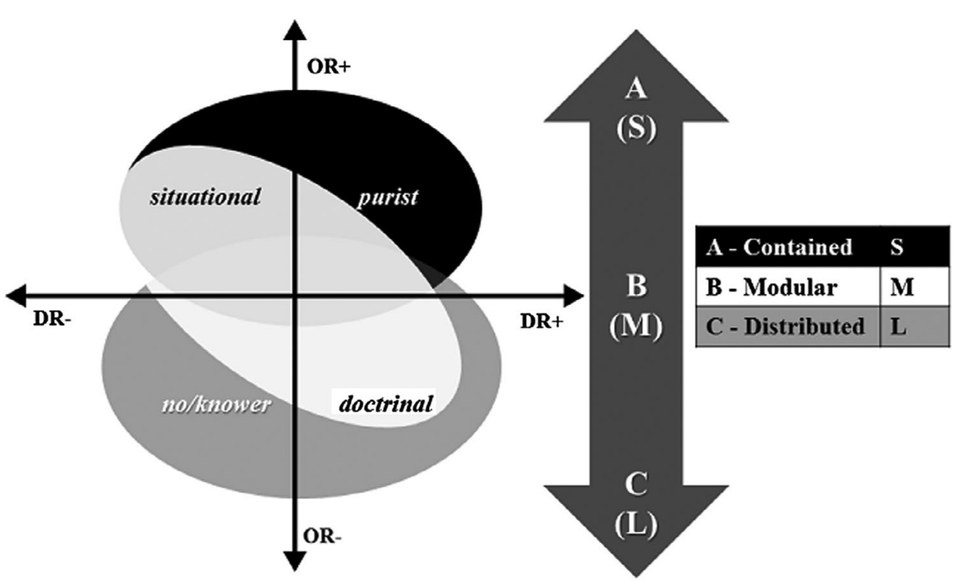

Figure 2. Knowledge-Practice Environment *Insight* scope and type.

case studies have been selected to demonstrate the relationship between context and the engineering problem-solving process.

Two contrasting case studies

Two case studies have been selected, one each from the Contained (A) and Distributed (C) Systems categories. The former sees practitioners working on the research and development or maintenance of stand-alone devices, such as vending machines or microwave ovens. Contained Systems companies are usually micro to very small businesses, where lateral staff relations and cyclical project work are more common. There is greater flexibility in such environments with regard to the use of time and space. The Distributed Systems category describes any manufacturing or factory environment where different machines form part of a holistic system to produce goods. These environments are usually highly regulated, production-target-driven, and involve larger teams in more traditional hierarchical organisational structures. It is common for such businesses to follow a particular business methodology, such as Six Sigma. This is a way of monitoring business processes and allocating staff roles to optimise efficiency.

Case studies A1 and C1 have been selected from these categories for three reasons. Firstly, they represent the norm (52% of all cohorts analysed) in that they have comparable disciplinary academic record patterns, with their highest achievements being in the logic-based disciplines and lowest in mathematics. Secondly, both technicians demonstrated and explicitly referred to preferring 'trial-and-error' learning, and were evaluated by their supervisors as having 'an experimental temperament' (A1) or 'he jumps around' (C1) – thus suggesting both A1 and C1 have a predominant *situational insight* orientation. Thirdly, their selected problems entail exactly the same disciplinary knowledge elements: the question of Voltage (Ohm's Law) in a particular system.

The following two sections will summarise the technicians' approaches, analyses and solutions to their problems in their particular contexts, using the *epistemic plane* to capture the overarching problem-solving process. The specific focus is the way in which they use and discuss disciplinary concepts. Given the technical nature of these concepts, samples of the data analysis are provided in an appendix to assist the reader.

A1 research & development technician

A1 has been tasked with modifying a motorised system used to control security access gates. The problem is that in the case of electricity failure (a common occurrence at the time in South Africa), the motor and the internal control system regulating the gate opening and closing will then draw power from the battery and continue to do so even if the power is restored. The internal control system can actually drain all the battery power and then the motor does not have enough power to operate the gates. Technician A1 needs to 'read' the voltage on the battery and add a component to disconnect the battery if the voltage drops below a specific point. There are several ways to do this, and A1 has experimented with a number of options based on 'a lot of older designs – I have a whole bunch – but if it's something new I do a quick google search.' (A1:107).

