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The conceptual nuances of technology-supported learning in engineering

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ABSTRACT
Enabling theory-practice bridging in engineering education is essential for developing twenty-first century graduate capabilities. Massification, resource constraints, and technological development have resulted in significant shifts to alternative forms of practical engagement, such as the use of online laboratories, but how do these contribute to learning? Based on three illustrative case studies at a research-intensive institution in the Global South, this paper offers a conceptualisation of the degrees of complexity entailed in multimodal approaches to teaching Fluid Mechanics, Finite Element Analysis and Control Systems at different stages of their respective programmes The paper examines the different levels of abstract-concrete learning when students engage with verbal, symbolic, graphic and physical representational artefacts designed to enable cumulative learning. The conceptual instruments are theoretically and methodologically drawn from Legitimation Code Theory dimensions, which lend themselves to the graphic analysis of knowledge practices. It is suggested that the explicit integration of and shifting between levels of abstraction and complexity with different kinds of technologies enables the kind of cumulative learning necessary to prepare technically-equipped graduates for complex twenty-first century engineering contexts.

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Engineering practicals; legitimation code theory; cumulative learning; technology-supported learning

1. Introduction

The International Engineering Alliance (IEA) defines engineering as 'an activity that seeks to meet identified needs of people and societies by the purposeful application of engineering sciences, technology and techniques to achieve predicted solutions that use available resources efficiently' (2013). The IEA competency profiles attempt to capture the requirements of twenty-first century engineering education, and as such, curricula and pedagogies aligned to international standards have seen significant redesign to facilitate the development of holistic graduates. Despite these well-intentioned educational initiatives, global industries continue to lament graduate lack of the essential 'soft' and technical skills (QS Intelligence Unit 2018). However, not only have the socio-technical contexts of engineering activities become increasingly complex, but the implied engineering technologies have proliferated exponentially with each Industrial Revolution iteration. The rapid development in technology requires universities to continually re-evaluate curricula, teaching practices and administrative systems.

The role of practical, applied work and access to appropriate tools and technologies are not only well established in engineering education, but have become increasingly important to meet

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employability demands (Winberg et al. 2020), particularly in environments without established industrial links or apprenticeship models. In the emerging markets and developing economies (EMDE) context, resource availability and associated expertise pose significant challenges to the education and development of engineering graduates required to contribute effectively to socio-economic growth (Schwartzman, Pinheiro, and Pillay 2015). Even well-resourced engineering institutions run the risk of teaching for redundancy, given the fact that 'nearly 50% of subject knowledge acquired during the first year of a four-year technical degree [will be] outdated by the time students graduate' (WEF 2018). So, the question for EMDEs may well be not what technologies or applied/practical work should universities teach engineering students, but – given significant resource constraints and dynamic technological evolution – *how* and *to what end*? Some concepts lends themselves well to integration with higher order technologies, while others may still more appropriately be experienced through physical engagement.

In an effort to maximise opportunities for the application of theory in practice, engineering educators world over have increasingly begun to harness the affordances of technologies. Virtual laboratories – variously termed online, web, distributed, remote or distance labs (https://www.igi-global.com/dictionary/virtual-lab/) – have been employed in education for over two decades, initially in the Physical and Biological Sciences (Faulconer and Gruss 2018). Although an emerging body of literature describes the benefits of the different modes of virtual learning in terms of accessibility, the extension of classroom theory and the development of 'procedural knowledge' (Lynch and Ghergulescu 2017), the predominant themes are systemic and affective in nature (Kruger, Wolff, and Cairncross 2021): in other words, concerning infrastructure, student outcomes and student satisfaction. There is little if any problematisation of the nature of forms of 'procedural knowledge' and the concomitant cognitive processes involved in virtual or online practical learning using different kinds of technologies and platforms.

The global COVID-19 pandemic – which forced an overnight shift to Emergency Remote Teaching (ERT) (Hodges et al. 2020) – saw engineering students world over deprived of access to their physical laboratories, and engineering educators hastily designing 'remote' practicals and 'at home projects'. While there has been much hype around the long-awaited irrevocable adoption of technology in education (Wolff 2020), an international report cites key challenges for EMDEs as being 'access to technical infrastructure, infrastructure, competences and pedagogies for distance learning' (IAU 2020). Secondly, anecdotal evidence of low self-regulated learning strategies and reportedly low digital fluency (Czerniewicz et al. 2020) indicate that students experience significant frustrations in navigating the 'digital world' remotely. The reported 'digital fluency' and 'digital divide' challenges in the Global South and EMDE contexts have implications for the achievement of global Sustainable Development Goals, given the dependence of the Global North on agricultural, mineral and labour resources from these regions (Gonzalez 2015). The sourcing, production and processing of these resources are increasingly adopting dynamic 4th Industrial Revolution technologies and approaches. It is, therefore, vital that engineering educators in the Global South enable training regimes and graduate capacity building that facilitate longer term economic viability. The role of an engineer in any context is to navigate complexity and steer towards practicality (Trevelyan 2014). The ERT era, while presenting traditionally contact-based engineering educators and students alike with considerable obstacles (particularly in the large-class, resource-constrained EMDE context), also presents the opportunity to interrogate *what kind of learning should/could be happening to bridge the theory-practice divide when using different kinds of technology*.

This paper discusses an approach to multimodal applied, practical engagement across a range of engineering courses at a traditional research-intensive institution in South Africa. Using a theoretically-informed analytical instrument from the Sociology of Education – namely, the Legitimation Code Theory (LCT) dimension of Semantics (Maton 2014) – the paper presents a graphic interpretation of levels of complexity in relation to modes of teaching designed to bridge the theory-practice divide across different engineering disciplinary areas. Drawing on lecturer course design, impact observations, qualitative student feedback, as well as performance data, the paper provides a nuanced understanding of *what* and *how* students may be cumulatively building knowledge through scaffolded, technology-supported forms of engagement, including physical and online tools. The use of the LCT semantic plane across empirical contexts is intended to raise awareness among engineering educators of implied levels of complexity when students engage with different forms of practical and online technologies both in different disciplinary areas (at different stages of the academic programme) and in synthesis, such as in design or Capstone projects. Furthermore, it is hoped that the demonstration of the application of the analytical instruments can contribute to the improved design of online and technology-dependent learning experiences both in and beyond engineering.

2. Research context

This study is located in the engineering faculty of a research-intensive public higher education institution in South Africa. The faculty has around 4000 students, and recruits roughly 750 new students each year for its six Bachelor's programmes. Large classes are the norm, with lecturers commonly teaching groups of 250 students in a cohort of 500–900, depending on the academic programme year. Students' workload follows a relatively standardised lecture-tutorial-practical ratio of 7:3:1. Final module outcomes are based on semester work, and two main assessments, with an additional assessment available for students who narrowly do not meet the passing grade. The faculty boasts an emerging scholarly Community-of-Practice supported by a national University Capacity Development Grant, which includes funding for a formal Recommended Engineering Education Practices (REEP) project, with the associated ethics protocols. REEP initiatives are implemented by faculty academics, supported by an Academic Development practitioner, and a core group – representing all departments – are recognised as REEP champions. One of the REEP focal areas is the judicious use of resources to better bridge the theory-practice divide in engineering education.

