European Journal of Engineering Education

ISSN: 0304-3797 (Print) 1469-5898 (Online) Journal homepage: http://www.tandfonline.com/loi/ceee20

Researching the engineering theory-practice divide in industrial problem solving

Karin Wolff

EUROPEAN JOURNAL OF ENGINEERING EDUCATION
https://doi.org/10.1080/03043797.2018.1516738

Researching the engineering theory-practice divide in industrial problem solving

Karin Wolff

SARChI Work Integrated Learning Research Unit, Cape Peninsula University of Technology, Cape Town, South Africa

ABSTRACT

Employer complaints of engineering graduate inability to 'apply knowledge' call for a better understanding of the theory-practice relationship in technology-driven twenty-first century industries. A novel systems-based model was developed to analyse how mechatronics engineering practitioners apply mathematics, physics and logic-based knowledge to practical problems in different industrial systems contexts. Theoretically and methodologically, the research draws on the work of Herbert Simon, Basil Bernstein and Legitimation Code Theory. The graphic analysis of the relationship between the problem solver and problem structure in different industrial contexts demonstrates that different ways of thinking are required in considering the 'what' and the 'how' of the problem under different conditions. Current curricula not only need to explicitly enable the shifting between different engineering thinking 'codes', but also need to promote a more conceptual grasp of contextual factors. This paper offers a research-informed perspective on what 'apply knowledge' really means in twenty-first century engineering contexts. (149)

ARTICLE HISTORY
Received 23 July 2016
Accepted 16 August 2018

KEYWORDS
Engineering problem solving; industrial practice; knowledge code-shifting

1. Introduction

There are many names that characterise this second decade of the third millennium – the information age, or digital age or the eve of the 4th Industrial Revolution. Educators are faced with the increasingly complex challenge of enabling new generations to acquire and engage with appropriate forms of 'knowledge' and learning that will enable legitimate socioeconomic participation in a rapidly evolving sociotechnical twenty-first century world. The urgency with which we need to address this challenge is supported by the voices of discontent via numerous workplace surveys – both local and international – which tell us that we, as educators, are failing at preparing our students for the world of work today (Kraak 2000; Griesel and Parker 2009; Young and Muller 2010; manpowergroup.com 2015).

One area in which we are clearly struggling is in engineering education. On the one hand, international literature abounds with statistics on falling engineering enrolment and completion rates (UNESCO 2010), poor retention rates (Bernold, Spurlin, and Anson 2007), and chronic industry complaints about competency (Felder 2012). In the USA, engineering education is regarded by some as in a state of 'quiet crisis' (Jackson 2007). In South Africa, the Human Sciences Research Council (HSRC) reports that the country is facing a scarce skills crisis never before seen (Du Toit and Roodte 2008), with unacceptably low graduation rates (NPC 2011) and a 50% average dropout rate on engineering programmes (CHE 2013). On the other hand, however, unemployment statistics in the UK, USA and South Africa (the site of the research) reveal an unacceptably high proportion of unemployed

CONTACT Karin Wolff wolff.ke@gmail.com

graduates in scarce skills STEM sectors, despite clear demand and very different socioeconomic conditions. Why is this?

There have been several attempts to explain the 'crisis' in engineering education, including massification (there are too many students in the system) and a crammed curriculum. One key contention attributes the 'crisis' to a disjuncture between 'science' and 'engineering' or the engineering curriculum and the field of practice (Bernold, Spurlin, and Anson 2007), (Andersson, Chronholm, and Gelin 2011), (Vogt 2008). This is echoed in retention studies where students who are not prepared for the theoretically-heavy curriculum opt to leave, having expected more practical engagement (Ahmed, Kloot and Collier-Reed 2015). The UNESCO report (2010) calls for a move away from the 150-year-old 'Humboldtian' discipline-based curriculum, and globally we have seen the redesign of curricula to include problem and project-based learning so as to enable a more relevant curriculum (Bernold, Spurlin, and Anson 2007) and the alignment of curricula to broader competency frameworks (IEA 2013).

Despite these shifts, poor engineering retention, graduation and employment statistics suggest the problem is not being addressed. Wheelahan (2007, 5) argues that the shift towards a more profession-facing, competency-based form of engineering education denies students access to the 'relational connections … and collective representations [about disciplinary] causal mechanisms'. The assumption in increasingly contextualised practice-based education is that the 'disciplinary basis of a subject-based curriculum is arbitrary' (Maton and Moore 2010, 6). In other words, we are missing the significance of the role of the 'disciplines' in the professions.

It is this disjuncture between science and engineering – or theory and practice – that provided the impetus for the research on which this paper is based. If the purpose of professional engineering qualifications is to enable graduates to effectively apply their disciplinary knowledge in practice, what does this look like? Given that the role of the engineer is commonly seen as one of problem solving (Sobek 2004) at the interface between science, technology, society and nature (UNESCO 2010), the research project on which this paper is based set out to investigate what engineering problem solving looks like (from the perspective of fundamental-disciplinary knowledge) in the field of industrial practice. The intention is to be able to look back at the curriculum with a better understanding of the theory-practice relationship.

2. Research context

The chosen field is one of the most rapidly emerging and expanding engineering sectors – that of controlled electro-mechanical systems (or mechatronics engineering). The reason for this particular focus is, firstly, that the core disciplines that underpin mechatronics engineering are significantly different, with different organising principles which require different forms of cognitive engagement (Wolff 2017). The core disciplines selected for the focus of the research in this paper are physics, mathematics and 'logic[1]'. Secondly, mechatronics engineering practitioners work across multiple sectors that vary in scale, scope and type. Methodologically, the multidisciplinary nature of the sector and range of contexts offer a broader platform through which to interrogate the efficacy of problem-solving practices in increasingly technologised industrial contexts.

