Throwing the baby out with the bathwater?

the role of fundamentals in 21st century engineering education

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***Abstract*—As the labor market increasingly demands equipped, problem-solving practitioners, engineering curriculum review is seeing a shift away from theory and towards practice. And yet, employers continue to highlight engineering graduate inability to 'apply theory' or effectively solve real world problems. The research on which this paper is based seeks to better understand the relationship between engineering theory and practice. Drawing on research in the fields of Artificial Intelligence (AI) and the Sociology of Education, the research project entailed the graphic analysis of the disciplinary basis and socio-technical contexts of 18 mechatronics engineering technician case studies. The problem-solving 'maps' reveal that key to successfully navigating the epistemic terrain of a real-world problem requires the recognition and realization of the different disciplinary rules, and an ability to code-shift between the different engineering disciplines. This paper presents two contrasting case studies which demonstrate the significance of disciplinary thinking and highlight the importance of explicitly integrating disciplinary 'code-shifting' opportunities into engineering curricula and teaching.**

Keywords— Engineering disciplines; problem solving; industrial practice; code-shifting

I. INTRODUCTION

Employer demands that graduates hit the ground running [1] have meant that labor-market and employability criteria have become key drivers of curriculum, teaching and learning reform in engineering education. Widespread engineering curriculum review has seen a shift towards the development of a 'holistic practitioner' with a range of graduate attributes intended to enable participation in complex, 21st century engineering sites of practice. As such, increasingly, educators are adopting a range of innovative strategies to enable access to technologies and workplace experience during the course of engineering studies. The shift towards 'practice' has seen – in some sectors – a shift away from 'theory'. The UNESCO Engineering Report [2] 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 is, after all, the key function of an engineering practitioner [3] [4]. But what exactly does engineering problem solving entail? Exposing students to ill-conceptualized or idealized real world problems or simply providing access to workplace learning may not foster the problem-solving abilities that 21st century industry requires. Indeed, industry complaints of graduate inabilities abound [5] [6], suggesting that problems are not being solved in the manner desired. Problem- and project-based learning are common approaches integrated into engineering curricula in the hopes of better equipping graduates. However, the range of contexts and exponential developments in technology mean that much of what we teach our students will be redundant by the time they do graduate [6]. The argument against such more vocationally-orientated training is that this approach denies students the opportunity to develop relational, causal and more conceptually holistic ways of thinking [7]. The contention in this paper is that in the rush to adopt alternative, practice-oriented forms of engineering education, educators may be missing the role that disciplinary knowledge plays in aiding problem solving in complex contexts.

A doctoral research project sought to understand the relationship between engineering theory and practice by examining the problem-solving strategies of practitioners in multidisciplinary industrial engineering sites. Drawing on research in the fields of Artificial Intelligence (AI) and the Sociology of Education, the research was designed to focus on both the disciplinary basis of particular engineering problems as well as the socio-technical contexts of their occurrence. The research saw the generation of problem-solving maps across 18 case studies, and enabled the identification of potentially typical problem-solving patterns in significantly different types of work contexts. Using an analytical tool drawn from Legitimation Code Theory [8], it was revealed that key to successfully navigating the epistemic terrain of a problem requires the recognition and realization [9] of the different disciplinary rules, and an ability to code-shift between the different engineering disciplines. The traditional engineering curriculum with its strong mathematics and natural science base cultivates very specific ways of working with knowledge, ways which differ significantly from those required when using different forms of technology, which are logic-based.

The paper briefly situates the research context before introducing the theoretical framework and analytical tools. It then goes on to present two contrasting case studies which open the discussion on the significance of disciplinary thinking and disciplinary code-shifting in engineering practice. The intention of these findings is to highlight the importance of explicitly integrating disciplinary 'code-shifting' opportunities into engineering curricula and teaching.

II. RESEARCH CONTEXT

South Africa (SA) is a signatory to the Washington, Sydney and Dublin Accords. As such, SA post-school institutions offer three distinct types of qualifications for the differentiated engineering profiles: the 4-year professional Bachelor's (engineer), the 3-year Bachelor of Engineering Technology or 1-year post-Diploma qualification (technologist), following the 3-year Diploma (technician). Given the national imperative to meet socio-economic development goals [10], the country is in urgent need of well-trained professionals. Not only is there a mere 10% of the number of engineers necessary for a developing economy, but the ratio of engineers to technicians is a low 1: 1.4 as opposed to the suggested international norm of 1:4. [11]. National data [12], however, indicating particularly poor graduation rates (41%), retention (<50%) and employment statistics [13] suggest that SA engineering programmes face challenges in attracting and retaining students in order to produce the required professionals.