Three REEP projects located across the physics, mathematics and programming disciplinary domains in engineering sciences have been selected for this paper: A 2nd-year Fluid Mechanics course in Process Engineering, a 3rd-year Finite Element Methods course in Civil Engineering, and a 4th-year Control Systems course in Mechanical and Mechatronics Engineering. All three courses have been the focus of curricular redesign and innovative pedagogical strategies over the past 5 years, and are regarded as case studies in their own right, with a number of formal research outputs (Pott, Wolff, and Goosen 2017; Pott and Wolff 2019; Kruger, Wolff, and Cairncross 2021). The three selected courses represent elements of the core disciplinary anchors in engineering science education, and have progressively integrated engagement with different kinds of software both in the face-to-face and online environments. Each course has revealed a particular challenge over the years, which, in turn, has led to the observation that students struggle to grasp particular concepts, or effectively use the appropriate analytical and practical tools (such as mathematics, software and equipment). These challenges have been exacerbated during the ERT period and required innovative strategies from educators in enabling students to engage effectively in the required applications. Drawing on these three case studies, the paper presents and analyses approaches to learning that are intended to enable the bridging of theory to practice through technology-supported application in different disciplinary domains.

3. Theoretically-informed research design

3.1. Legitimation code theory

Legitimation Code Theory (LCT) (Maton 2014) has in recent years contributed significantly to the analysis and understanding of engineering knowledge practices. LCT is a framework consisting of multiple dimensions which aid in the design, analysis and review of knowledge practices. The key idea behind LCT is the notion of what constitutes 'legitimate' practice? LCT has rapidly gained traction in educational fields as a means to making the 'hidden curriculum' explicit; a means to enable students to access the 'rules of the game'. The LCT dimension of Specialisation, for example, has aided in differentiating between the *knowledge* and *knower* aspects of engineering curricula (Winberg 2012), where the latter is often overlooked in STEM education, and yet are embedded in Graduate Competency Profiles (IEA 2013) through attributes such as ethics, professionalism and teamwork, for example. Using LCT instruments has helped lecturers to design holistic curricula which take the development of engineering attributes into account (Quinn 2019).

This paper draws on the dimension of Semantics to differentiate between forms of knowledge and associated learning entailed in three different engineering science courses. Each course represents a significantly different kind of knowledge structure, which implies different forms of learning and application (Bernstein 2000). The natural sciences (such as physics) build cumulatively in a relatively hierarchical fashion, with each new concept subsuming preceding concepts. Learning, here, is sequential, and preceding concepts need to be grasped in order to cope with increasing complexity. Mathematical sciences have what is termed a 'strong' horizontal knowledge structure in that each mathematical language has its own particular features which are acquired in a similar sequential, cumulative manner to the natural sciences, but there are multiple forms of mathematics – each of which could be applied to the same problem (in different ways). In this case, learning should not be restricted to one-method-only approaches. Students are best served by applying different approaches (and mathematical languages) to the same problem. The third structural form is a 'weak' horizontal knowledge structure. This is a form of knowledge that has a multitude of variants, borrowing from other knowledge families, and where one sees redundancy and obsolescence. Human languages are an example of this structure, as are programming and control systems 'languages'. Learning these three different disciplinary forms of knowledge requires different applications of time and different forms of representation and practice. Together they constitute the basis of complex engineering problem solving (Wolff 2018) which requires practitioners to 'code-shift' (Maton 2014) between different ways of thinking.

The LCT Semantics dimension can help us to see some of the different features of these forms of knowledge. A *semantic range* is one which can describe the degrees of context-dependency of knowledge: from the physical object to the abstract conceptual idea. Strong semantic gravity (SG +) [such as a concrete object bound by its context] and weak semantic gravity (SG-) [such as the abstract articulation of a concept, which transcends 'context'] represent the two poles of a semantic gravity continuum. The poles on the continuum are probably intuitive to many engineering educators who use practical examples to illustrate a particular concept. However, it is not sufficient to merely provide a practical example of an abstract concept. This is known as a downward escalator – where the shift is always from abstract to concrete and stops there, simply moving on to the next abstract concept (Maton 2014). It is necessary to move, iteratively, between concepts and contexts of application in such a way as to enable 'cumulative knowledge-building' (Maton 2013), which is the process of 'connecting the dots', as it were, between *why*, *what* and *how* – this movement (or 'semantic waving') builds both knowledge explicitly, and intuition implicitly.

Determining a semantic range enables the description of stages between the abstract-concrete poles. A number of engineering studies draw on the LCT semantic range to enable educators to more explicitly teach different levels of abstraction (Auret and Wolff 2017; Pott, Wolff, and Goosen 2017; Dorfling, Wolff, and Akdogan 2019; Pott and Wolff 2019). Each of these levels requires different forms of representation, different mathematical and/or computational tools and different mediating artefacts (Wolff 2020). A useful additional analytical instrument, here, is the differentiation between graphical, symbolic and verbal meaning-making systems (Rahmawati, Hidayanto, and Anwar 2017). Each of these forms of representation may differ in the level of abstraction.

Table 1 presents a sample of faculty case studies using the semantic range to differentiate between five levels of meaning across different engineering sub-disciplines: from the weakest semantic gravity (SG-) of the principle (or concept) to the formulaic, representational and model

Table 1. Faculty semantic range case studies.

Semantic range		Engineering case study examples		
Levels of meaning		Civil Engineering	Mechanical Engineering	Process Engineering
Weak semantic gravity (Abstract/ Theoretical)	Principle	Structural forces determining bracing	Principle of projection	Conservation of mass & energy
	Formula & Calculations	C_r=∅Af_y (1+λ^2n)^(−1/n)	First and third angle projection	Mathematical expressions of process control
Strong semantic gravity (Context-bound; Concrete/Practical)	Representation	Technical schematic drawings	Orthographic drawing showing different views of an object	Block diagram schematic of process control
	Model	3D/simulations of structural behaviour	CAD model of the object (orthographic views derived from the model)	Software simulation system
	Real	Physical structure (real building)	Physical object	Physical process control systems

levels – which progressively strengthen in semantic gravity – and ending with the strongest level of semantic gravity represented by the ‘real’ or physical object in context (SG+). Although presented in verbal or symbolic form, one can deduce that a number of the levels can be graphically represented, with both the civil and mechanical engineering examples drawing heavily on graphical, schematic representations of technical drawings.