In order to contextualise the ensuing theoretical framework, a brief overview of the research participants and data collection process is given here. 50 volunteering novice mechatronics engineering practitioners[2] working in a range of industrial sites across the Western Cape region of South Africa were approached to participate in the research project. Each had up to five years' working experience. They were asked to complete a questionnaire to determine the nature of and manner in which they most recently solved a particular controlled, electromechanical problem. This enabled the selection of 12[3] matched cases of differing scale in the three different mechatronics engineering systems categories. Phase two saw the audio/video recording of the selected practitioners re-enacting their problem-solving process with the actual artefacts in the industrial site of practice. [The questionnaire and re-enactment texts were transcribed (verbatim) into discrete, thematic statements onto an electronic spreadsheet for analysis using the instruments described in section 3 of this paper]. This technique firstly captures a narrative of the problem-solving context and specific processes, and then provides a 'script' which enables the coding not only of 'specific aspects of the problem-solving approach' (Atman and Bursic 1998), but also specifically sought disciplinary references. As a development of the 'think-aloud' protocol, these verbal protocol analysis approaches have become increasingly common in a range of qualitative studies. In addition to these texts, interviews were held with supervisors/employers to establish the nature of the environment and a full academic and personal profile was drawn up for each of the participants. It is important to note, though, that individual performance was not the focus of the study, rather patterns of problem-solving activity in different contexts[4].

The complexity of the interrelations between artefacts, problem-solvers and contexts is mirrored in the Health Sciences, where practitioners draw on disciplines such as physiology and pharmacology in the context of vastly differing sociotechnical systems (Gorman et al. 2000). These variables suggest that in order to understand 'problem solving' in twenty-first century technology-based practice, a complex systems perspective is necessary. As such, the research design employs a metaphor drawn from the empirical site – that of an integrated modular system. A modular system is one consisting of several sub-systems (combinations of components), which – when integrated effectively – fulfil a specific production purpose. The components of the research system presented in this paper are the problem solver, the internal problem structure (disciplinary basis), the external problem environment and the problem-solving process. Each of these 'components' requires both a different theoretical lens as well as a different set of investigation methods. To this end, the research draws on a range of fields, including the sociology of education, cognitive science and artificial intelligence. The 'production purpose' in this research is to produce 'patterns of problem solving' that help to explain the relationship between science and engineering in real world sites of practice.

It is hoped that the methodology and findings will contribute to a more informed perspective on education for sectors within and beyond engineering, where technologies are profoundly impacting on professional practices. The paper unfolds in three parts. Part one (following the two preceding introductory sections) presents an overview of the research design (systems framework) through which to consider 12 different case studies. Part two demonstrates the application of aspects of the framework to a single case study. Part three presents a number of significant research findings and suggests implications for engineering curriculum and pedagogic redesign better aligned to the requirements of the twenty-first century.

3. Theoretically-informed research design

An example of a contained system in mechatronics engineering is the vending machine, whose primary purpose is the convenient dispensing of products. However, when considered in a particular *context*, the vending machine itself is but a module in an integrated system which has three core processes (each consisting of its own components and sub-systems):

- the dispensing mechanism which is triggered electromechanically or digitally by use of coins, notes and/or keypad instructions;
- the provision of dispensable products, which is determined by the context (school snacks, automated banking, beverages) and physical feasibility;
- the supply-chain process, which includes information management (how many content items are sold over what period of time) and economic decisions regarding costs, maintenance and consumer behaviour, for example.

Each of these core processes has an entirely different focus and disciplinary basis: the machine, the users, and the supplier or owner. Different sciences and practices inform decisions in these different core processes.

Imagine, if you will, that the research problem in this paper has set out to understand how best to analyse the efficacy of the vending machine operation in particular contexts. For our purposes, the work of sociologist, Basil Bernstein (2000), is key to understanding the nature of different disciplines (the *content* of the vending machine); Herbert Simon's (1996) distinction between the inner and outer environments of an artefact – which is key to linking science and human purpose – informs the research design framework (the *context* of the vending machine); and Legitimation Code Theory (Maton 2014) – which provides multiple sets of tools to analyse knowledge practices – is used to interpret actual problem-solving activity in industrial contexts (the dispensing mechanism AND consumer behaviour *processes*). The following three sub-sections detail how these different theorists' work has been adopted in the research.

3.1. Context: the inner and outer elements in problem solving

The polymath, Herbert Simon (1916–2001), is regarded as one of the founding fathers of fields such as decision making, information processing, complex systems, and artificial intelligence, to name a few. Although he realised that 'a global theory of problem solving' (Funke and Frensch 1995, 42) was not possible across different knowledge domains, nor generalisable from the laboratory to the real world, a key contribution was the means to relate science as concerned with *analysis* and human purpose as a process of *synthesis* to 'attain goals' (Simon 1996, 3). Simon differentiated between the *inner* and *outer* environments of a particular artefact or phenomenon. 'The inner system is an organisation of natural phenomena capable of attaining goals in some range of [outer] environments', which, in turn, 'determine the conditions for goal attainment' (Simon 1996, 11). The concept of the inner/outer construction in the problem-solving situation establishes the research design framework.

The base metaphorical 'component' of the research design is *the case study*. Each case study represents a Problem Situation in which a Problem Solver in a particular Problem Environment undertakes a Problem-solving Process in relation to a Problem Site (an artefact) so as to achieve a desired goal. Together (Figure 1), these components represent the case-study Knowledge-Practice Environment (KPE), at the heart of which is the actual Problem Structure characterised by a relationship between mathematics, physics and logic.

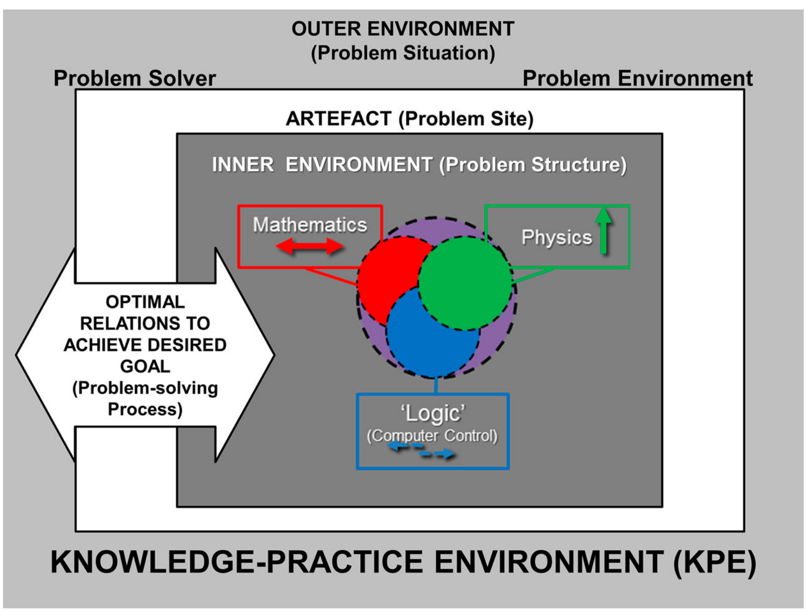


Figure 1. Key features of the problem-solving space within a Knowledge-Practice Environment.

