Exploring the role of Disciplinary Knowledge in Engineering when learning to Design

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Abstract: Three mechanical engineering teams are followed through their capstone design project as they navigate the ambiguous and contradictory requirements of a typical engineering design course. The pedagogy tends to be both weakly classified and weakly framed in terms introduced by Sociologist of Education, Basil Bernstein; leaving the decisions about what knowledge to draw on, in what sequence, and how, to the discretion of the students. The differential success of the three teams is analysed in terms of their use of disciplinary and practical knowledge to make decisions about their design and to produce a prototype. The semantics dimension of Legitimation Code Theory was used to analyse the data. The analysis suggests that meaning was completely encapsulated in the material product of design, at the expense of reflective or conceptual reasoning. While technical knowledge was evident in the process of design, it was the relation of this knowledge to the material artefact that mattered, but only secondarily to the functioning of the artefact. Consequently, simple artefacts were privileged over more complex artefacts, understandable in terms of simplifying the solution to a particular problem, but raising questions about dealing with more complex problems. When performance can be asserted with certainty without evidence of reflective or conceptual reasoning, it raises questions about technical solutions in the face of the uncertainty of the complex problems. If we want engineers to contribute to the grand challenges of our era, we need to think about how to reward both complexity and reflection, without losing simplicity and practicality.

Keywords: engineering education, engineering design, disciplinary knowledge, sociology of knowledge, pedagogic codes (classification and framing), LCT (semantics), application of knowledge.

1. Introduction

In this paper I attempt to tell a story of knowledge during a process of mechanical engineering design. The setting is a fairly typical capstone engineering design course in America. Small groups of students are assigned a project to design and build a prototype device. This story follows three of the design teams through their Preliminary Design Review, Critical Design Review and into their Final Design Review and evaluation. The research attempts to unravel some of the things that contribute to the success of some teams and the failure of others. However, the story is told through the eyes of a social realist, drawing strongly on a Bernsteinian understanding of knowledge transmission and acquisition, and concepts developed from Bernstein's huge body of work, in Legitimation Code Theory (LCT).
1.1 Engineering Design

Design has always been an important subject in an engineering curriculum, but it plays a complicated role in student development. For many engineers, design is the defining feature of engineering practice. Even when engineers are not formally design engineers, there is a sense in which they always design solutions to practical problems. This understanding of the engineering profession is evident in engineering education reports commissioned by professional bodies from as far back as the 1950s (Grinter, 1955), and still prevails today (R. King, 2008). There are three distinct aspects to seeing design as the determinant aspect of engineering practice. Firstly, design in a science-based profession takes the form of the application of scientific principles to solve design problems, somewhat unproblematically. Secondly, design as a particular problem solving process focuses on the process without necessarily considering the expert knowledge that underpins the process within any particular design discipline. And thirdly, design as practice becomes a complex mixture of knowledge, process and the enabling skills or graduate attributes needed for successful professional practice. The expert knowledge and the expertise required to use that knowledge seems often to be either assumed or ignored. In this paper, I draw explicit attention to the knowledge and the expertise required to use the knowledge to design, and the manner in which the pedagogic practices either foreground or background the knowledge.

For those who see engineering as the application of science, design courses are seen to offer students opportunities to apply their scientific and engineering knowledge to 'real' problems. Yet historians and philosophers of technology have discredited the idea that engineering (and by implication engineering design) is simply the application of scientific knowledge (Galle & Kroes, 2014; Hughes, 2009; Layton, 1993; McClellan & Dorn, 2006; Pitt, 2010). Rather, they point out that often, technological artefacts emerged before the scientific principles that explain them. For example, Smeaton and Watt contributed to the invention and development of the steam engine long before Carnot developed the thermodynamics necessary for its analysis (McClellan & Dorn, 2006). Perhaps in more recent times engineering has been far more strongly founded on scientific principles (Seely, 1999), but the debate around the primacy of science over technology continues. A similar tension exists between science and design, with particularly the 1990s seeing much of the engineering curriculum reform aimed at 're-introducing' design into curricula considered too science focused at the expense of design (Harris, Grogan, Peden, & Whinnery, 1994). However, even with a strong scientific foundation and the explicit increase in design in the curriculum, the complaint that “Although industry is generally satisfied with the current quality of graduate engineers it regards the ability to apply theoretical knowledge to real industrial problems as the single most desirable attribute in new recruits. But this ability has become rarer in recent years...” (J. King, 2007, p. 7) persists. Similar comments can be found in R. King (2008). This suggests that viewing design as merely the application of scientific principles to real problems is inadequate.
A large body of research on the process of design from a multiplicity of design disciplines has shown that there are far more complex relations between design problems and design solutions than can be attributed merely to a linear problem solving process involving the application of engineering science in the solution of problems (Dorst & Dijkhuis, 1995; Schon, 1984; Visser, 2009). Many engineering schools do tend to retain a fairly linear process of design marked by certain milestones at which point aspects of the solution become relatively fixed. For example, usually the product requirements are negotiated and set at a preliminary reporting stage, a concept solution is committed in a concept report stage and the detailing is refined prior to the finalising the design (see for example Bittner and Schmitt (2010)). However, within each phase a range of iterative, creative and testing cycles may be introduced (Crismond & Adams, 2012). But as Dorst (2008, p. 5) states "... it takes only an afternoon to explain one of the design process models to a group of design students. But knowing that model doesn’t make these students designers at all...". There is a great deal behind this statement including the creative conceptualisation of candidate solutions, the complexity of the real design process, the ontological aspect of becoming (Adams, Daly, Mann, & Dall'Alba, 2011; Cross, 2004; Lawson, 2004). But it also raises the question of what knowledge students need to recruit in a particular design task, and how they recruit that knowledge to address a particular contextual problem, and what the effect of bringing the knowledge into relation with other knowledge has. Rather, there appears to be a tacit presumption that students in a design challenge have access to or can access the disciplinary knowledge required to design, and that the application of this knowledge within the design context is unproblematic.