These examples of different levels in a semantic range have enabled the academics to structure course material engagement that explicitly and iteratively shifts students through the levels. The final column in the table refers to a particular study on which this paper draws: a Process Engineering course in the faculty’s Chemical Engineering department (Auret and Wolff 2017). The authors note that students managed the formulaic and representational work entailed in calculating mass and energy balances using Matlab, but struggled to make the transition to the simulated model in Simulink. Similarly, Magana et al. (2017, 367) report student difficulties in ‘implementing algorithmic representation in Matlab’ in a modelling and simulation course, as a result of an inability to see the connection between the overall goal of the algorithm and the underlying disciplinary concepts. Initial attempts to enable more explicit visualisation saw the authors experimenting with ‘transparency’ through two forms of scaffolding: soft scaffolding is immediate peer/instructor feedback, and ‘hard scaffolding’ is coded into the simulation learning environment (Magana, Vasileska, and Ahmed 2011). While in their 2017 paper Magana and colleagues manage to make transparent the three underlying disciplines (physics, mathematics and programming), and tailor their simulation teaching strategy accordingly, we believe the use of an analytical instrument such as LCT Semantics can help to address the issue of transparency even further. In our case study context, the process control findings highlight a potential limitation of merely using ‘context-dependency’ as a defining characteristic of enabling cumulative learning. The shift from paper-based calculations to constructing a block diagram or physically pumping water up a tube or running a simulation represent a significant shift in complexity. This shift in complexity in the natural sciences mimics the hierarchical knowledge structure itself: as each new concept absorbs the preceding concepts in the subsumptive chain (for example, the concept of force subsumes the concepts of mass and acceleration, the latter having subsumed the concepts of space and velocity), the new concept becomes ‘conceptually denser’ in meaning. However, complexity in the mathematical sciences differs in that it is not the concept that subsumes others, rather it is the range of possible mathematical approaches that expands. In other words, mathematics represents methodological density. The selected case studies offer an opportunity to conduct a more nuanced analysis of the nature of this complexity, using a different analytical instrument from the LCT Semantics ‘toolbox’ (Maton 2014).

3.2. Using the semantic plane as analytical instrument

The semantic plane (Maton 2014) enables the visualisation of knowledge practices on a Cartesian plane, demonstrating the relations between abstract-concrete (semantic gravity: SG) manifestations and simple–complex meanings (semantic density: SD). Although the +/− denotation of the vertical SG axis on the plane is mathematically inverted and counterintuitive to engineers (Figure 1), it is helpful to see this as a shift away from the concrete (SG+) (on the ground, as it were) to the abstract (SG-) (in the air). The semantic plane effectively identifies four distinct quadrants which may help an educator to build the learning experience, starting at the bottom left and moving in a clockwise direction: concrete examples with simple meanings (SG+, SD-); abstract concepts with simple meanings (SG-, SD-); abstract concepts with complex meanings (SG-, SD+); and finally, concrete examples with complex meanings (SG+, SD+). This sequence is not presented as a recommendation, rather, the intention is to highlight the different characteristics of the different quadrants, and to enable lecturers to 'see' the differences (Maton 2014).

The semantic plane has been used in numerous studies, including the differentiation between types of HE curricula (Shay 2012) and the nature of engineering project work (Winberg et al. 2016). A study conducted by Blackie (2014) operationalised the semantic plane to demonstrate the combination of context-dependency (semantic gravity) and levels of complexity (semantic density) in teaching chemistry concepts (Figure 1). This paper takes the Blackie conceptualisation into the engineering domain.

3.3. Methodology

The semantic plane enables the relative location and scope of each of the instructional modes entailed in enabling students to apply their theory in practice in the context of three selected case studies at different stages of the academic programme: 2nd-year Fluid Mechanics, 3rd-year Finite Element Analysis/Methods and 4th-year Control Systems. Although each of these courses is located in a different engineering qualification, it is possible to envisage the potential of cumulative knowledge-building through application across years of study in each of the relevant qualifications.

The lecturers on each of the case study courses had identified various student learning challenges as early as 2016. As part of the faculty REEP initiatives, and under the umbrella of faculty-wide impact evaluation ethics clearance, various interventions had been trialled and analysed in each of the courses. Methodologically, a design-based research (DBR) approach is adopted, which sees an iterative,

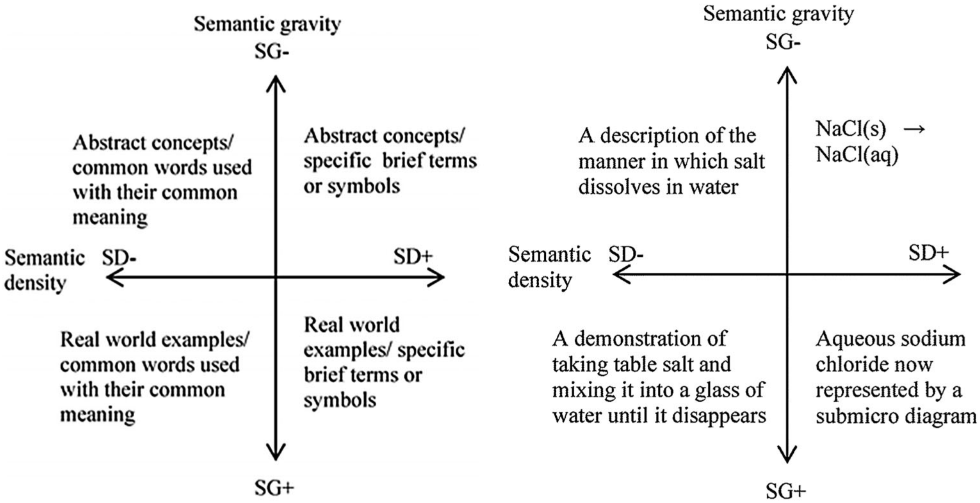

Figure 1. Semantic plane analysis of Chemistry teaching (Blackie 2014).

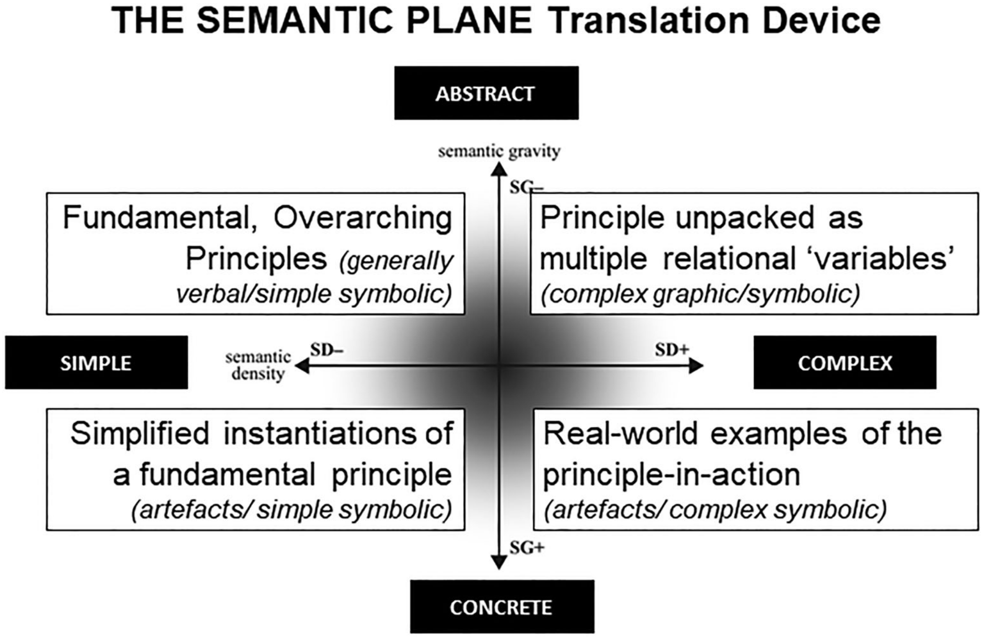

Figure 2. Semantic plane case-study translation device.

theory-informed design-implement-review process for the explicit purpose of 'understanding the relationships among theory, designed artefacts, and practice' (Design-Based Research Collective 2003). In other words, DBR as a methodological approach for the educators reflects the empirical focus of the paper: enabling students to bridge the theory-practice divide through application. Furthermore, the faculty's Community-of-Practice (Lave and Wenger 1991) approach sees ongoing, collaborative, professional development, and the regular sharing of practices through contact-based and online forums, as well as formal dissemination through publication. Concerns around improving technology-supported teaching in a resource-constrained national context, particularly during ERT, saw a group of REEP champions forming a collaborative group to interrogate teaching and learning practices in the respective case-study courses. The specific focus of the group is to understand and improve integrated problem-solving (IPS) processes in their respective contexts, particularly in relation to supporting learning through the use of online simulation platforms, virtual models and physical technologies.