Following a decade which has seen major curricular revisions and reform across the higher education sector, as well as professional body engagement with the design of internationally-aligned engineering qualifications, the country is nowhere near meeting the envisaged graduation rates [14]. Of particular concern is the high number of unemployed engineering technicians, despite ostensible industry demand. A national industry survey cited the inability to 'apply knowledge' as a key concern for employers [5]. These worrying statistics in light of the increasing trend towards practice-oriented training led to the hypothesis that the relationship between engineering theory and practice in 21st century contexts needs to be better understood from both an empirical and theoretical perspective, particularly in the case of technician qualifications (diplomas). These qualifications, offered by the Universities of Technology (UoT), are situated at the lower end of the higher education framework, and are different from their vocational counterparts offered by the Technical Vocational Education and Training (TVET) colleges. The TVET qualifications are unambiguously practical in nature. The professional Bachelor's, similarly, is unambiguously theoretical. Muller [15] describes this difference as contextual- versus conceptual-coherence curricula. The diploma straddles both, including a compulsory period of Work-Place Learning (WPL) and a more theoretical base than the TVET curriculum. The focus of the diploma is intended to be industry-specific, and the WPL period is meant to enable trainees to demonstrate the acquisition and application of appropriate workplace practices in order to meet all competency requirements for graduation. The key competency in all engineering qualifications is the ability to 'solve problems'. In the case of the diploma (technician), these problems are classified as 'well-defined' [4]. However, employer dissatisfaction with trainees, the high dropout rate on diploma programmes [14], and rapidly evolving technologies in engineering work contexts demand a more 'sophisticated' understanding [16] of the conceptual and contextual nature of problem solving for our 'supercomplex' [17] world.

Problem-solving literature across fields has tended to focus on methodologies, types of problems or, at best, establishes the key features pertaining to the components in the problem-solving system – the components being the 'problem solver' (with his/her internal subject factors) [18], the problem-solving process (activities) relying on different cognitive layers [19], and the problem 'context' or environment [20]. Much of the available research on engineering problem-solving focuses on design contexts. Two particularly informative studies conducted at MIT highlight not only the significance of 'context' and 'human behavior', but the importance of problem identification [3] [21]. However, none of the studies engages with the 'contextual' implications of different *disciplinary* forms of engineering knowledge. This knowledge-blindness [8] has significant implications for curriculum design and teaching which is intended to help graduates to apply knowledge to solve real problems that are not design orientated.

A PhD research project at the University of Cape Town, supported by the National Research Foundation, was conducted between 2013-2015 to investigate how engineering technicians work with different forms of disciplinary knowledge when solving engineering problems in industrial settings. Given the national focus on STEM education, well-reported evidence of a pervasive digital divide, and the ubiquitous integration of computer-based technologies in a range of professional fields beyond engineering, the study hoped to shed light on the relationship between different forms of 'science' and the impact on professional 'practice'.

A. Research Sites & Participants

With the rapid development and integration of computer-based technologies in engineering practice in the 21st century, and the reliance on technicians to integrate, maintain and operate such technologies, one of the sub-questions that drove the research was the extent to which the complexity of such technologies was impacting on poor student, trainee and graduate performance. Prior research on student capstone design projects had already determined that the organising principles of mathematics, physics and logic differ significantly [22]. The seeming absence of references to disciplinary forms of knowledge in problem-solving literature, as well as researcher observation in industrial sites of the pervasive use of generic descriptors such as 'hands-on' or 'showing initiative' not only supported the academic versus industrial disjuncture between 'science' and 'engineering' [23], [24], [25], but indicated that there is a serious need to interrogate the synergistic role played by the disciplines in multidisciplinary, science-based practice.

Engineering is said to be about the harnessing and modification of 'the three fundamental resources that humankind has available for the creation of all technology: energy, materials, and information' [26]. Mechatronics engineering represents precisely this relationship, being concerned with the automated control of electro-mechanical systems, such as those found in manufacturing sectors. Mechatronics curricula are broadly designed around three core subject areas: structures, power and control. From a disciplinary perspective, *structures* and *power* draw on the mathematics and physics underpinning mechanical and electrical engineering. *Control*, in mechatronics, is based on the 'logic'[1] and mathematics of computer engineering. In SA, mechatronics technicians are to be found across sectors such as electronics prototyping, machine building, systems integration design and implementation, control panel building, manufacturing, and production process control. These sectors range in scale from micro to large businesses. Such differences

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[1] The study of (deductive) 'inferences that depend on concepts that are expressed by the 'logical constants' such as *and, not, or, if…then*' (Britannica Concise Encyclopaedia, 2006).

in foci and scale have implications for the kinds of problem-solving processes technicians are likely to undertake.