For those who see design as the link to professional engineering practice, design has the further challenge of being the subject usually used to meet accreditation requirements for a range of diverse skills associated with graduate attributes and conceptions of 'becoming', in preparation for engineering professional practice (for teaching and assessing graduate attributes see Shuman, Besterfield-Sacre, and McGourty (2005); for student perception on their professional development see Martin, Maytham, Case, and Fraser (2005)). Dym et al (2005) argue that this significantly detractions from the intellectual challenge of learning to design. Again, this perspective on design detracts from the complexity of learning to apply theoretical knowledge to a specialised design problem context.

Within this complex understanding of what counts as design, and what gets taught and learned in design courses, discussions on the selection of knowledge, and how it might be transformed in application to a context are largely absent from the literature (although Bucciarelli's (1994) conceptualisation of object worlds does relate). Other professions also identify the problem of graduates who struggle to apply their disciplinary knowledge in the practice of their profession. In a study of recently graduated doctors and nurses, Smeby and Vågan (2008) challenge the idea that inadequacies in graduate professional performance is merely a result of insufficient knowledge foundations. Rather they recognise that theoretical knowledge needs to be recontextualised from its abstract form taught in the academy into a contextual form in practice. And they recognise both the complexity of recontextualising knowledge and the limitations for practicing in an educational context. Christiansen and Rump (2007) suggest similar findings for
engineering in their study of engineers with different levels of experience facing the same complex, situated problem. They recognise the role of experience in reading a context and integrating ideas across a context and also how to use knowledge in a specific context. Both studies indicate that learning to use disciplinary knowledge in specific contexts, such as students face in capstone design courses, is more difficult than might be at first assumed.

1.2 Theorising knowledge and pedagogy

There have been a number of calls to a return to knowledge in education (Case, 2011; Muller, 2000; Wheelahan, 2010; Young, 2008) from what has become known as the social realist perspective on sociology of knowledge (Moore, 2012). Based on the work of British sociologist of education Basil Bernstein (2000), the theorists in this tradition argue that some knowledge is more powerful than other knowledge, and that social transformation requires that more people access this powerful knowledge. Bernstein's life project was always to understand why education appeared to reproduce social inequality and to find ways to disrupt this reproduction. His early work compared the pedagogic practices in schools with those in the homes of families of different classes. He showed that middle class homes aligned with the pedagogic practices of the school, while working class homes clashed with school pedagogy. This gave students from middle class homes a distinct advantage in meeting the evaluative criteria set in schools than their working class peers. This in itself is not unusual, but what Bernstein and others have argued is that many progressive pedagogic models aimed at introducing a pedagogy more aligned with for example working class home pedagogies, have failed to shift students into the mode that matters. Rather, they argue that social mobility means gaining access to the privileged pedagogic codes associated with powerful knowledge (Muller, 2000; Wheelahan, 2010; Young, 2008).

In this way of thinking, powerful knowledge is considered to be that knowledge which is abstracted from the empirical context of its discovery such that it can be transferred and applied across multiple contexts. Powerful knowledge is reliable in that it has been tested against criteria of conceptual consistency within a particular body of knowledge and subjected to tests of empirical and descriptive accuracy defined by particular disciplinary practices (Young, 2000). Bernstein (2000) described powerful disciplinary knowledge as strongly insulated from everyday knowledge and from other 'knowledges', subject to its own internal rules of coherence and adequacy. This separation he argued, gives knowledge its power. On the other hand, knowledge trapped in context, integrated with other knowledge with no clear principles of coherence is less powerful knowledge. This idea of the power to separate and thereby maintain an independent identity, he called classification. Strongly bounded or separated disciplines (strong classification) are contrasted to weakly bounded or integrated knowledge (weak classification). This argument tends to imply that access to powerful knowledge requires induction into the conceptual structures and knowledge practices within particular disciplines and the insight into the boundaries between disciplines that enables the navigation of these boundaries. From this perspective, school subjects are necessarily strongly classified.
The second part of access to powerful knowledge involves control over various aspects of the pedagogic practice. Bernstein (2000) called this framing. The idea of being inducted into a particular set of knowledge practices and the associated conceptual structures suggests transmission and acquisition of the concepts and practices. Bernstein identified five elements over which control in a pedagogic exchange could rest with either the transmitter (strong framing) or the acquirer (weak framing). The control over selection, sequencing and pacing of the knowledge determines what matters in terms of the instructional discourse. But more subtly, Bernstein saw all instructional discourse is embedded in regulative discourse, or the socially constructed norms of behaviour. The evaluative criteria he argued include aspects of social conduct and are influenced by the hierarchical relationship between the transmitter and acquirer. Where selection, sequencing and pacing are controlled by the transmitter, the evaluative criteria are explicitly clear and controlled by the transmitter and the social base is explicit, Bernstein labelled the pedagogic practice strongly framed (+F). When these aspects were in the control of the acquirer, it is weakly framed (-F). The challenge with weak framing is that what matters for evaluation becomes tacit, because in a school setting the transmitter is always in control of the assessment.