Drawing on both quantitative and qualitative evidence of student performance and course feedback, the IPS group posed the following question: *What kind of learning could/should happen when using different kinds of technology to bridge the theory-practice divide in different engineering knowledge areas?* Working collaboratively, and drawing on the principles of sociocultural mediated learning (Kozulin 2002), the group reflected on their previous and current practices in their respective courses, and collectively analysed the nature of learning in their contexts using the semantic plane as a 'translation device' (Figure 2). The following sections describe and analyse each of the case studies in relation to the particular concepts and forms of technology-supported application as implemented at different stages in the respective courses.

4. Semantic plane case studies

4.1. Fluid mechanics – linking theory to the real world

4.1.1. Context

Fluid mechanics forms a key portion of the second-year curriculum in chemical engineering (and often mechanical engineering as well). It includes fundamental analysis of the physics of fluid flow, ranging from derivation of Navier-Stokes solutions, to simplified empirical relations for pressure drop. The course therefore presents a challenge to students, both in terms of (i) the mathematical complexity of working with Navier-Stokes equations, (ii) the heuristic approach of using empirical relations, and (iii) how these differing mathematical approaches relate to the actual physical settings (pipes, pumps, and valves). The link between mathematical representation, and physical reality is an important one in the context of this course, with students needing to master complex mathematical and graphical representations, as well as the physical manifestations of the principles of fluid mechanics in the form of real pump and piping networks.

4.1.2. Challenge

Students struggle with the content of the course at several levels. In the first instance, working with and manipulating the mathematics of the Navier-Stokes equations requires students to pull knowledge from other courses (pure and applied mathematics) and bring those skills to bear on a context specific embodiment. Beyond the difficulty in manipulating the mathematics, students in particular battle to link the mathematical representations with what they represent – the flow of fluids. This link between representation and physicality is key in fluid mechanics, and forms the basis for intuition and application in real world situations (such as in the selection of pump sizing for piping systems, or design of turbines).

In the second instance, engineering education tends to focus heavily on the theoretical (in this case the mathematical), and only demonstrate the physicality of the representation indirectly – potentially through videos of physical examples, simulated environments, or even heavily monitored practicals. This has further been exacerbated in the Covid era, with further shifts towards virtual or online spaces. A space is needed for students to experience and develop an intuitive feel for the theoretical material. A focus on this more practical aspect is further often highlighted by alumni giving feedback on what aspects of the curriculum were most useful – often they will recommend more interaction with the physical; plant visits, practicals, and hands-on application of theoretical knowledge.

4.1.3. Initiative

Two initiatives will be discussed here, highlighting differing approaches to technology-assisted learning, specific to fluid mechanics. The first initiative utilised a physical, non-assessment driven learning model (no formal grades are assigned) where students were split into small groups, and tasked with pumping water up a small piping network, given a box of limited equipment (Pott, Wolff, and Goosen 2017). This approach relies on the anchoring of advanced concepts within a simple and real context, with motivation driven by peer interaction. The students are required to analyse the system to understand the physical requirements, and then draw on the knowledge and heuristics developed in the course on pump curves, pressure drop, pump and piping networks and systems dynamics (located in the SG–, SD– quadrant) in order to develop an appropriate solution (under the pressure of peer competition).

The intervention aimed to facilitate the transversal of the semantic plane from a simple concrete problem with simple technologies (basic instructions and a bucket of components) (SG+, SD–), through the simple and abstract (using pump curves describing the equipment they have) (SG–, SD), to create a solution of greater complexity anchored in physicality (SG+, SD+). This drawing on abstraction and theory, in order to bring appropriate and complex solutions to what appears to be a simple problem is what engineers commonly need to do in industrial situations. For the theory portion, students rely on computing and plotting characteristic pump curves for the different pumps they have available, to solve the problem. This transversal between the calculating space, the representational space (putting the data onto curves using excel) and the physical space facilitates cumulative learning. As a level of abstraction upward, students later need this methodology to conceptualise modelled piping networks with both mathematical and graphical models, using software such as excel (or more advanced software for piping and pumping solutions). (Figure 3)

However, this initiative (and other practical implementations) could not be performed during remote teaching. In order to encourage students to explore fluid mechanics through strong context dependency and through reference to theory, an assignment was given which asked students to prepare a 5-min presentation on a real-world fluid mechanics-based phenomenon of their own choosing. The presentation was assessed by their peers, to drive engagement, and assessment was based on demonstration of understanding of fundamental fluid mechanics principles embodied in their chosen phenomenon. This, again, then aims to facilitate the epistemic movement of students from concrete and simple systems (of their own choosing) (SG+, SD–), through application and integration of theory as applied to the situation (SG–, SD– and SD+). Again, this assignment makes use of the broader online laboratory – students need to conceive of a fluid mechanics related topic, and research it in detail only in the online space; sufficient so that they can present this to their peers, to a technical depth. The implicit use of online resources, to scaffold learning, gives students agency to pursue their curiosity (without the need for expensive, and limited physical laboratories).

Explicitly using the semantic plane quadrants as a framework (Rootman-le Grange and Blackie 2018) aids the peer assessment process. The movement across the semantic plane is what the other students look for in the peer assessment of each presentation – has the student considered the fluid mechanics of the system? Have they adequately and clearly explained the theory behind the phenomenon, in terms of the theory they have learned in class? The initiative hoped to replicate the benefit of in-person, context-driven learning, through peer-assessment-driven, integration of the highly contextual (as chosen) with theoretical understanding, while simultaneously developing digital fluency through the use of accessible technologies such as smart phones and presentation software.

4.2. Finite element analysis – Building mathematical complexity

4.2.1. Context

Finite element analysis (FEA) is one of the most frequently used technologies in a diverse spectrum of engineering fields. As a result of its implementation in accessible software packages, it is often used as a ‘black box’, without an appreciation for the theory and approximations that underlie the results.