50 mechatronics engineering diploma graduates (from one of only two UoTs in SA who offer the course) volunteered to take part in the research project during 2014. These graduates are all employed in a range of industrial sites dealing with controlled, electromechanical systems. The participants had from one to five years' experience in these sectors at the time of the study.

B. Research Methods

The first research phase entailed an online problem-solving survey to determine appropriate cases for phase two. The survey covered personal and company contextual questions, and then focused specifically on any recent technical problem encountered and how it was solved. 27 of the volunteers responded, and these texts enabled the classification of work contexts into three distinct mechatronics Knowledge-Practice Environments (KPEs) [22]:

- Micro to small R&D companies designing, building and maintaining 'contained systems', such as intelligent medical devices or single-function stand-alone devices;
- Small to medium Systems Integrating or Machine Building companies, whose work was classified as 'modular systems';
- Medium to large manufacturers where one finds 'distributed systems' and a focus on production process.

Six cases were selected in each category for follow-up, video-recorded interviews following a semi-structured 're-enactment' protocol. This protocol entailed the participant taking the researcher through the problem described in the original survey in relation to the actual artefacts and problem site. In other words, the technician re-enacted the problem as he/she had originally encountered it and detailed how he/she discovered the problem, what was done and why. The phase two interviews were transcribed into discrete statement sections onto a spreadsheet, and coded for underlying disciplinary references, from broader disciplinary categories such as 'mechanical' or 'electrical' to more specific mathematics, physics, and logic references.

The analysis focused on three stages of the problem-solving process: approach, analysis and solution. The evolution of the analytical instrument is detailed in the following section.

III. THEORETICAL FRAMEWORK

Herbert Simon's work in decision making and AI provided a key theoretical principle for the research: the distinction between the inner and outer environments of a particular artefact [27]. The 'inner' system in this research is constituted by the relationship between the mathematics, physics and logic of a particular problem in the controlled electromechanical system. The 'outer' system consists of the problem solver, the problem context and environment. The outer problem-solving components entail people and protocols which may determine ways of approaching and solving problems, irrespective of the 'inner' disciplinary basis.

The Sociology of Education provided the theoretical language to describe the nature of disciplinary differences in the 'inner' system, as well as the problem-solving practices entailed in the 'outer' system components. Bernstein's [9] characterization of how new knowledge is produced, reshaped for curriculum texts, and reproduced in educational settings offers valuable insights into how knowledge is structured. Hierarchical knowledge structures (such as the natural sciences) grow by subsuming and integrating concepts. Ohm's Law, for example, entails a chain of concepts and formulations to do with electrons, electricity, electromagnetism, conductivity, resistance and so on. To be able to grasp the reduced concept of V=IR, one would have developed an understanding of all the preceding concepts and their relation to each other in a strongly 'vertical' concept chain. Learning such types of disciplines takes years and begins with the earliest sensory observations of early childhood (which may also lead to misconceptions).

In contrast, horizontal knowledge structures such as mathematics or politics grow by the addition of different 'languages' of the same knowledge type [9]. Hence, we find many 'algebras' or political systems. Understanding one of these is not necessarily dependent on the understanding of another. A *strong* horizontal knowledge structure means that each of the 'languages' has specific, recognizable rules and forms of syntax peculiar to itself. On the other hand, a *weak* horizontal knowledge structure is one that develops by borrowing rules and concepts from other disciplines or 'languages'. Disciplines with horizontal knowledge structures imply the learning of 'masses of particulars' [15], and those with weak structures even more so, with the added challenge of rapid redundancy as well as proliferation. This latter type of knowledge is evident in computer programming. In the field of mechatronics engineering, for example, the computer control of a system could take any shape, be accomplished with a host of platforms and programming languages, each of which has its own rules, but which are also constantly evolving. This implies a very different form of learning to that entailed in understanding Ohm's Law. As simplistic as these knowledge structure characterizations may appear, they do enable a broad classification of the three core disciplines in mechatronics engineering within the 'inner' environment of a particular 'problem' artefact: physics (hierarchical knowledge structure), mathematics ('strong' horizontal knowledge structure), and logic ('weak' horizontal knowledge structure).

Legitimation Code Theory (LCT) [8] is a growing field within the Sociology of Education which offers a range of tools for understanding what people do with 'knowledge': how it is shaped, who 'knowers' are, what is valued and legitimated through kinds of knowledge practices. One of the LCT dimensions – Specialization – focuses on how or why knowledge claims are made, and has been particularly useful in illuminating curriculum decisions across the educational spectrum. The LCT Specialization concept of *epistemic relations* focuses specifically on the nature of knowledge and provides a means to consider the relationship between the *what* and *how* of a knowledge practice.