Each of the case study components, in turn, has properties and features informed by research from different fields (which are too extensive to detail here[5]). On their own, each component is essentially a different kind of system, and in order to understand the components in isolation, a necessarily mixed methodology was employed.

Let us consider the KPE components from a theoretical perspective, beginning with the outer environment, the so-called 'problem space' (Lajoie 1993). According to Funke and Frensch's (1995) summary of the literature a key external feature is related to people in the problem-solving context. Cognitive science and psychology highlight the significance of problem-solver experience, cognitive and non-cognitive abilities, such as motivation and concentration. Artificial Intelligence (AI) problem-solving research adds the dimension that 'context' is the relationship between the problem solver and the other entities (agents or objects) in the problem-solving system (Brezillon 1999). The central object in our system, the artefact, is the site of the problem itself. Just as the problem solver has different features, so too the artefact may be as simple as a single 'contained' device (a vending machine, for example) or a sub-system on a manufacturing line. As for the problem-solving process, most of the literature focuses on a conceive-design-implement-operate (CDIO) or similar linear design/process methodologies. One study which attempts to demonstrate the multiple layers and iterative elements in the problem-solving process describes the problem solver as drawing on different cognitive layers: conscious and subconscious (Wang and Chiew 2010). The authors suggest the 'subconscious' entails tangible experience: sensation, memory, perception and action. The 'conscious' layers have to do with meta-cognitive, meta-inference and higher cognitive functions.

Whilst all these factors in investigating engineering problem-solving activity are relevant, one dilemma is that they do not account for the nature and role of disciplinary knowledge. Simon (1996) was the first to concede that the problem-solving process differs significantly across knowledge domains. If the problem-solving process entails understanding and moving between the inner environment of the artefact (science) and the outer environment in which the problem solver exists and problem emerges (engineering and human purpose), then a more refined set of theoretical tools is required, and preferably a set of tools which can apply across the components entailed in the KPEs. This paper introduces such a set of tools, drawn from the sociology of education, in order to contribute to a more informed understanding of the role of the disciplines in enabling ways of thinking in different contexts.

3.2. Classification of boundaries between 'inner and outer' environments

The sociologist, Basil Bernstein, developed a theoretically-informed language of description (Sadovnik 2001) to capture the nature of social structures, the perpetuation of social power relations through principles of communication ('codes') and the differential regulation of forms of consciousness. Power relations create, legitimise and reproduce boundaries between categories (whether they be subject areas, objects, or people) and thus establish relations of order (Bernstein 2000, 5). These boundaries can be described using Bernstein's concept of *classification*, which can be strong or weak. 'Classification' is the *demarcation of boundaries* between entities such that those entities clearly announce their identity – they have distinctive features, names, principles and processes that would not be confused with those of a different entity. When they stand in isolation, clearly separated from other entities, they are said to be strongly classified (C+). Where there are distinct boundaries between specific production processes, for example, with respect to the space allocated to the processes and the role of specific stakeholders, these spaces and stakeholder relations could be termed strongly classified (C+). In contrast, where a process or sets of equipment could be/are set up in any space, the boundaries with regard to space allocation would be weakly classified (C–). Similarly, if there are greater stakeholder relations across functional/departmental boundaries (or these do not exist), stakeholder relations could be said to be weakly classified (C–) as opposed to the strong classification of hierarchical organisational structures with dedicated departments. The same principle could be applied to 'time'. Where processes are run at specific times, or in demarcated cycles or shifts, 'time' could be seen as strongly classified (C+). Where there is greater flexibility with regard to the duration of processes and activities (within a broader 'productivity-orientated' time framework, naturally), time is weakly classified (C–).

Using this theoretical language, three different types of mechatronics engineering working contexts within the scope of the research were analysed and defined. They range from large, visibly structured, continuous process manufacturing environments to small, flexible, project-orientated R&D type businesses. Table 1 presents the classification of three types of mechatronics engineering KPEs. The different classifications have implications for 'goal attainment'. In other words, the outer environment configuration determines conditions with regard to stakeholder relations, reporting lines and procedures, levels of autonomy, forms of written and verbal discourse, and access to the tools and resources required to engage in effective practice.

A second layer in the classification system focuses on the artefact. Mechatronics engineering practitioners work in and in relation to any environment where there are computers controlling machines. The most common environments would be described as manufacturing, materials processing, packaging, production, and automation plants. The nature of work in these environments ranges from the design, manufacture and modification of actual stand-alone, discrete *devices* (contained systems) or the building/ integration of sub-systems into existing automated *systems* (modular systems) to the management and maintenance of production *processes* in undertaken by these systems (distributed systems).

Each of these three systems types can range in scale from small to large. A third classification layer within these systems is the concept of a unit of the physics-mathematics-logic relations (illustrated as a single Venn diagram) which constitutes a 'contained system'. A modular system consists of multiple such units, and a distributed system contains sets of modular systems. Table 2 is a representation of the mechatronics engineering systems categories, depicting the disciplinary 'units', examples of sectors and outer environment classification types.

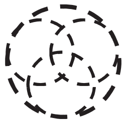
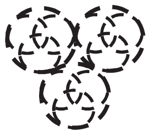
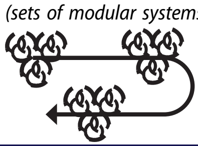
3.3. 'Content': disciplinary knowledge in the 'inner' environment

Let us now turn to the disciplinary 'unit', the inner environment of the problem-solving situation. The principle of classification is extended in Bernstein's work on knowledge structures. There are two kinds of discourses: formal, explicitly structured 'vertical discourse' and context-specific 'everyday' horizontal discourse (Bernstein 2000). Within vertical discourse, which describes educational

Table 1. KPE classification.