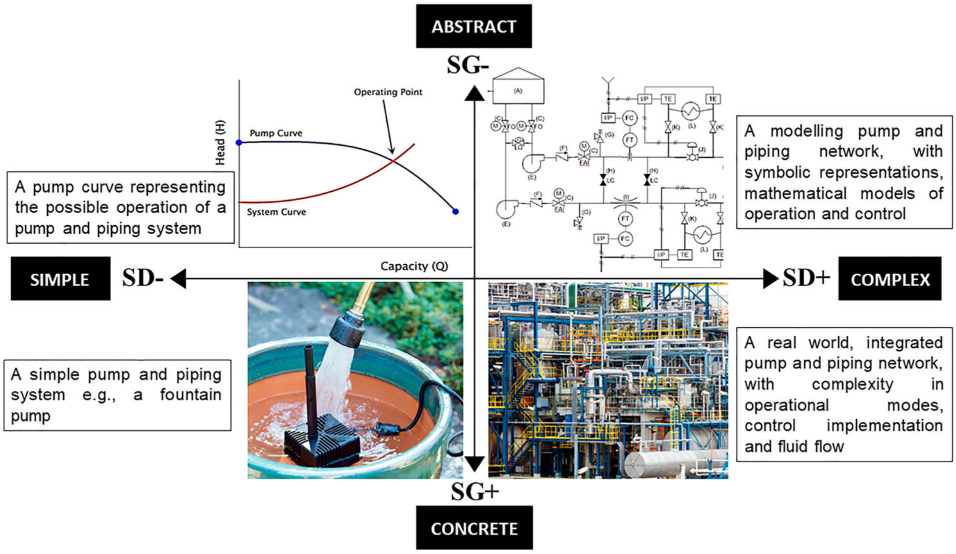

Figure 3. Fluid Mechanics semantic plane.

While this approach might be sufficient for routine work, cutting edge applications require the practitioner to appreciate the limitations and advantages of the method. Engineering students completing their 3rd year should be comfortable consolidating and applying their foundations in mathematics and physics in unfamiliar and variable contexts (IEA 2013), rather than only using predefined recipes in problem solving. A 3rd year engineering informatics course introduces civil engineering students to the theoretical foundations of Finite Element Analysis (FEA), as applied to the solution of problems describing stationary conductive heat transfer and linear elastic deformation.

4.2.2. Challenge

While ostensibly focussed on the theoretical formulation of FEA, the course provides an opportunity to consolidate and incorporate the material from earlier subject areas in the context of unifying principles. Key bottlenecks in student comprehension have been observed as the ability to identify appropriate concepts from previous courses in the FEA context, as well as generating simplified model representations of real-world problems that can be probed numerically or analytically.

Within this framework, students work through the derivation of the system of equations that is solved in FEA, where the solution is represented approximately as a piecewise assembly over a mesh. The key insight is that this piecewise representation allows a seemingly unsolvable boundary value problem to be broken into a large number of relatively trivial problems, which are then solved by harnessing the primary strength of computers: repeatedly doing relatively simple tasks. In other words, the horizontal, iterative movement on the semantic plane, moving between denser (SD+) and simpler (SD–) mathematical tasks. The intention here is the development of deductive reasoning and hypothesis construction (Adlong et al. 2003).

While this finite dimensional approximation is completely general, it is best developed in the context of relatable physics, in this case stationary heat conduction and linear elastic deformation. This requires an emphasis on foundational principles in the module, which inevitably highlights the accumulated deficiencies in understanding the physics of materials with which students enter the third year. With limited integration among siloed disciplinary areas (applied mathematics, foundational physics, and strength of materials), students find themselves struggling with concepts with which they should be familiar, because it is presented in an unfamiliar context using a more advanced mathematical framework. As a result students are often unable to visualise the theory in the context of a real system.

4.2.3. Initiative

To address these concerns, the course was redesigned to place greater emphasis on consolidating the preceding course mathematics and physics foundations in a modelling context. This is followed by a focus on the development of FEA itself, emphasising the unifying principles that form the foundation of the method, independent of the particular physical problem under consideration. This emphasis is anchored using two distinct real-world FEA examples for context and orientation (SG +, SD–). The chain of comprehension is developed by repeated traversals of the semantic plane to cover each concept, always with the end-goal of instilling an appreciation for the foundational principles (at their simplest, overarching levels) of a given part of the course (SG–, SD–).

Figure 4 illustrates such a concept development traverse, in which the finite dimensional approximation which underlies any FEA solution is developed by illustrating the representation of the temperature field in a homogenous plate resulting from contrasting temperatures sustained along its edges (SG+, SD+). Throughout the progressive development, each key concept is illuminated from diverse perspectives using multiple modes of articulation via verbal, graphic and/or symbolic representation translation (Rahmawati, Hidayanto, and Anwar 2017), providing a nuanced and varied means of adjusting the semantic density.

At salient stages of the course, students are asked to apply and refine their understanding algorithmically (essentially a fourth mode of representation), by solving a few FEA-related tasks for a trivial mesh using Matlab. These tasks include manipulating the mesh, evaluating the entries of an element

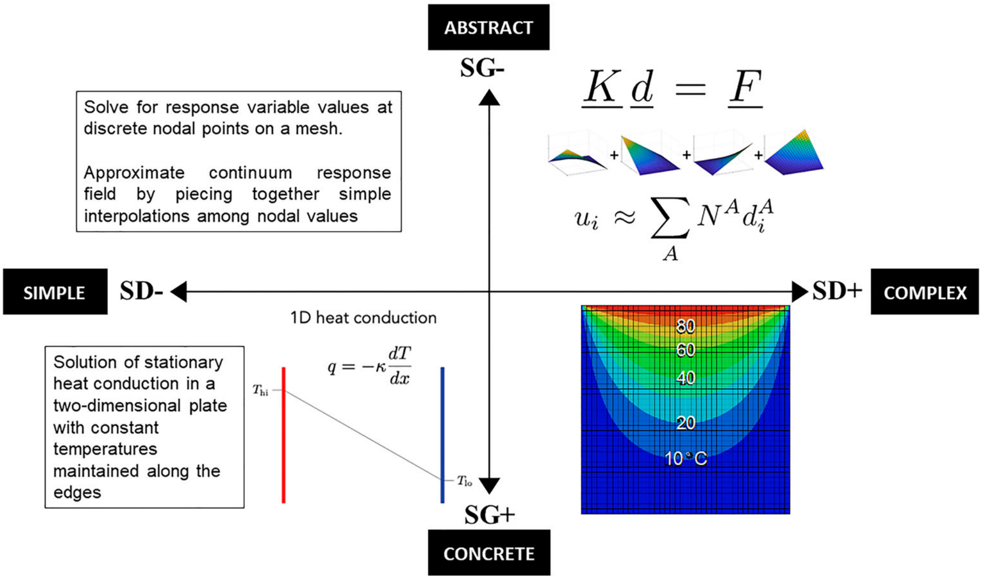

Figure 4. FEA semantic plane.

matrix, assembling the global matrix based on mesh topology, accounting for boundary conditions, and solving for the final solution, with each of these stages representing the cumulative development of increasing semantic density (SD↑). Students complete these tasks in groups with online collaboration using the Live Editor notebook. In addition to submission of the final result, students are also asked to briefly explain their approach by elaborating on their code in their group's Matlab notebook. In essence, this strategy mimics the Magana, Vasileska, and Ahmed (2011) 'hard-coded' transparency by scaffolding the simple–complex steps through iteration.