Captured as the two axes of a Cartesian plane (figure 1), the relative strength (+) or weakness (-) of both the phenomenon (what) and approaches to that phenomenon (how) give us four quadrants which indicate the basis (*insights*) from which a knowledge claim is made. By way of example, when a production line is halted as a result of a power dip, the underlying cause could be traced to Ohm's Law – a physics principle which has accepted phenomenal (what) and procedural (how) properties. Working with Ohm's Law would require a *purist insight.* When a standardized methodology is followed irrespective of the phenomenon – such as applying Six Sigma methodologies to measure operational efficiencies – this requires *doctrinal insight.* So, too, the inverse: when the phenomenon is foregrounded and there may be several approaches or solutions, a *situational insight* is appropriate. Each of these *insights* on the *epistemic plane* is a form of 'code'. In R&D environments, for example, one would tend to see more decisions based on *purist insight* than the *doctrinal insight* necessary to maintain large batch/mass-production in manufacturing environments.

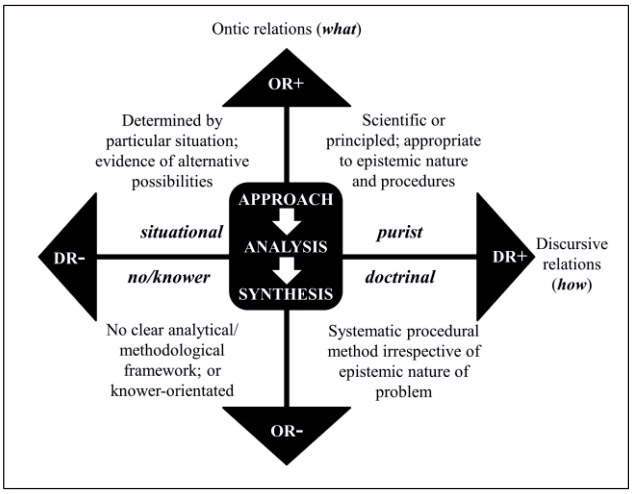

Fig. 1. Modified and annotated epistemic plane [8]

The epistemic plane (figure 1) was developed as an analytical tool to examine the *basis* [8] of decisions practitioners made as they undertook the problem-solving process. This *basis* was evident from the outset through the manner in which the technician wrote or spoke about the problem, and could be contrasted with or compared to the protocols evident in the specific industrial contexts.

The two theoretical instruments – knowledge structure characterizations and epistemic *insights* – provided perspectives on kinds of 'codes' implied in engineering work. Problem solving literally means navigating between these different codes across the *epistemic plane*. The research produced a set of graphic maps attempting to broadly capture how engineering technicians in different mechatronics industrial contexts actually do this.

IV. CASE STUDIES

Two case studies from the same KPE category (modular systems) have been selected for this paper. In all cases, a full participant profile (including academic record and supervisor feedback) and company profile (based on their online presence, actual infrastructure and official protocols) were drawn up. These profiles and the interview analyses suggested certain preferences or dominant *insight* modes. It is important to note that the focus of the research was less the participant's 'state of knowledge' [28] than the actual disciplinary knowledge itself as underpinning (and potentially having a causal effect on) human action. To ensure interpretative validity, and in acknowledgement of the fact that the research falls within the sphere of socio-cultural practices, the fullest possible picture of all variables was sought. The focus of this paper is the relationship between the problem structure and problem solver in two specific problem contexts in similar industrial sites.

A. Case study B1

Participant B1 was employed by a very large (6000+) communications company and his role was the needs-analysis, design and implementation of communication interfaces between existing processes for food and beverage processing clients. The problem he selected occurred when he was required to integrate a scanning device on a conveyor system in order to send pallet information to a central data management system (SAP). However, the pallets were being rejected as the SAP system was not receiving the full barcode. B1 identified the cause as 'the PC application (written by someone else) is splitting up the barcodes'. Required to solve the problem in the most effective, sustainable way with the shortest loss of productivity, B1 did not conduct a disciplinary root-cause analysis (*purist*); rather, he selected the most efficient (*situational*) solution by removing the PC, its barcode application and the cable, and chose to integrate a small communications module with which he was more familiar.