Since this is a new, context-specific design, there is not an 'off-the-shelf' solution. A1's approach (and natural orientation) is from a *situational insight* perspective. The problem of enabling the battery to disconnect is predominantly determined by the arrangement of components in relation to each other with respect to the flow of current and the impact of these components on the overall energy relationships in the circuit board. The choice of where to position certain components and in what relationships to the others is determined by what the system needs to 'do' *in this particular situation*, but is also ultimately the practitioner's decision based on the laws of physics and spatial allowances. In other words, there is both a circuit 'logic' as well as a level of contextual decision-making. The circuit 'logic' is mainly dictated by the laws of physics – Ohm's Law specifically.

A1 describes having tried two kinds of components to trigger the battery disconnection. (see Appendix for a sample analysis). In each case, he uses physics and mathematics to analyse why these components fail to solve the problem (Figure 3).

An interesting observation during the analysis stage of his problem-solving description is the iterative movement back and forth between the circuit diagram and the actual physical board, as well as between totally different components and sub-circuits. There is not necessarily a logical or procedurally efficient sequence to his explanation. Although he refers to physics concepts, such as dissipation, current and voltage, he does not do so from a strongly *purist insight* basis, rather a fairly constant *situational insight*. In other words, he uses the current situation (being interviewed with his various resources at hand) as a frame for explaining a number of things, often also changing tack or remembering additional points. He moves into the *purist* quadrant when he identifies the cause of the problem as requiring better 'current surge' regulation and uses Ohm's Law to clarify this. However, his analysis does not move to a *doctrinal* basis when he explains his calculations:

> … and so like here you can see [*refers to scribbled calculations in note book*] I said … maximum … uhhh 0.8A divided by 40 = 20 mA base current … and then I said … uhh, Ohm's Law – what did I work out for this … [*mumbling to self*]- this is the base resistor – uhh 16 – what's the 16? Oh, that's the voltage – at the maximums, the extremes – 16 – and then I went back to … oh yes, you see this is another issue we had … (A1: 121–123)

He confirms that he does not calculate that much, and has at times been 'totally out', but that he did do so for this particular problem. He eventually settled on a particular component, and synthesised a solution to regulate the voltage and disconnect the battery. In other words, he 'synthesised' a solution for this particular problem in this context by implementing one of a number of solutions (*situational insight*), NOT based on strong 'legitimate procedures' for a strongly bounded knowledge claim (the control of voltage). He drew from his own experiential knowledge, in addition to existing circuit diagrams and an Internet source.

What is important in this case is the fact that A1 has the *relative luxury of time* to work at his own pace and in his own way within the small 5-man R&D team. There are no significant or obvious formal company protocols in place in this division, making communication a more informal, verbal daily update. The small team have been hired for their diversity and their particular strengths. It is noteworthy that

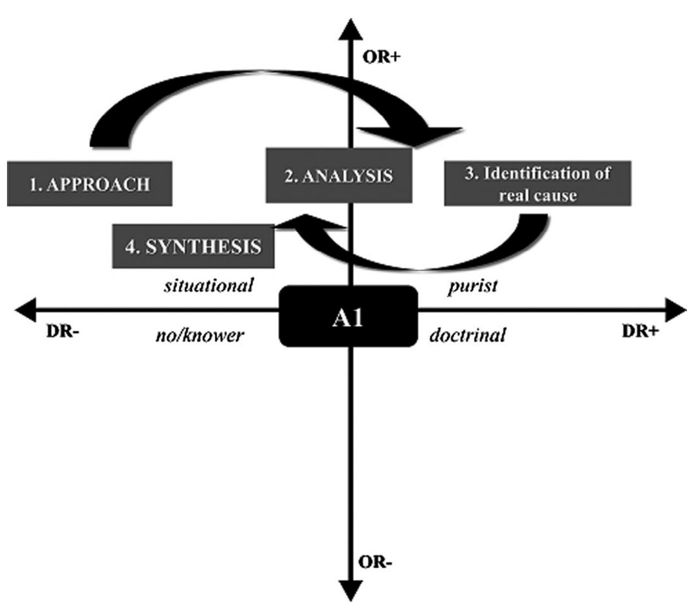

Figure 3. A1 Problem solving map.

each of the team members (also case study participants, but not reported here) demonstrates a different dominant *insight* orientation.