4.3. Control systems – using technology to scaffold complexity

4.3.1. Context

Given the steady uptake of automation solutions, mechatronics engineering courses offer an ideal opportunity to address the challenge of how to prepare graduates for the complexities of dynamic, twenty-first century, technology – and data-driven environments. State-Space Control (SSC) is a 'signal processing paradigm' (Smith and Brown 2003) which enables the determination of the state of all possible components in a dynamic system at different moments in time. In order to control any dynamic system, each component and its relation to the other components (called variables) must be understood as having properties, behaviour and a 'state' at any given moment. This state as well as change in the system can be captured using vector-matrix representation. The regulation of the system requires the determination of input variables so as to obtain desired outputs. State-space concepts are applied across a range of disciplines, such as the stimulus-response experiments used in neurophysiology (Smith and Brown 2003) and the parametric (state-space forms) statistical tools used to analyse structural shocks in economic sectors, so as to create forecasting models (Stock and Watson 2016).

In an engineering context, SSC entails the 'description of the internal state of a system by considering all the relevant state variables and the system response to inputs' (Kruger, Wolff, and Cairncross 2021). Graduates are likely to apply the SSC concepts in the implementation of feedback control mechanisms across various sectors, e.g. production automation, process control, autonomous vehicles and biomedical engineering. SSC represents a broad and significant concept in engineering education – that of *relational thinking*: the ability to understand the nature, state and implications of any single component within a larger, structurally and causally dependent dynamic system.

4.3.2. Challenge

In a 4th year control systems course, a predominantly theoretical approach (with limited practical exposure) to teaching concepts such as SSC consistently revealed gaps in student understanding of the potential practical implementation. Lecturer observation and formal assessments demonstrated that students struggled to visualise concepts and 'got lost in' the abstract mathematical work, very similar to the Magana, Vasileska, and Ahmed (2011; 2017) as well as Auret and Wolff (2017) cases. The class size (±200) and financial constraints prohibited expansion of the existing laboratory practicals.

4.3.3. Initiative

In order to scaffold learning and facilitate a form of hard-coded transparency (Magana, Vasileska, and Ahmed 2011), a Physical-Virtual-Simulated (PVS) system was developed in 2018 consisting of a relatively simple physical Ball-on-Beam (BoB) demonstration system (SG+, SD-), its virtual equivalent and simulations using Matlab Simulink software (Figure 5). The physical system is introduced to students in demonstration mode, where they are able to observe and vicariously experience the response to the ball being shifted and the beam rotating to return the ball to a desired position. This experience enables the intuitive interpretation of the causal effects of SSC concepts.

The 'virtual' system is built using the same simulation functionality as the 'simulated' system (i.e. Matlab Simulink), but with two distinguishing properties representing a decrease in semantic gravity (i.e. less 'real') and at a relatively equivalent simplified level of complexity (SG–, SD–):

- the simulation is constructed from modelling the physical system (using Matlab Simscape) instead of modelling the mathematical representation of the physical system.
- the simulation is visualised as an animation of the physical system's response at user-defined speed (i.e. in real-time, slower, or faster).

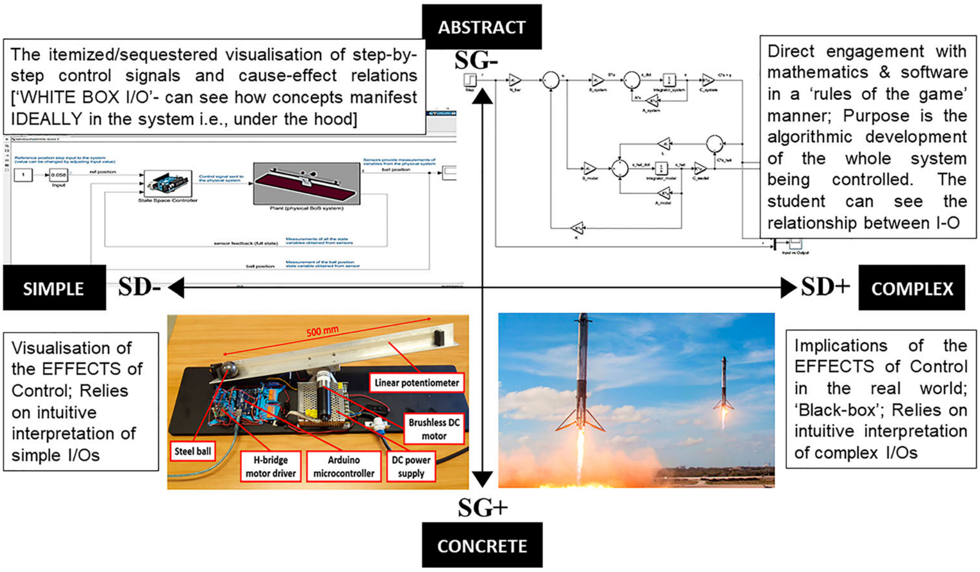

Figure 5. Control Systems semantic plane.

Students engage in stepwise fashion with the complex mathematics and programming in the Matlab Simulink algorithm environment (SG-, SD+) This is a similar approach to the FEA case study. Students are able to generate an idealised visualisation (SG-, SD-) in the virtual model. In principle, the learning cycle is intended to enable iterative code shifting between the top two quadrants, each of which represents 'white box' or 'glass box' (i.e. transparent) engagement with step-by-step signal control and causal relations. The graphic output (SG-, SD-), as in the case of the fluids pumping curve, offers a symbolic and potentially experiential anchor, such as observing the physical BoB movement, but slightly more abstract. In contrast, there is no physical causal relation experience when building the simulation algorithm at its most complex (SG-, SD+). The artefacts have been used in three iterations to date, beginning in 2019. It is worth noting that the shift to ERT in 2020 revealed significant challenges in the independent engagement with the simulated environment, which suggests a need to create more scaffolded, code-shifting opportunities.

5. Discussion

The overarching question for these case studies is *what kind of learning should/could be happening to bridge the theory-practice divide when using different kinds of technology*. Against a background in which there are several calls for a shift to online, remote and simulated technological engagement as a means of enabling less costly and time-consuming practical engagement (Balamuralithara and Woods 2009; Balakrishnan and Woods 2013; Hsu 2008; Pyatt and Sims 2012), this paper has sought to problematise building conceptual grasp through a range of contextual, technology-based mediating devices across engineering science domains. The aim is to enable a better understanding of what may be possible in online, remote and simulated learning. Despite claims for improved theoretical grasp in simulated environments (Balamuralithara and Woods 2009), some researchers have argued that simulated practicals lead to oversimplification (Feisel and Rosa 2005), lack of opportunities to troubleshoot equipment (De Jong, Linn, and Zacharia 2013) and navigate real world messiness (Pyatt and Sims 2012). In the sociology of education (on which this paper has built its analytical instruments), there is a strong warning against context-specific competency training (Wheelahan 2007) – in other words, simplified contexts may constrain the learning to those contexts, and not enable the access to powerful forms of knowledge necessary to navigate twenty-first century complexity (Wheelahan 2007). The preceding descriptions and analyses of initiatives designed to enable students to apply theory to practice have illustrated the interpretation of levels of complexity that need to be taken into account when designing learning using different forms of representation and associated artefacts/tools both physically and online. There are three key observations to be made about the *intended* learning.