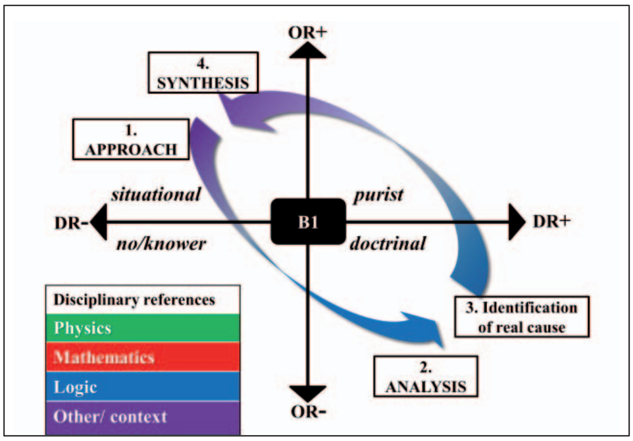

Fig. 2. B1 problem-solving map

B1 is a low mathematics and physics achiever, with a significantly higher academic record in logic-based subjects (programming). This form of knowledge sees an iterative movement between two diametrically opposed ways of thinking: the rules of a particular programme (*doctrinal*) and the multiple possibilities of a particular 'control' situation. The dominant *insight* orientation of the client environment is *doctrinal*: standardized and regulated food processing, packaging and distribution systems that are required to function responsively and competitively in the supply chain between raw materials and consumer distribution outlets. B1's *situational insight* orientation emerged from his claim that most of his work is 'trial-and-error'. His survey response was brief and included a computer-generated sketch and no indication of an attempt at discipline-based analysis. B1's entire problem is logic-based. It is a matter of understanding *what* is connected to *what*, and *what* is 'speaking to' *what* in *what* language and with *what* rules. These rules are not standardized, and are dependent on suppliers of the specific components. One might argue that a more disciplinary deconstruction of the problem (*purist insight*) could have led to the identification of the code problem, and while this would be appropriate and is indeed the practice in an R&D environment, commercial enterprises do not necessarily have the luxury of time for such analysis in the absence of component/system-specific expertise [29]. It is interesting that he ignores the 'knower/no' quadrant – given the fact that 'someone' had written the original code that led to the barcodes being split at the SAP end. This bears testimony to the 'weaker' horizontal knowledge structure implied in logic programming: No two programmers' code looks the same, albeit in the same language or for the same purpose. The productivity impetus of this situation demanded the most efficient solution at the least cost, even if that meant buying replacement equipment instead of paying for hours of programming time. The client and supervisor confirmed that B1's solution was appropriate and effective in this context. This is a case of what is called a 'code match' [8].

B. *Case study B5*

The contrasting case study is also located within the 'modular systems' KPE, but in this case at an international machine building company for the food and beverage industry. Technician B5's problem entailed the integration of a carbonation unit, with a new supply pump, on a bottling line. When constructing the unit, he observed that the supply pump to the refrigeration unit would not fit on the carbonation unit base frame. Figure 3 broadly captures B5's problem-solving process.

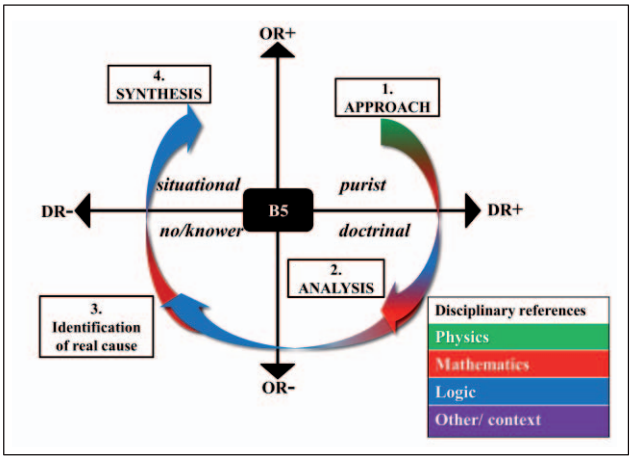

Fig. 3. B5 problem-solving map

His approach to the problem is *purist*, in that he begins his description with the purpose of the pump within the carbonation system and its specifications in typical design report detail. He spent much of the problem-solving process measuring and rechecking the design dimensions (*doctrinal insight*), before venturing into the carbonation unit and pump documentation (created by suppliers – hence the *knower insight orientation)* only to finally discover that the pump could be installed upside down. He finally solved the problem (dictated by *situational insight*) by deciding to install the pump beneath the carbonation unit frame. He spoke of being frustrated at not knowing how to solve the problem 'analytically', not knowing where to look.