Classification	Strong C+	Mixed C+/–	Weak C–
Space	Clearly allocated areas for specific, dedicated equipment/processes; visible boundaries between these areas	Preferred areas for dedicated processes, but changed to accommodate seasonal or cyclical requirements	Activities can effectively take place in any area
Stakeholder relations	Visible organisational hierarchy; clearly defined roles; departmental structure	Clearly defined roles, but periods of 'integrated' team/ project work	No fixed 'departmental structure'; team/project orientated approach to stakeholder relations
Time	Dedicated continuous process cycles; shift-orientated; staff clock-in/out systems	**Batch manufacturing**: dedicated process cycle (differs between batches) **Project work**: specific timelines & phase deadlines, but flexibility within phases	Broad timelines and deadlines established, but discrete phases at discretion of practitioner/ team; Flexible working hours
Examples	(1) Multinational corporations (automotive; steel; mining; beverage) (2) Parastatals (Energy & communications)	(1) Batch manufacturing SMEs (2) Machine builders (3) Systems integrators (SMEs)	(1) R&D prototyping (Micro/Very small) (2) Specialist device development & maintenance (Micro/Very small)

Table 2. Mechatronics systems classification.

System	Examples	Industries	Typical Classification
Contained 	• Microwave oven • Automated medical device • Vending machine • Access control system	• Tech R&D • Prototyping • Component suppliers	**S: C-** **M: $C^{+/-}$** **L: C^{+}**
Modular *(sets of contained-type systems)* 	• Production machine • Production sub-system	• Machine Builders • Machine Suppliers • Systems Integrators • Panel Builders	**S: $C^{+/-}$** **M: $C^{+/-}$** **L: C^{+}**
Distributed *(sets of modular systems)* 	• Production line • Manufacturing plant • Factory	• Manufacturing • Packaging • Food & beverage processing	**S: C^{+}** **M: C^{+}** **L: C^{+}**

knowledge, there are two primary structures which reflect the way in which knowledge has progressed in the field. Hierarchical knowledge structures, represented by the natural and physical sciences, attempt 'to create very general propositions and theories, which integrate knowledge at lower levels' (Bernstein 2000, 161). Hence, we see a 'subsumptive progression' of knowledge over time, where new theories or concepts extend and integrate earlier ones, and are often formulated as 'laws' or formulas. Physics is the key hierarchical knowledge structure in Mechatronics engineering, and one example is Ohm's Law (which has already subsumed several concepts).

In contrast, horizontal knowledge structures 'consist of a series of specialised languages' of the same family (Bernstein 2000, 161). Mathematics is an example. Each of the mathematical languages of algebra, geometry or trigonometry has its own rules. These horizontal knowledge structures are said to be 'strong', demonstrating 'an explicit conceptual syntax capable of relatively precise empirical descriptions' (Bernstein 2000, 163). By way of example, the 'explicit conceptual syntax' in the theorem of Pythagoras ($a^2 + b^2 = c^2$) clearly announces itself as mathematics, and stably identifies the relationship between the lengths of the sides of a right-angled triangle. Working with hierarchical and strong horizontal knowledge structures is fairly straight forward: there are recognisable, established concept chains and procedures.

Horizontal knowledge structures with 'weak grammaticality', such as those of the social sciences, are those where the 'capacity of a theory to stably identify empirical correlates' is weaker (Young and Muller 2007, 188). These are forms of knowledge characterised by proliferation, and redundancy, where there is a borrowing of concepts and methods across types of the same knowledge. This is particularly evident in Information Communication Technologies (ICTs), a 'region' which is at the heart of twenty-first century computer-based engineering practice, and which represents the third key discipline in this research: 'logic'. The implications of such knowledge structures are that those working with such knowledge need to constantly refresh their knowledge base, adapt to new forms, and respond to a different set of organising principles. This is significantly different from the established rules of physics and mathematics (in the field of the applied sciences). So, the question the research posed is:

> What happens when these three significantly different disciplinary structures meet in a problem-solving moment in each of the three different types of industrial and systems contexts?

3.4. Legitimation code theory: analysing relations

Given the nature and range of variables across the problem-solving components, it was necessary to identify an analytical tool that could speak to each of the features. One key analytical tool also emerges from the sociology of education. Legitimation Code Theory (LCT), which extends the concepts of Basil Bernstein, comprises a multi-dimensional conceptual toolkit, where each dimension offers concepts for the 'analysis of organizing principles underlying practices to enable research to determine difference, variation and similarity, and to explore change over time' (Maton 2013, 10). One such dimension focuses on the epistemic nature of knowledge practices: *Epistemic relations* (ER) 'highlights that practices may be specialized by both *what* they relate to and *how* they relate' (Maton 2014, 175). These two aspects are set in relation to each other on a Cartesian plane. The 'what' axis is about the strength of the 'ontic relations', how strongly bounded or legitimately recognised a concept is. The 'how' axis is about the strength of the discursive relations – the procedures or approaches to a phenomenon. In relation to each other, the plane reveals four quadrants which demonstrate different strengths of 'what' and 'how' Figure 2.

Each quadrant represents a specific *insight*, a way of thinking or 'code'. A phenomenon with strong ontic relations and discursive relations requires a *purist insight* (top right). Simply put, this is a phenomenon which all in the field agree is of a certain nature or principle and which has a fixed approach, such as the application of Ohm's Law. When 'how' something is done matters more than the phenomenon, we speak of a *doctrinal insight* (bottom right) – such as the application of mathematical models or the procedural rules governing production processes. *Situational insight* is where the problem situation determines the practice, meaning there are choices in *how* to approach a particular phenomenon, but the focus of the potential solution is strongly bound by a particular idea. An example here is the selection of a control device for a system, where there may be a myriad of choices but the situation will govern a particular selection. The bottom left quadrant is the weakest point of the epistemic relations and is either characterised by an 'anything goes' philosophy (no particular *insight*) or the practice demonstrates a shift away from knowledge and towards a *knower code*.