5.1. Conceptual and contextual differences matter

As can be seen from the three case studies, each quadrant on the semantic plane represents a specific level of complexity *in context*, and can be illustrated using different forms of verbal, graphic and symbolic representation. Differentiating between these representational forms (and selecting appropriate artefacts/tools) in the different disciplinary contexts in relation to specific concepts enables the educator to plot a semantic journey intended to enable the linking of concepts to contextual examples through iterative application. The key point here, firstly, is the recognition that different ways of making meaning in the different disciplines matter, both within disciplinary contexts and at different stages of a course and programme. For example, with the final year looming, the FEA lecturer actually begins by contextualising the role of an engineer in society (SG +, SD+), where principles of design are guided by an ability to construct models. In contrast, the 2nd-year fluids case study sees a narrower contextual focus, starting with the most complex (SG−, SD+) in the form of the Navier-Stokes equations and derivations, moving on to graphical representations (SG−, SD−), then into the simplified real world practical context or a student's own environment (SG+, SD−).

Secondly, what constitutes simple abstraction (SG−, SD−) in fluid mechanics is not the same as in FEA or control systems, for example. Neither is the simple, context-dependent representation necessarily similar. The practical engagement with pipes and pumps (SG+, SD−) is not as 'black box' as the BoB system demonstrating system response. In other words, not only do students 'see' (in real time) the pumping operation, but they are actively engaged in making decisions that result in visible consequences. This experience reinforces the cumulative, subsumptive knowledge building of a hierarchical knowledge structure. In contrast, in the case of BoB, students observe the consequences of 'hidden' control (how the Arduino has been programmed to respond). In the control case, the decisions are not governed by a 'hierarchy' of physical phenomena. Rather, they are represented by decisions negotiated between different kinds of disciplines (physics-dictated phenomena and mathematics-dictated relations), implemented through a weak knowledge structure – in other words, one of multiple possible control systems and languages (Wolff 2015). In both these cases, however, the causal relationships are experienced in real time in relation to physical artefacts. In the case of FEA, the bottom left quadrant could be represented as an equation or a graphic similar to the output plots in the other two case studies, which in turn represent greater abstraction in their respective contexts.

Yet another differentiating variable is 'time': the link between physical, active learning and the associated abstractions in the fluids case study occurs over a shorter period of time, with students physically moving between the active practical and the associated calculation-based tutorial on the same day. This is similar to engagement with the simple BoB system in the control systems case study. However, the use of two different representational technologies (bode plots and virtual animation) at the SG−, SD− level provides more scaffolding and causal effect experience in the latter case.

5.2. Iterative code shifting

The intention of cumulative learning is the ability to link theory to practice through application. The commonly reported 'siloed' curriculum and approaches to problem solving routinely illustrate student difficulties in applying different concepts to problem-solving contexts. The derivation of equations describing fluid flow is conceptually distinct from the implementation of fluid flow in a physical practical. The two interventions described in the fluids case study demonstrate two examples attempting to encourage movement between siloes of understanding, in other words, to enable code shifting. Students need to pull on theoretical formulations (which we can position as having a weak semantic gravity (SG-)) of physical phenomena (stronger semantic gravity (SG+)).

Cumulative learning occurs when the semantic journey enables *iterative, scaffolded* and more transparent code shifting around the semantic plane, and building increasing complexity. There is no ideal code-shifting pattern, and each case study context can determine both a different starting point as well as semantic journey. Whereas in the fluid mechanics case study the aim is to teach and consolidate specific procedures for Navier-Stokes solution derivations, in other words a deepening of the work in the upper right quadrant (SG−, SD+), the FEA case study is about moving from the abstract complexity of the upper right quadrant to a range of application contexts and examples in such a way as to develop a broader conceptual grasp of the overarching modelling principles (SG−, SD−). This iterative movement to distinct FEA project contexts is supported by an appreciation of the generating principles upon which the method relies. Without this foundation and iterative code-shifting practice, the implications of assumptions made in a given FEA analysis may not be fully appreciated.

It is precisely the concept of *iteration* where increased independent engagement with technology can be meaningful. In studies on the usefulness of virtual, remote or simulated technology-based learning, when the messiness of equipment trouble-shooting is not an issue, then students report value in being able to 'explore and manipulate experimental variables' (Pyatt and Sims 2012) and engage in self-regulated repeated practice (Wolff 2018). However, there are two further observations to be made here. Repeated, self-regulated, supported practice can build confidence and improved perception of performance – so-called self-efficacy (Hsu et al. 2021). These are essential characteristics in developing engineering judgement, a key graduate competency. But self-regulated practice relies on intrinsic motivation (Wu et al., 2020), which is significantly constrained by well-reported engineering student workload. ERT conditions, furthermore, revealed that students' sense of isolation and lack of immediate support severely affected their levels of motivation (Booysen and Wolff 2021). Secondly, in resource-constrained contexts such as EMDEs in the Global South, independent and reliable access to appropriate technologies to enable independent practice has emerged in Covid-era education as potentially exacerbating the digital divide (Czerniewicz et al. 2020).

5.3. Technology-supported learning

The different semantic characteristics in the case studies have implications for the forms of technology (as well as levels of technology engagement) that are used to support learning. Phenomena that are observable in everyday artefacts or relatively simple technologies (such as pumps and pipes) offer an obvious opportunity to enable code shifting, and educators routinely integrate these kinds of artefacts into their teaching. Even as simple a physical set up as a pumping competition is able to generate both interest, peer engagement, and conceptual shifting between semantic gravity and density (as students observe and respond to their peer's activity in relation to the interpretation of a concept). The transition to ERT did not prohibit the fluid mechanics lecturers from enabling technology-supported code shifting. Indeed, the real-world examples of fluid flow expanded to include students' own examples, captured as homemade videos and uploaded to the learning management system for peer review and feedback. This form of remote peer learning enabled an additional, iterative code-shifting loop in that students were required to observe other interpretations of the same concepts across a range of contexts. It is often the case that one can easily see the error (or lack of depth of knowledge) in another before recognising it in oneself. While there is no direct comparison between the virtual-assignment in comparison to the physical-practical, the epistemic motion plots a similar trajectory on the semantic plane. Furthermore, the available technologies to enable this form of code shifting can be relatively simple and affordable.

Physical and virtual technologies can afford different and complementary leverage on students' knowledge trajectories. This is most evident in the control systems case study, where the three systems versions (physical BoB, virtual animation, and simulation environment) are not only closely linked, but actually scaffolded versions of increasing complexity in and of themselves (see Appendix for an elaboration on the semantic framework for the three systems). However, the control systems simulation environment is software dependent, as in the case of FEA. In both these cases, lecturers have observed the need to differentiate between the engagement with the technology in and of itself and the use of the technology as a tool to reinforce conceptual grasp through application. Where the use of the technology is scaffolded, and iteratively linked to the underpinning concepts, students can benefit from both physical and virtual engagement (Balakrishnan and Woods 2013).