In contrast to B1, B5's academic profile reveals distinctions in mathematics and physics, but low achievement in logic-based subject areas. Ultimately, the carbonation unit problem did not demand the neat, linear computational process of mathematics (strong horizontal knowledge structure), nor the analytical deconstruction of physics (hierarchical knowledge structure). It literally required thinking 'outside of the box' – [what are all the possible pump mounting positions?] and a recognition that the laws of physics and mathematics were not dictating the position, rather this was entirely the supplier's decision. Hence, the answer was to be found in the supplier documentation. It is apparent though that this technician approached the problem from a *purist insight* basis, spending a great deal of time on measurement and function. In contrast to B1's relational, schematic sketch of the problem in the survey phase of the research, B5 – typical of the *purist* or *doctrinal* case studies – presents his problem in numbered sequence and avoids any personal pronouns. This can also be contrasted with the *situational* practitioners who tended to use first person, narrative problem-solving descriptions.

B5's discomfort at having to wade through user documentation under pressure appears to support the claim that his preference for analytical or deductive order (as evident in his higher physics and mathematics achievement) is challenged by knowledge structures with weaker organising principles, as well as elements in the working environment which may be dictated by 'knowers'. Indeed, under the 'general challenges in your working environment' contextual survey question, B5 listed 'verbal communication'. Verbal communication and user documentation do not rely on science-based laws. Each supplier's documentation is different, with different terminology, and frequently not up to date [30]. The kind of knowledge required in such cases (as with software) is developed through experience, and relies on the diagonal, iterative movement between *situational* and *doctrinal insights*.

V. DISCUSSION

The two case studies illustrate particular practitioners with contrasting disciplinary strengths solving two different types of engineering disciplinary problems within the modular systems category (KPE B). B1 represents a *code-matching* [8] scenario, where the participant's 'logic-based' orientation enabled the efficient solution to a logic-based problem. I suggest he 'recognized' the phenomenon ('get the whole barcode to the SAP system') and the fact that there were a number of possible approaches (*situational insight*). Once he had made his selection, it was a case of methodologically applying that particular selection's rules. This movement between the *situational* and *doctrinal* characterizes much of the technology-based engineering work in machine building and systems integration (figure 4). The particular situation (customer needs) requires one of several possible solutions – each of which has its own specific methodological implications.

In contrast to this diametrical relationship, KPE A (contained systems) in this research was seen to have a dominant *purist* and *situational insight* orientation. In other words, in R&D, prototyping and intelligent device development and maintenance industries, there is generally a stronger allegiance to a particular phenomenon driven by strongly defined principles (the laws of science) and requiring the selection of feasible approaches. Successful practitioners in KPE A needed to be strongly theoretically orientated as well as open to 'principled' choices.

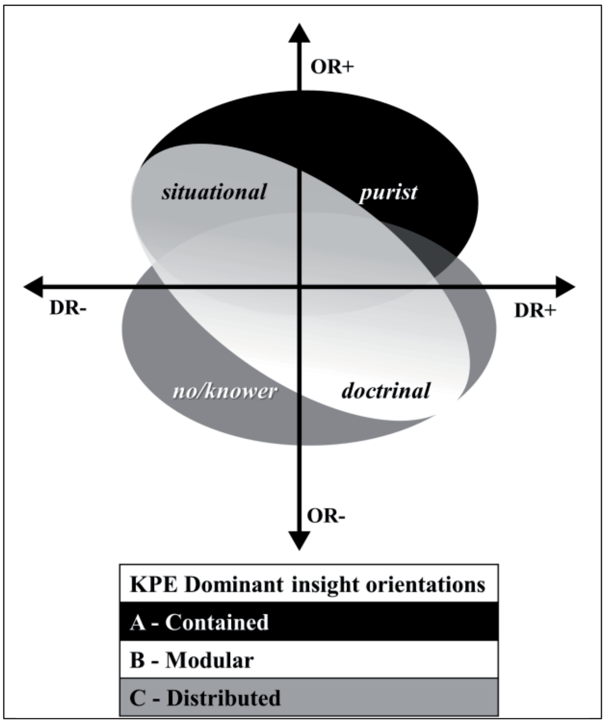

Fig. 4. KPE dominant insight orientation

KPE C, on the other hand – distributed systems – employs the highest numbers of technicians and sees most of its problems (in this research) as occurring in relation to the bottom left *knower* quadrant: the problem cause is most frequently an action or decision by either a supplier or operator or stakeholder in the problem-solving context.

These KPEs dictate certain *insight* preferences, based on explicit or implicit values. Where a practitioner does not have a natural orientation to that preferred by the environment, he/she is likely to experience a code clash [8], such as in the B5 case study. B5's *purist* orientation (expecting a fixed approach to a fixed phenomenon) was challenged by the 'weak' disciplinary basis of the problem. Being responsive to the *situation* meant shifting his mindset from the idealized design process which so often exemplifies the projects issued in engineering design education.