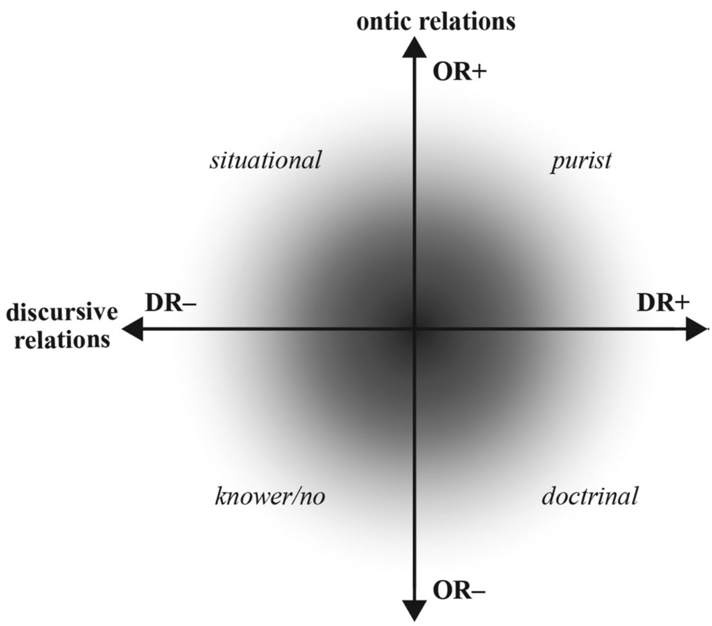


Figure 2. The epistemic plane (Maton 2014, 177).

The Epistemic Plane was used at multiple levels to analyse the problem-solving case studies. In addition to the classification of industry and problem types, the transcribed texts were analysed for indications of predominant *insight* orientation of the outer environment (the company and problem solver) as well as how participants referred to the disciplinary aspects (inner problem structure). It was also the primary tool used to map the problem-solving trajectory of each participant across three stages of the problem solving process: approach, analysis and synthesis. The trajectory arcs were colour-coded to represent the three different disciplines (red – mathematics, green – physics, blue – logic) and other contextual references (purple). In other words, the re-enacted problem-solving description was analysed for references to specific kinds of fundamental disciplinary knowledge as well as *how* the practitioner expressed this knowledge.

4. Sample case study analysis

This section of the paper details an example of the application of the tools of analysis to a case study in the first KPE category (A), that of Contained Systems. An existing automated access control system, designed and installed by a local company, is used by several dozen gated and business communities. Part of the system is a particular custom-made motor, several of which begin to act up after 6 months of operation in the field. Donny[6] is assigned to investigate. His role in the company is one of mechanical and electronics quality management. The investigation reveals that the size of the brushes in the motor are not according to their specifications. The problem, it turns out, is caused by an international manufacturer's decision to cut costs by shaving a mere millimetre off the millions of brushes they produce. These brushes are supplied to the motor manufacturers who, in turn, sell hundreds of thousands of motors around the world – one company being Donny's. As an interim measure, the company replaced (at great cost) the existing brushes with those of a different type of motor, but which 'fit' the brush-holders better. The international suppliers refuted the local investigation findings during an endless spate of 'fiery debates' and convoluted communication.

From the outset, Donny demonstrates a systematic and methodologically structured approach to the investigation (*doctrinal insight*) through four major phases from the non-invasive experimentation and testing to the invasive testing phase. These phases are broken down into 28 distinct steps in his questionnaire text, with numbering up to the third level. During the re-enactment interview, Donny describes the identification of the problem in a rigorous, scientifically analytical and 'principled' manner, beginning with 'sensory' observations. At every step of his explanation, he draws the schematic representation of the motor components alongside the actual motor, and explains the mechanical and electrical aspects with relevant mathematics and physics principles:

> You know the normal set up of this motor … the wires go in, up through the coil and from the coil down into the armature and then the brushes … [which] touch the commutator and then it magnetises the coil. Now you have the two permanent magnets opposing it … so it generates a magnetic field onto the commutator (Donny)

His analysis demonstrates both legitimate procedures in reference to tightly bounded objects, hence a *purist insight*. Solving the problem was an entirely different matter, and required a considerable shift in perspective. Once he had discovered the incorrectly sized brushes:

> I … contacted them and … they claimed their tests showed everything was working fine … Their engineer said it can't be the brushes because the brushes don't influence speed. They sent us lots of beautiful graphs which made no sense at all! (Donny)

It would appear that the local and international engineering practitioners view the 'science' differently. A key illuminating moment during the interview was when Donny was asked if this problem could be seen as a result of 'human error?' 'No', he replied firmly, 'it was a deliberate design change ignoring our specifications'. Despite this statement, the real cause of the problem lay in a decision taken by people, and the subsequent 'argumentative' engagement with those people indicates a distinct *knower* phase in the problem-solving process. The interim solution for this particular situation was to replace the existing brushes with those of a different type of motor, at considerable expense to the company. So, the synthesis phase demonstrates *situational insight* following a *knower insight* phase.

The overall problem-solving trajectory in this case (Figure 3), when mapped onto the Epistemic Plane, demonstrates the basis of practice as shifting across all four *insights*. From the texts and personal profile, it appears the participant is more comfortable articulating the processes that demand stronger discursive relations (DR+), as these are forms of meaning making common to the sciences and their standardised application procedures. Donny is a relatively high achiever in the physics and mathematics domains, and the environment has fixed processes in place, thus also tending towards the right-hand side of the plane. There does not, however, seem to be a particular set of commonly understood 'discursive' practices in place to deal with the different knower perspectives. When working internationally, the first and obvious 'code clash' that may emerge is that of language itself. There are not necessarily common terms for business processes, and much may be 'lost in translation'. Human language closely resembles 'horizontal discourse', which is a 'tacit acquisition of a particular view of cultural realities' (Bernstein 2000, 165), as opposed to 'science' which ostensibly speaks across cultures. In the case study in question, even the ontic relations (OR) with respect to 'science' did not speak across cultures initially, with experts on two different sides of the world disagreeing about the impact of the 'brush size' on the functioning of the motor.