C1 – manufacturing technician

Technician C1 works for an automotive components manufacturer with over 200 employees, and a host of suppliers and clients all over the world. The focus is on efficient production processes, and, as such, there are standardised protocols and procedures which govern all aspects of the business: in other words, the company favours a *doctrinal insight*. This is supported by the numerous protocol posters on the factory walls, as well as visible procedural documentation at each manufacturing station. The problem C1 chose to detail was one of a particular measuring device on a production line. The device (a linear probe) measures the height of components, and when they are not according to specification, the device triggers a signal (voltage) and the component is sent to the reject bin. Hundreds of components were being rejected, and it was clear that the fault lay with the measuring device itself.

> We knew there was voltage interference. We started off by changing one probe, then the cables. Usually you have interference if you run high voltage cables nearby. I changed the cables to shielded, but this probe is a newer form. The first thing is 'part or process': I did a gage 1 study to see if it is repeatable, because then we know it's the process. I checked the power supply to see if it's a steady voltage range output; I checked the earthing; I checked the probes. At the end of the day we realised it's the LEDs (C1: 72-85)

Following the *doctrinal* methodology preferred by the company, C1 describes and demonstrates his procedural root-cause analysis process during which he determined (over a three-day period) that an inappropriate 'connector bank' had been supplied by European manufacturers. All cables from the measuring device 'probes' go to a single connector bank, which in turn is connected to the controller by one cable. The connector bank in question is intended for digital inputs and has built in Light Emitting Diodes (LEDs). These, however, cause voltage interference in the highly sensitive analogue probes, and thus cause the height measuring device to reject components. The interim solution was to bypass the connector bank and wire all the probe cables directly into the controller (which caused various delays and slowed down overall production process).

C1's natural *situational insight* orientation emerged during the re-enactment interview. The written questionnaire response had followed a standard, *doctrinal* problem identification methodology, with a numbered sequence of standardised steps (indicated as sub-headings). However, C1's actual interview did not follow a logical sequence. He moved around between concepts and contextual elements, trying to clarify these for researcher benefit. This *situational insight* orientation reflects the disciplinary basis of 'logic' in mechatronics engineering: the control of a system is a strongly bounded phenomenon (we know that we need to control something for a fixed end result), but how we do it – given the vast range of technologies, control systems and programming languages – is entirely dependent on the situation or practitioner preference. C1's academic record reveals this is his strong suit, and suggests that this is his preferred 'way of thinking'. This way of thinking in this context, however, may be problematic, since the driving ethic in such environments is procedural and production efficiency, with the least cost and waste of time. Given the 5 years' experience C1 has already gathered in this context, however, I believe that the company's *doctrinal* methodology gave this practitioner a reliable framework or *basis* from which to operate, albeit that it was not naturally internalised. His supervisor confirmed this:

> His process is very structured when he understands how the machine operates, but if he's not familiar with the process he jumps around quite a bit. (C1 supervisor)

C1 has two disciplinary boundary-crossing challenges (indicated as no-entry signs on Figure 4). The first is the movement from the standardised approach to all problems in this environment into the *purist* quadrant: here, he attempts a purist explanation, accompanied by sketching (for researcher benefit) how Ohm's Law works in this case (a classic hierarchical knowledge structure, with a recognisable concept chain):