In the case of FEA, enabling iterative code shifting around the semantic plane is intended to enrich students' appreciation both of the method – FEA – and the actual software tools they may use as future engineers. FEA as methodology and the associated software tools are often used as 'black box' instruments to illustrate applications in design and analysis in related engineering fields. In order to deepen the understanding of how the mathematical framework of the method is built – notably evaluation of the Galerkin weak form to compute the entries of the element stiffness matrices, and assembly of the global system of equations – students work through trivial problems involving only a few elements with a numerical scripting package such as Matlab.

5.4. Student feedback

A key limitation of this study is that there is a degree of context-dependent relativism in the selection of concepts, the forms of representation and the accompanying technologies across the case studies. However, the explicit code-shifting pedagogical strategies are intended to enable what we have described as 'cumulative learning', the principles of which may well be applicable in other modules and contexts. Although the focus of this paper is not a quantitative impact evaluation, student feedback (routine surveys integrated into all courses in the faculty), assessment performance, lecturer observations and research group reflection reveal two points worth noting:

Second-year students who engaged with the fluids practical (2019, pre-ERT) report that 'the practical was motivating, … provided a positive and competitive atmosphere … and provided a glimpse of the important aspects in fluid flow' (Pott, Wolff, and Goosen 2017; Pott and Wolff 2019). Similarly, control systems students mention benefits such as 'the use of Matlab and virtual model made the application much easier as results could be better monitored than purely analysing response graphs' (Kruger, Wolff, and Cairncross 2021). This is a reference to both forms of representation within the top left quadrant in this case study: the simplified animation and the response plot. In other words, students may benefit from having access to multiple possible representational forms within each quadrant on the semantic plane. Student feedback in the FEA case study also indicates a general refinement in their understanding of the work, illustrating the extent to which their view of FEA as a 'black box' is transformed into one of a 'glass box', where they understand the engine behind the FEA result.

The second observation and key challenge, we suggest, emerged as a result of the requirement for students to work independently during ERT: the question of the complexity of the *technology* versus the complexity of the *purpose* of the technology (Balakrishnan and Woods 2013). Students reported significant difficulties at the most practical, systemic level, such as installing the correct software versions or system incompatibility (Kruger, Wolff, and Cairncross 2021). Lack of familiarity with a particular form of software can lead to students conflating the complexity of the tool with the complexity of the application of concepts. Digital fluency, while commonly assumed among today's students, varies considerably – particularly in the resource-constrained Global South (Brown and Czerniewicz 2010; Czerniewicz et al. 2020) – and does not necessarily translate into educational contexts (Currant et al. 2008). An interesting observation from a different research project in the same faculty is that in cases where students were able to use an artefact (screenshot of a response plot or syntax, for example) in a mediated, online discussion forum, they could receive immediate feedback and perceived this opportunity as contributing to cumulative learning (Booysen and Wolff 2021; Kruger, Wolff, and Cairncross 2021).

A contribution of the case study analyses in this paper is a potential pedagogical heuristic (Figure 6). If cumulative learning is enabled through iterative code-shifting cycles between different forms of complexity and context-dependency (using different artefacts, technologies and representations), then educators may be well served to consider multiple patterns, starting in different quadrants and employing different iterations of the verbal, symbolic, and graphic representational modes.

The case study analyses, student feedback and research group reflections suggest that further work needs to be done on problematising the use of software as the 'key technology', particularly in

Figure 6. Cumulative learning heuristic.

resource constrained contexts with differentiated digital fluency levels. The Integrated Problem-Solving research group is actively engaged in experimenting with methods to understand student engagement with technologies and the implications of different levels of self-regulated learning (Booysen and Wolff 2021). Given the important relationship between the development of engineering judgement and self-efficacy practices, understanding how students *are* learning and what the constraints are to cumulative knowledge building are key engineering educator imperatives.

6. Conclusion

Three case studies have been presented, which examine different physical and online technology-supported initiatives designed to enable cumulative learning in key engineering modules. The LCT Semantics dimension enables the illustration of intended learning at different levels of conceptual complexity, as visualised on the semantic plane. Each case study demonstrates a different semantic journey in which students are encouraged to code shift by engaging with different forms of representation and artefacts/technologies. The key observations are (i) the importance of recognising the different levels of complexity and possible supporting artefacts, and (ii) the need to design iterative, code-shifting learning activities. An important finding across the case studies is the potential conflation of tool complexity with conceptual or application complexity. This warrants deeper investigation and problematisation, given not only the ubiquitous use of complex technologies in engineering practice, but also the digital divide in poorly resourced educational contexts. It is hoped that this study may offer educators an analytical and empirically-informed perspective on which to base pedagogical design aimed at improving applied conceptual grasp and long-term knowledge retention using appropriate technologies.

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Appendix: Control Systems – Semantic transparency framework

SSC mediating artefacts		Physical	Virtual	Simulated
Purpose of Artefact		enables the visualisation of the EFFECTS of Control; Relies on intuitive interpretation of I/Os	enables the itemized/sequestered visualisation of step-by-step control signals and cause-effect relations ['WHITE BOX I/O'] – can see how math. concepts manifest in the system	enables the direct engagement with mathematics and software in a 'rules of the game' manner with the purpose of algorithmic development of the whole system being controlled. The student can see the relationship between I and O
Functionality evidence		Response may be quantified by real-time response plot, and qualified by tangible, multi-sensory (human senses) observations.	Response quantified by a graph or response to disturbance, and qualified by single-sensory observation (visual).	Response quantified by a graph, and qualified by an interpretation of outputs.
Limitations		Physical system may mask what's under the hood, but can anchor purpose through what/how something manifests	The virtual system is an idealised visualisation/representation	The simulated system is an abstraction [BLACK BOX I/O – i.e. not under the hood]
Semantic Range		SD-	↔	SD+
Principle (SG-)	Feedback control to achieve a desired response	The physical response of the system can be experienced/witnessed (through multiple senses). The limitations of theoretical/mathematical analysis are exposed.	The effects of the mathematical design can be visualised, in real time and retrospectively. The virtual system is ideal, and all assumptions made in the mathematical analysis still hold.	Mathematically, we can design our system (using gains, integration/differentiation, pole placement) that will (in theory) result in a desired response.
Formula & Calculations	Mathematical analysis for SS control law and estimator design	Assumptions should be tested, extra limitations apply (e.g. non-linearity, actuator/controller limitations, sensor noise)	Some variance/discrepancies can be introduced (e.g. some inaccuracies in the model can be inserted)	Assumptions made with an ideal system, e.g. the model used in the design is assumed to be accurate.
	Graphic examples (User)	Student calculations (Pen & paper Tutorial exercises) E.g. nature of ball rolling on beam	Mathematical component-, behaviour- and interaction-related equations (Pen & paper Tutorial exercises)	Input/Output equations; Implementing I/O equation as block network in Matlab Simulink. ['Defining' process, creating the algorithm]
Representation	Block diagram schematic of feedback control	Blocks are embodied as physical components/subsystems.	Blocks are linked to visualisations.	Blocks only contain/communicate mathematical expressions.
Model	Feedback control system	Physical system	Mathematical model represented through physical modelling. Model accompanied by visualisation.	Purely mathematical model
	Result	Observe the demo model	Animation	Output response plot
Real (SG+)	Simplest: Drone [moving from A to B]; Complex unstable system: SpaceX rocket landing			