In contrast, Donny's company also has a small R&D lab with significantly different protocols. Staff relations, time and space in the lab are weakly classified, with greater evident flexibility. A second research participant at the company, who works in the R&D lab, is not required to deal with customers or suppliers. He was required to work on the internal control system for the same motor using new control technology, and had fewer standardised methodological procedures on which to draw. As a result, he adopts a predominantly *situational insight* throughout the explanation of the problem and subsequent solution, as is encouraged in this particular context. And then again, a third participant at

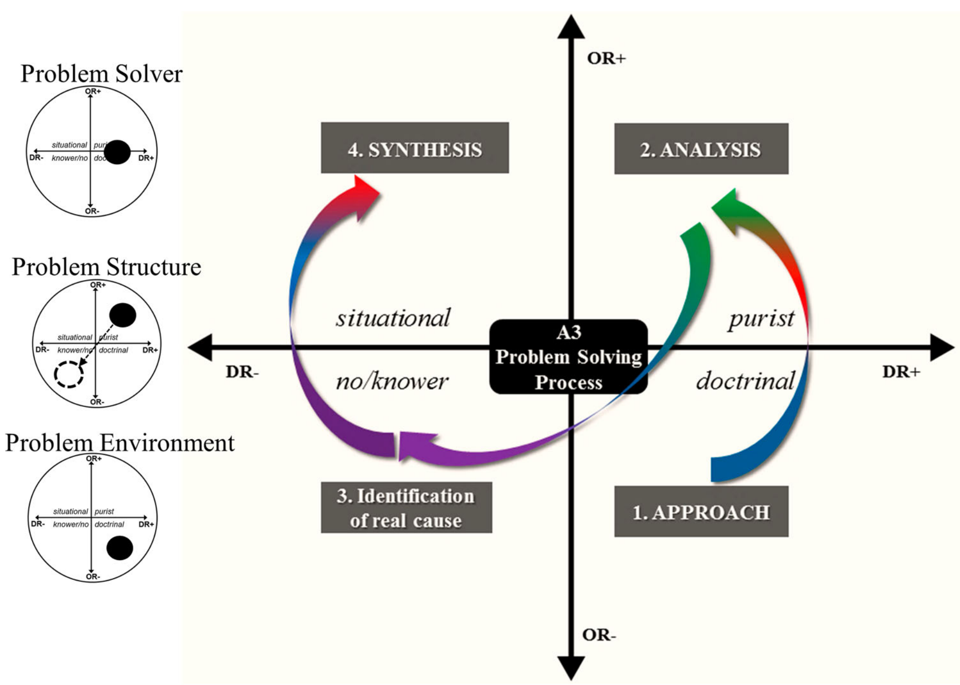


Figure 3. Case study A3 analysis.

a different research site (a large-scale manufacturing company) faced a very similar problem to Donny's (supplier error), but was so bound by a rigid (document-driven) problem-solving methodology that he did not trust his own initial sensory observation. It took three days following protocol to reach a conclusion which was staring at him from the outset.

5. Significant problem-solving research findings

The case study analysis presented in the preceding section is one of now 41 case studies across engineering sectors employing the same methodology. Figure 4 presents a graphic summary of the original 12 mechatronics engineering problem-solving maps across the three KPEs.

What may be evident at first glance is two key pattern 'types':

- KPE A and C: A potentially archetypal macro-to-micro clockwise cycle through all *insights* starting in the *doctrinal* quadrant.
- KPE B: The iterative, diagonal shifting between diametrically opposed *insights*.

As a general rule, the different practice environments (KPE categories) are characterised by the difference between greater allegiance to phenomena or methods, with smaller companies tending towards the former, and larger companies towards the latter. This manifests as environments requiring practices based on *situational insights* and *doctrinal insights* respectively. These *insight* orientations are diametrically opposed, and represent the two environments in which systems integrating practitioners (the core role of a mechatronics graduate) are required to work *simultaneously*. In other words, the different environments characterising the field regard as legitimate two significantly different approaches to problem solving. Practitioners based in one environment and who service the other are required to navigate between two opposing *insights*.

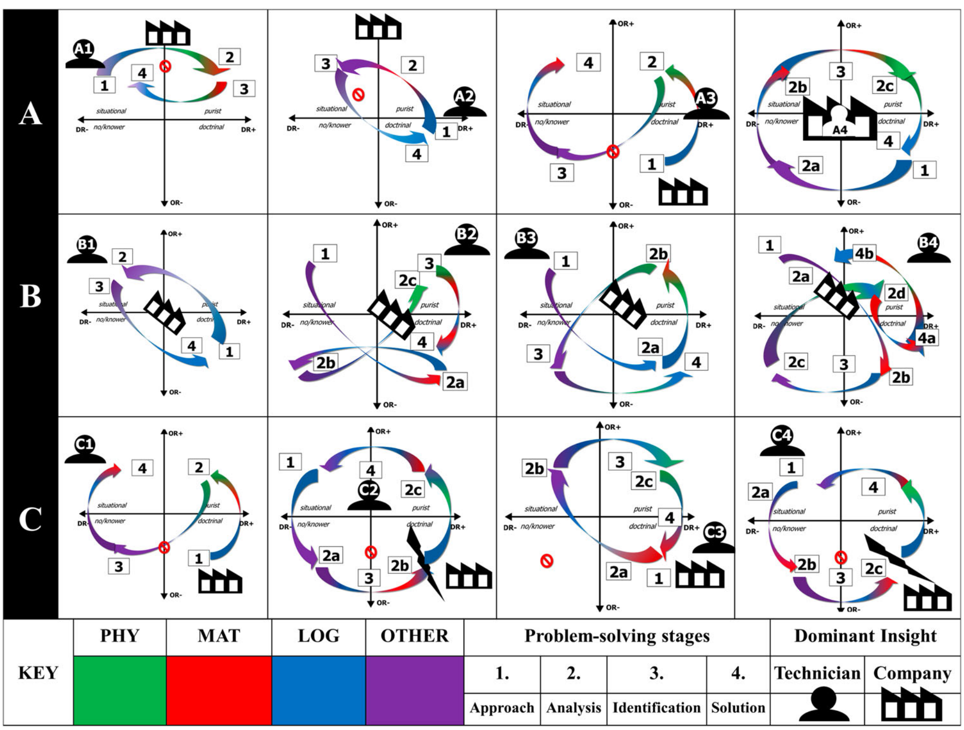


Figure 4. Summary of problem-solving case study maps.