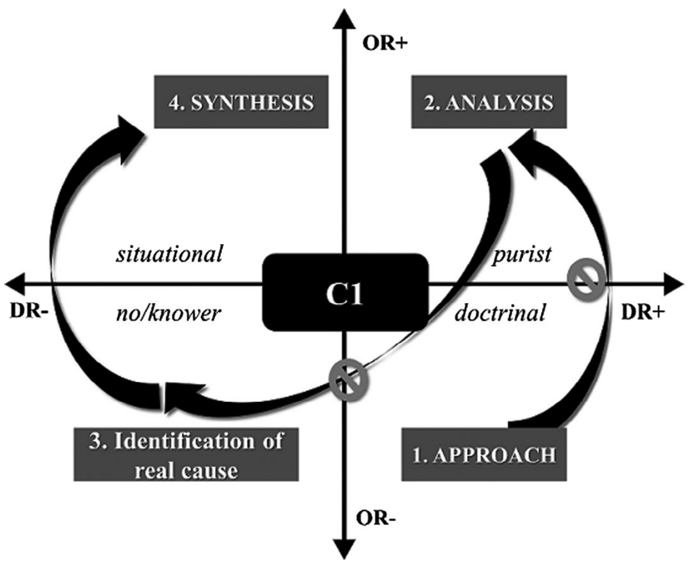

Figure 4. C1 problem-solving map.

> … the system of a linear probe works on resistance. You don't have that resolution where it is exactly 0, but close – you have the LED inline and when you press it in full (the probe), you get 10 V. But the LED has a certain resistance as well – so basically its Ohm's law: there's a conversion in the PLC, it calculates the resistances. (C1: 61-67)

The problem, however, is at a more conceptual level than the physical voltage calculation. If he had followed his natural *situational* inclination and shifted into the left-hand side of the epistemic plane (stood back to observe all the possible causes of the problem), he could have asked himself why the LEDs were getting brighter and dimmer. A subsequent shift into the more analytical, linear thinking implied in physics-based problems (*purist insight*) would have been a clue to the analogue versus digital cause of the problem. However, he followed the company methodology (*doctrinal*) of starting at the point of problem occurrence and systematically worked his way along all components, testing and replacing each. This meant that the problem-solving process took three days. Alternatively, if he had considered the people in the 'problem' (the second boundary-crossing challenge into the *knower* quadrant), he would also have solved it far more efficiently. If he had looked at the documentation (which people produce), he would have seen they had been supplied the wrong component. But, the supplier is a highly reputable international supplier. C1 knew that the supply company had been taken over by the owner's less experienced son, but he 'assumed it was meant to be like that … European machine suppliers think they're of a high standard'. So, the cause of the problem lay in the *knower* quadrant, and the solution required *situational* insight – an interim solution (one of several possibilities).

The assumption of the reliability of new components or equipment and their documentation is proving to be one of the greatest challenges in engineering problem-solving. It emerged across most of the case studies – somewhere in the more complex system an operator, supplier or stakeholder is responsible for a decision that leads to an error. These challenges are located in the lower left quadrant, and it is these that the practitioners are least equipped to deal with, particularly in large *doctrinally* orientated engineering environments. The procedures in these environments are based on an assumption that people in the system need to behave as procedurally and reliably as the inanimate objects in that system. In other words, these environments dictate an *insight* orientation on the right-hand side of the epistemic plane, and yet, one look at the labour issues in the manufacturing sector should suffice to highlight the danger of ignoring the *knowers* in the equation.

The question that needs to be asked in this category is whether or not all practitioners – no matter their *insight* orientation – can be trained to cope in such environments. These types of industries in their traditional roles are the largest employers of mechatronics technicians/technologists, and their *doctrinally* orientated systems require a strong grasp of appropriate business process *discursive relations* where there is no focus on a specific technical phenomenon (the dominant foundation of their training). Where a practitioner does not recognise and realise these practices appropriately, such environments represent a code clash.