Further case studies in the research project in question highlight the relationship between the *insight* orientations of practitioners and those valued in the different contexts. There is no ideal type or relationship. Rather, technicians with a naturally trial-and-error or *situational* perspective tend to cope better in engineering contexts where custom-made machines or systems are designed and built (KPE B). In contrast, *purist* practitioners tend to cope better in environments such as KPE A without the pressure of meeting production targets in highly *doctrinal* industries (KPE C). This question of code shifting and code clashing needs further examination.

A. Code shifting

The most common code-shift challenge (figure 5) that emerged in the research is that from right to left on the epistemic plane; in other words, the movement from defined or limited approaches to numerous possibilities, particularly those possibilities dependent on 'knowers' in the problem-solving system. Those practitioners with an evident logic-based orientation (*situational*) found the diagonal shift from left to right and back easier to navigate. In a number of the case studies not discussed in this paper, strongly *situational* practitioners found the shift into the *purist* quadrant problematic. The six modular systems (KPE B) case studies tended towards the logic-based knowledge domains. The one feature they all have in common is that the problem structure is characterised by a *doctrinal* element either in relation to the epistemic basis (*purist*) or the polar opposite, a social basis (*knower*). In other words, the problems in the modular systems KPE are methodological problems based on mis-recognized principles or unanticipated vendor decisions. This is possibly the most complex of the KPEs, in that technicians are required to simultaneously recognize phenomena and procedures that are diametrically opposed. In B1's case, the technician did not lose sight of the principle and applied an appropriate methodology. In B5's case, the technician 'wanted' the problem to be one of 'principle' (this is the way this machine has been designed), but the situation required that he move into the *knower* quadrant to determine how many possibilities someone (a particular pump supplier) had made available for this particular problem (*situational insight*).

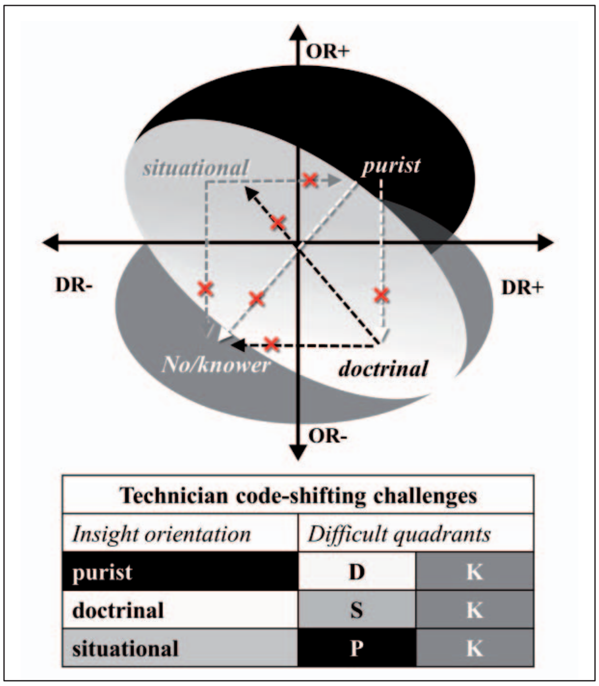

Fig. 5. Technician code-shifting challenges

B. The significance of disciplinary thinking

It will be evident from the graphic representation of the analyses (figure 5) that all three technician 'types' found the shift into the *knower* quadrant challenging. This quadrant represents possible 'weak' phenomena (in other words, those open to interpretation) as well as an increase in the range of potential approaches. Not only were most of the problem causes across the research project located in this quadrant, but only two practitioners of the 18 case studies (A4 and B2) explicitly and successfully moved into this quadrant during the problem-solving process as part of their analysis of the overall situation. What these two practitioners have in common is that they are top academic achievers in physics and mathematics. However, A4 is also one of an anomalous 2.9% of the five-year cohort analyzed who achieved distinctions in both mathematics *and* the logic-based subjects; whereas B2 was the oldest participant at the time of the research (30) and had had 4 years' working experience in contrast to A4's one year.

The two case studies presented in this paper – B1 and B5 – represent two more academically normative participants of the cohort analyzed for the larger research project (n=295). B1 represents 52% of the technicians who barely make it through the mathematics and physics components of their course work (if not actually fail the first time around), but who thrive in *situational* environments and who are often described as being 'hands-on'. I suggest that this indicates a responsiveness to the way in which the logic-based knowledge initially announces itself – a world of choices and context-dependent decisions – and which is more characteristic of the nature of the engineering endeavor. Real world problems are 'messy' [8].