A problem-solver pattern which emerged across all contexts is the relationship between high mathematics *and* logic-based academic achievement, articulative capacity, and fuller problem-solving cycles and descriptions. Such practitioners were most successful in recognising the legitimate *basis* of practice at all stages of the problem-solving process. In other words, they recognised different ways of thinking at different stages. Problem solvers with low achievement in mathematics and high achievement in logic (which represents the norm on the originating qualification) displayed a distinct preference for *situational insight* and this revealed code-shifting challenges. In other words, these practitioners often found it difficult to work in highly *doctrinal* environments.

Further findings show that the smaller the environment, the more likely the problem-solving process is dictated by practitioner preferences in response to their perception of the problem structure, whereas in larger environments, the process is dictated by methods regarded as legitimate in that environment. In the latter case, if a practitioner has an opposite orientation, he/she finds the process challenging. The problem structures all entailed a relationship between physics, mathematics and logic. The problem-solving process requires recognising the fundamental disciplines and their interrelationship in the physical system. The successful problem-solving practitioner navigates these disciplines – in no particular order – through a conscious shifting between different realisations of both the allegiance to phenomena and the legitimate ways of approaching those phenomena. Simply put, the practitioner changes his/her way of thinking and acting depending on the particular phenomenon in focus at a particular moment during the problem-solving process. The practitioner shifts between different *insights* ('codes') in relation to the disciplines suggested by the problem structure in context.

6. Implications for engineering education

The implications of the research findings, briefly, suggest three key recommendations 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 fundamental engineering disciplines enable the development of significantly different ways of thinking and meaning-making.
- The acknowledgement that engineering education cannot (and should not) hope to simulate all possible real-world problem contexts. Students may be far better served through the development of a more conceptual grasp of complex problem-solving environments.

The issue is not that there are different kinds of knowledge and practices in engineering (one look at both the competency criteria and the traditional silo curriculum pays testimony to this fact). On the contrary, the issue is the evidence that engineering practitioners are found wanting in the ability to apply this knowledge (Griesel and Parker 2009) – and 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 not explicit in the curriculum. Opportunities to enable code-shifting are provided in 'project-based' subjects or capstone courses, for example, but there is no explicit induction into what is required to be able to recognise and realise the different forms of code in a single problem-solving moment. The use of relatively linear methodologies, such as the CDIO process, may not necessarily sufficiently capture the idea that there are different conceptual and contextual 'codes' implied at each of the key conceive-design-implement-operate stages, and that grasping the 'codes' requires iterative practice from different perspectives. And herein lies our first challenge as engineering educators: making the codes explicit. However, this task requires an understanding and appreciation of the different 'codes'.

With regard to 'real world' contexts, I suggest our role is to step out of contexts and understand them from a more conceptual perspective. Here is an ideal opportunity to make explicit the difference *and* relationship between *theory and practice*. The relation between an abstract formulation of different kinds of problems in types of 'messy' contexts and the empirical actualisation of that formulation represents the 'space of possibles' (Maton 2014). It is the duty of engineering education to enable access to this space if our graduates are to cope in what will become even more complex sociotechnical practice environments. Practically, issuing the same project brief to different students (or groups) with different sets of constraints and affordances situated in different contexts may afford students the opportunity to understand the implications of context.

7. Concluding comments

The paper has set out to demonstrate a complex systems approach to understanding the problem-solving process entailed in mechatronics engineering practice, so as to be able to inform engineering curriculum reform. A methodologically pluralist research strategy was applied to categorise different mechatronics engineering contexts, both with respect to system type and industrial scale. 12 case studies were identified across three Knowledge-Practice Environments, and the analysis of each determined particular kinds of patterns in the different environments. The patterns suggest that despite the common disciplinary basis, the *insights* preferred by the environment and problem solver in each case study impact on the problem-solving process. Essentially, successfully solving a complex engineering problem requires code-shifting behaviour, and it is this aspect that is not explicitly introduced or developed in current engineering curricula. The second observation is that the most challenging 'boundary crossing' occurs in relation to the horizontal, discursive relations axis. Practically speaking, when the 'how' is standardised and familiar, practitioners are comfortable in their approach to and analysis of problems, and synthesis of solutions. The dilemma is that in dynamic, technology-based fields, the '*how*' is becoming increasingly unfamiliar, both with regard to new technologies and global interactions. Our curricula, I suggest, may not sufficiently introduce the range of weaker discursive practices – in the context of both knowledge and knowers – required in real world engineering problem situations. This may well be an opportunity for engineering educators to rethink the approach to standardised 'project work' methodologies, as well as ways in which to acknowledge the implications of different kinds of knowers in engineering problem contexts.

Notes

1. The study of (deductive) 'inferences that depend on concepts that are expressed by the 'logical constants' such as *and, not, or, if … then*' (Britannica Concise Encyclopaedia, 2006) and which discipline underpins 'logic programming' – 'The study or implementation of computer programs capable of discovering or checking proofs of formal expressions or segments' (www.dictionary.reference.com).
2. Both technicians and technologists from the same originating qualification (one of only two in the country)– the Diploma in Mechatronics Engineering at a regional University of Technology. The term 'practitioner' is used for both professionals. All practitioners in the study are working as either technologists or engineers, irrespective of their formal qualification.
3. The study has subsequently expanded across all engineering sectors and consists of 41 detailed case studies.
4. For a detailed explication on the methodology with sample texts see: Wolff 2018a.
5. For further insights into the data analysis methodology, see: Wolff 2017. Wolff 2018b.
6. Pseudonym.

Acknowledgements

This work was supported by the South African National Research Foundation.

Disclosure statement

No potential conflict of interest was reported by the author.

Funding

This work was supported by the National Research Foundation (South Africa) under Grant # 95324.