Rethinking the engineering curriculum

The case studies presented in this paper serve to highlight two different types of contexts in which two different engineering practitioners with the same training, academic strengths and *insight* orientations are required to solve problems underpinned by the same disciplinary bases. The first case study (A1) illustrated a code-accommodating environment in that the environment valued the different kinds of *insight* orientations of its team. The second case study (C1) demonstrated a more typical environment for mechatronics practitioners, where the focus on efficient production processes means a tendency towards standardised, *doctrinal* procedures. The A1 environment is experimental and flexible and would traditionally value a *purist insight* perspective, in contrast to the C1 context which is highly regulated and compliance-driven. Both practitioners are not procedurally-orientated, and neither has the necessary science-based disciplinary foundation from an academic performance perspective. This is evident in A1's case in the *situational basis* of his attempts at *purist* analysis. In C1's case, the basis appears to be an imposed or acquired *doctrinal* one. In other words, neither is as responsive to hierarchically-structured knowledge as they are to the horizontal knowledge types evident in logic-based systems. However, A1 is in a supportive environment and C1 has been at the company for long enough to have acquired a sense of the order that a *doctrinal insight* orientation can provide. In other words, he has recognised the 'code' required in this environment as a result of experience. A number of the case study participants in the same or similar contexts could not cope with such *doctrinal* orientation, and resigned from these environments. These happened to be practitioners with either a *purist* or *situational insight* orientation. These were practitioners for whom a strongly bounded phenomenon is more important than rigid procedures. On the other hand, one of C1's colleagues (also a participant in the research) demonstrated a natural *doctrinal* orientation, preferring fixed procedures, and is highly successful at the company.

The question is: what does this mean for the engineering curriculum? I suggest that the research provides an empirical basis to make a few comments regarding a necessary shift in our approach towards engineering curriculum principles, and a few recommendations with regard to practices engineering educators may wish to consider.

Principles

Contrary to the UNESCO (2010) engineering report and progressivist trends in engineering education, this research project found that the 'fundamental' disciplines make a significant contribution to problem-solving in shaping the ways in which practitioners approach, analyse and implement solutions in real world contexts. Where there is a 'code clash' between what the environment favours and how the practitioners think, the problem-solving process is impeded. Where the environment facilitates or enables the practitioner to adapt productively, there is the potential for a 'code match'. The research findings suggest a few key principles for engineering education:

- The necessity to enable explicit code shifting between different ways of approaching different phenomena in engineering problem solving;
- The recognition that the different organising principles in the core engineering disciplines enable the development of significantly different ways of thinking and meaning-making. The possession of the recognition and realisation rules (Bernstein 2000) associated with these different disciplines enables more effective problem solving. At a literal level, practitioners who recognise the different

principles, procedures, people and possibilities, and who are able to produce the associated discursive practices in relation to these elements, comfortably navigate the entire epistemic plane.
- Engineering education cannot (and should not) hope to simulate real world problem contexts. Students may be far better served through the development of a more conceptual grasp of complex problem-solving contexts.

Practices

What may the practical implications be? Two suggestions are put forward here. Firstly, the epistemic shifts across the engineering curriculum (Shay, Wolff, and Clarence-Fincham 2016) from natural to engineering sciences and then design and application require more explicit signposting. There are multiple opportunities in the 'engineering science' and applied technology subjects – particularly in diploma curricula – to stop and interrogate (as well as refresh) the disciplinary basis, the principles underpinning a particular phenomenon and its related procedures. In other words, these are opportunities to strengthen the *ontic relations* (what). Doing so consciously encourages code shifting across different knowledge structures. Furthermore, the technology-based subjects lend themselves to considering alternative forms of application and alternative approaches. This enables the student to code shift between fixed and multiple ways of approaching a problem – thus stretching the *discursive relations* (how) continuum.

Secondly, I suggest that the traditional engineering project presents an ideal opportunity for the development of a more responsive engineering practitioner. The habit of issuing the same project, or different decontextualized projects needs to be rethought. By situating the same problem in multiple possible contexts with different variables (such as budget, resources, scale and stakeholders) and then being afforded time to compare each other's solutions, students may be encouraged to develop both a more conceptual as well as realistic perspective on the implications of principles, procedures, possibilities and people under different conditions. Such an approach – although clearly demanding a concerted effort on the part of educators to rethink their curricula and teaching – may facilitate better exposure to the ranges implied by the epistemic plane. The possibilities for engaging industry in enabling access to real world problems – both for students and lecturers – could be pursued by way of case studies or a mentorship ethic, where industry professionals are encouraged to become involved in some manner in the classroom itself. Despite the reported logistical challenges in higher education and industry collaboration (Mutereko and Wedekind 2015), if better alignment is not achieved between what students are taught and what graduates actually do in real world contexts, we will perpetuate the education-workplace 'articulation gap'.