B5, on the other hand, represents 20% of the cohort who achieved distinctions for mathematics, but struggled with the technology and logic-based subjects. When the study commenced in 2013, only 10 of the 295 graduates over the preceding 5-year period were unemployed, and all 10 had one feature in common: they had all achieved distinctions in mathematics, but poor performance in the logic-based subject areas. In stark contrast to the unemployed mathematics-distinction achievers, 62% of the graduates who had achieved between 50-59% for mathematics were not only employed, but highly successful (industry feedback), as were 100% of those who had failed mathematics the first time around (having achieved between 30 – 49%).

Mathematics represents the largest stumbling block in engineering education [24]. The findings in this research study of a correlation between mathematics *and* logic performance in relation to code-shifting behavior, as well as poorer industrial problem-solving for high mathematics/low logic achievers suggest we have not sufficiently grasped the significance of mathematical ways of thinking in engineering practice. I contend that the high mathematics/low logic achievers are more comfortable in the *doctrinal* space – they have developed particular ways of seeing things, which - I would add – have been reinforced through years of recognizing and realizing [9] the organizing principles of stronger knowledge structures. The same characterization may apply to the *purist* practitioners in this study, all of whom were high achievers in the physics-based subject areas.

The research data show problem-solving patterns which demonstrate a symbiotic, structuring relationship between problem solver, problem structure and the problem environment. Each of these may manifest as having a different dominant *insight* orientation, with each *insight* representing a different kind of code as to the 'what' and the 'how' of the problem. Solving the problem requires the navigation of different 'codes' across the problem-solving stages over a period of time. Each code has different rules. Successful practitioners recognize and realize the different code conventions, and engage in code-shifting practices that may be evident both in the way they navigate the physical environment as well as in their discursive conventions.

VI. IMPLICATIONS FOR ENGINEERING EDUCATION

The preceding analyses and discussion may be seen as examples of the structuring effects of knowledge [9]. However, the intention in this research and paper is not to suggest a form of determinism – that practitioners and environments have certain ways of solving problems, and that these are somehow fixed. The issue is not that there are different kinds of knowledge and practices in engineering, nor that there are different orientations to practice. The issue is the evidence that engineering practitioners are found wanting in the ability to *apply knowledge* [5] when faced with complex real world problems. The contention in this research is that such application requires the ability to *consciously shift* between the different forms. It is this shifting that is problematic for the technicians in the case studies. It is this shifting that is not explicit in the curriculum. And it is this very shifting that implies a more complex level of practice in 21st century engineering problem solving contexts.

What does this mean for engineering educators? Opportunities to enable code-shifting are provided in 'project-based' subjects, for example, but there is often no explicit induction into what is required to be able to recognize and realize the different forms of code in a single problem-solving moment. And herein lies our first challenge as engineering educators: making the codes explicit. In order to do so, we – as educators – need to understand and appreciate that the different disciplines enable different ways of thinking. Any single problem-solving moment may offer the opportunity to 'stop and think': what is the principle here? Who are the role-players? What are the possibilities? And in each of these, what are the procedures? For the principles and procedures of Ohm's Law and those of purchasing a component are entirely different, and yet in our idealized engineering education environments, we treat these (if we even consider the latter at all) as 'content', not recognizing that they require different kinds of time and space to learn and apply.

A second key challenge lies in the complex nature of the environments for which we are preparing graduates. The curriculum cannot possibly hope to take all the variables and permutations into account. Doing so would mean the recreation of contexts that can only exist in the real world of work, and which would require periods of learning that extend beyond the parameters set by qualification duration. I suggest it is the naïve simulation of context in problem-based/project-based learning which has led to losing sight of the intricate relationship between the 'what' and 'how' of a problem as determined by the entirety of the Knowledge-Practice Environment.

So, if HE cannot simulate the real world and provide enough realistic examples of ways of approaching different problems in different contexts in the face of a rapidly evolving technological landscape, what is our role? I believe our role is to step out of contexts and understand them from a more conceptual perspective. This can be accomplished through providing opportunities to interrogate complexity from a more conceptually-informed basis. Imagine, if you will, issuing the same project to an entire class, but providing each group with different functional, budgetary and contextual specifications. The 'science' at the heart of each project would appear to be exactly the same, but using different sources of power or building to significantly different scales for different kinds of end users would offer an ideal opportunity to make explicit the difference and relationship between theory and practice. It is the duty of engineering education to enable access to the range of *insights* and ways to *code shift* if our graduates are to cope in what will become even more complex sociotechnical practice environments.

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