Notes on contributor

Karin Wolff has been in education for over two decades, and in engineering education since 2008. She has worked as a lecturer, curriculum specialist, and in staff development at four South African universities. Her doctoral research (University of Cape Town) looked at complex engineering problem solving. She is currently continuing this research across engineering sectors as a Research Fellow in the Work-Integrated Learning Research Unit (Cape Peninsula University of Technology).

References

Ahmed, Nazeema, Bruce Kloot, and Brandon I Collier-Reed. 2015. "Why Students Leave Engineering and Built Environment Programmes When they are Academically Eligible to Continue." *European Journal of Engineering Education* 40 (2): 128–144.

Andersson, Staffan, Jannika Andersson Chronholm, and Birgitta Gelin. 2011. "Student Retention in Engineering Education - Examples of how it Looks and what can be Done." *Utvecklingskonferensen för Sveriges Ingenjörsutbildningar*, 53–57. Accessed June 1, 2012. http://www.ep.liu.se/ecp/075/011/ecp12075011.pdf.

Atman, Cynthia, and Karen Bursic. 1998. "Verbal Protocol Analysis as a Method to Document Student Design Processes." *Journal of Engineering Education* 87 (2): 121–132.

Bernold, Leonhard, Joni Spurlin, and Chris Anson. 2007. "Understanding our Students: a Longitudinal Study of Success and Failure in Engineering with Implications for Increased Retention." *Journal of Engineering Education* 96 (3): 263–274. Accessed June 17, 2012. http://www.jee.org/2007/july/2.pdf.

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

Brezillon, Patrick. 1999. "Context in Problem Solving: A Survey." *The Knowledge Engineering Review* 14 (01): 47–80.

CHE. 2013. *A Proposal for Undergraduate Curriculum Reform in South Africa*. Pretoria: Council on Higher Education.

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

Felder, Richard. 2012. "Engineering Education: A Tale of Two Paradigms." In *Shaking the Foundations of Geo-Engineering Education*, edited by B. McCabe, M. Pantazidou, and D. Phillips, 9–14. Leiden: CRC Press. Accessed June 17, 2012. http://www4.ncsu.edu/unity/lockers/users/f/felder/public/Papers/TwoParadigms.pdf.

Funke, Joachim, and Peter Frensch. 1995. "Complex Problem Solving Research in North America and Europe: An Integrative Review." *Foreign Psychology* 5: 42–47.

Gorman, Paul, Andreas Meier, Chantal Rawn, and Thomas Krummel. 2000. "The Future of Medical Education is no Longer Blood and Guts, it is Bits and Bytes." *The American Journal of Surgery* 180 (5): 353–356.

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

IEA. 2013. *Graduate Attributes and Professional Competency Profiles*. International Engineering Alliance. http://www.ieagreements.org.

Jackson, Shirley. 2007. "Waking up to the 'Quiet Crisis' in the USA." *College Board Review*. Winter/Spring. Accessed April 1, 2013. www.rpi.edu/homepage/quietcrisis/CBReview.

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

Lajoie, Susanne. 1993. "Computer Environments as Cognitive Tools for Enhancing Learning." In *Computers as Cognitive Tools*, edited by Susanne Lajoie, and Sharon Derry, 261–288. New Jersey: Lawrence Erlbaum Associates, Inc.

manpowergroup.com. 2015. *Talent Shortage Survey*. USA: The Manpower Group.

Maton, Karl. 2013. "Making Semantic Waves: A key to Cumulative Knowledge-Building." *Linguistics and Education* 24: 8–22.

Maton, Karl. 2014. *Knowledge and Knowers: Towards a Realist Sociology of Education*. London and New York: Routledge.

Maton, Karl, and Rob Moore. 2010. *Social Realism, Knowledge and the Sociology of Education: Coalitions of the Mind*. Edited by Maton, K and Moore, R. London: Continuum.

NPC. 2011. *National Development Plan Vision 2030*. Pretoria: National Planning Commission.

Sadovnik, Alan. 2001. "Basil Bernstein (1924–2000)." *Prospects: the Quarterly Review of Comparative Education* (UNESCO: International Bureau of Education) XXXI (4): 687–703.

Simon, Herbert. 1996. *The Sciences of the Artificial*. 3rd ed. Cambridge, MA: The MIT Press.

Sobek, Durward K. 2004. "The engineering problem-solving process: good for students?" *American Society for Engineering Education*. ASEE.

UNESCO. 2010. *Engineering: Issues, Challenges and Opportunities for Development*. Paris: UNESCO Publishing.

Vogt, Christina M. 2008. "Faculty as a Critical Juncture in Student Retention and Performance in Engineering Programs." *Journal of Engineering Education* 97 (1): 27–36. Accessed June 23, 2012. http://www.jee.org/2008/january/5.pdf.

Wang, Yingxu, and Vincent Chiew. 2010. "On the Cognitive Process of Human Problem Solving." *Cognitive Systems Research* 11: 81–92.

Wheelahan, Leesa. 2007. "How Competency-Based Training Locks the Working Class out of Powerful Knowledge: a Modified Bernsteinian Analysis." *British Journal of Sociology of Education* 28 (5): 637–651.

Wolff, Karin. 2017. "Engineering Problem-Solving Knowledge: The Impact of Context." *Journal of Education and Work*. doi:10.1080/13639080.2017.1380299.

Wolff, Karin. 2018a. "A Language for the Analysis of Disciplinary Boundary Crossing: Insights from Engineering Problem-Solving Practice." *Teaching in Higher Education* 23 (1): 104–119. doi:10.1080/13562517.2017.1359155.

Wolff, Karin. 2018b. "Theory and Practice in the 21st Century Engineering Workplace." In *Knowledge Curriculum & Preparation for Work*, edited by Stephanie Allais, and Yael Shalem, 182–205. London: Sense Publishers.

Young, Michael, and Johan Muller. 2007. "Truth and Truthfulness in the Sociology of Education." *Theory and Research in Education* (SAGE Publications) 5 (2): 173–201.

Young, Michael, and Johan Muller. 2010. "Three Educational Scenarios for the Future: Lessons From the Sociology of Knowledge." *European Journal of Education* 45 (1): 11–27.