The social realist framework adopted in this paper, and in particular the LCT *epistemic plane*, offers an invaluable tool to consider the nature of the theory-practice relationship in professional curricula and practice beyond engineering. Twenty-first century professions from medicine to accounting imply the integration of fundamental disciplines, standardised protocols and context-specific possibilities in socio-cultural spaces. It is only when we recognise and make explicit these differences that we might hope to better equip our graduates for a 'supercomplex' (Barnett 2000) world.

Notes

1. The qualification for technicians situated at a level below a three-year Bachelor's in Engineering Technology Degree, and two levels below the professional engineering Bachelor's Degree.
2. The environments – referred to as Knowledge-Practice Environments (KPEs) – were categorised using factors such as scale and nature of work.

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Appendix: Data analysis samples

A1 Stage	Transcription	Discipline	Insight
Approach	This was working in a prototype version, then I put it on this board [new PCB], *then I encountered the problem*, and there are some calculations there – but I'll get to that	CONTEXT	*Situational*
	Basically, one of the first problems that I thought was you need a current in here [PFET section] – well actually it comes out here – current flowing in this direction [towards left] to switch this PNP on correctly	LOGIC	
	We had a previous problem here [bottom of diagram] with one of these circuits. These transistors were blowing up because they weren't being switched on properly	LOGIC	
Analysis	You have a base resistor here – and these transistors have a gain of uhh 40 I think – ja 40	PHYSICS	*Purist*
	So here we're switching – uhh – I mean it's going straight through there [searches a moment] 24 V here	LOGIC	*Situational*
	Then you'll have 24 V flowing straight through here … Now this can deliver up to 800 mA	PHYSICS	*Purist*
	So that transistor needs to be able to handle 800 mA, so if you take 800 divided by 40 [writes out calculation on diagram], you get the base current that you need, which is [thinks a second] 20. So you need 20 mA	MATHS	
	and basically, as the current goes above a certain level – it's got a 'hold' current and a 'trip' current	PHYSICS	
	the 'hold' current is the maximum value that will constantly hold the current. So this is 0.4 hold and 0.8 trip current	MATHS	
	So you can put 0.4 A through there the whole time – no problem. And then as soon as you start going above that it will start heating up. And then at 0.8 it will reach a temperature, where as it gets hotter the resistance increases. It gets very hot, and then the resistance is in the Mega Ohms – which then basically reduces the current flowing through there, and then it will reset	PHYSICS	
C1 Stage			
Approach	We knew there was voltage interference – We saw the LEDs were … getting brighter as you move the probe	CONTEXT	*Doctrinal*
	We started off by changing one probe, then the cables. Usually you have interference if you run high voltage cables nearby. I changed the cables to shielded, but this probe is a newer form. I did a gage 1 study to see if [the problem] is repeatable – where we measure a known value 100 or 50 times. I checked the power supply to see if it's a steady voltage range output; I checked the earthing and the probes	LOGIC	
Analysis	The system of a linear probe works on resistance – Here you have the LED inline and when you press it in full you get 10 V. But the LED has a certain resistance as well so basically its Ohms law –	PHYSICS	*Purist*
	there's a conversion in the PLC, it calculates the resistances … [draws circuit to demonstrate 'inline' layout]	MATHS	
	This connector block is used for a digital input – Once you connect a digital input here [points], You get your 3 wires 0 V, 10 V, Ground, and then your signal, the black wire – is an inductive sensor. If a piece of metal gets detected, the light on the sensor goes on to say that – okay, that input is activated	LOGIC	
	The probes are analogue, but were wired directly to this connector – but it's supposed to be used purely for digital	LOGIC	*Purist*
Identification of Cause	It's not a common connector, there are various types and I assumed it was meant to be like that. European machine suppliers think they're of a high standard – but they supplied the incorrect connector	CONTEXT	*Knower*