Bringing classification and framing together and recognising that they can vary independently of each other, introduces four pedagogic codes (+C/±F). The previous discussion on powerful knowledge along with a preference for explicit pedagogy suggests that +C/+F is more likely to provide access to powerful knowledge for more students. A number of studies at schools have demonstrated that -C/-F tends to further disadvantage the most disadvantaged students. But design offers an interesting challenge to this assumption because design is necessarily weakly classified (-C). It is completely dependent on the context of the problem and requires the integration of multiple disciplinary traditions. In order to allow a problem to retain its weak classification, students need to be responsible for selecting the knowledge needed, and decide on the sequence in which to approach the various parts of the problem, in other words, the pedagogy needs to allow weaker framing (-F) (Wolmarans, 2013).

2. Engineering Design: a shift in pedagogic code

As is typical of a design course, the pedagogic code in the mechanical design course in this study tends towards -C/-F. There is an expectation that students will draw on the traditional disciplinary knowledge they have learned in previous courses or access as necessary, but these 'knowledges' are explicitly expected to be integrated (-C). The very first sentence of the Course Syllabus states that "[T]he purpose of this course is to offer guided practice in integrating various engineering sciences into practical engineering design projects." (CP:p1) However, the responsibility for the selection and sequencing of the knowledge to be used is left to the student to determine. "It is expected that fundamentals from these courses [statics, dynamics, thermodynamics, etc.] will be vigorously pursued where project opportunities clearly exist for applying them."(CP:p3) and "... the projects are open-ended and a thorough process is nearly as important as the solution itself. This means that your obligations and expectations will not be as clearly spelled-out as in more traditional classes." (CP:p2). Sequence and pacing are defined by
the process (presumably whichever design process is taught in this program), but the selection of theoretical knowledge and the sequence of its application is left to the students (-F).

The manner of conduct and the relationship between the students and their instructor/tutors, an aspect of framing that Bernstein called the social base, is most clearly presented in "In summary, treat your instructor as you would your boss in your first job. Treat your team mates as you would your colleagues in your first job." (CP:p2) Here students are being positioned as employees, but also professionals. There is a complex code of conduct expected, but always with the students unquestionably subject to the decisions of the instructor (+F). This strong framing of the social hierarchy in the class is evident in the interactions during the final design review and appears to have significant influence on the grading.

Students are required to produce a working prototype, however, in the Course Prospectus document, discussion of the material product of design is limited to "A display of your prototype including a poster will be required at the end of the semester and your instructor will provide more information on this." (CP:p4) The rest of the paragraph on Prototyping is about rules of conduct in the laboratory. In contrast to the Course Syllabus document, the FDR (Final Design Review), which is the main evaluative event in the course, foregrounds the material product of design and completely backgrounds abstract theoretical knowledge. The instructor in the role of assessor presents students with two questions: "One, is it fully assembled? ...if it is not fully assembled per the prints, what has changed and why? Two, is it fully functional? If it is not fully functional, what is not working and why ... which will lead you into how do you fix it, probably." (I: 'RFT'-FDR-1:p1) The rest of the evaluative event is a discussion lead by students with questions interspersed by the instructor. In essence, students are required to provide evidence of assembly and function using their prototype. This shows that while the instructor is completely in control of the evaluative criteria (+F) they are extremely tacit throughout the process and ambiguous in the course prospectus (-F)

This brief comparison of the course objectives as presented to students at the start of the course in the Course Prospectus document and the main evaluative event at the end of the course analytically distinguishes between the theoretical (and practical) knowledge used during the process of design and the material product itself. It suggests that performance of the material artefact is the principle judgement of a successful design. This raises questions about the extent to which that performance is dependent on theoretical reasoning, as implied in the objectives of the course. In this we see both a weakening of the boundary between theoretical knowledge and the everyday context in which the design problem emerges, and a weakening of framing over the evaluative criteria in the ambiguity between the relative importance of the two domains, the abstract theoretical and the concrete.

In design, classification is weakened in two distinct ways. Firstly, the boundary between abstracted, theoretical disciplinary knowledge and the everyday context, which is the design problem setting, is necessarily weakened. Secondly, the boundaries between the various engineering sub-disciplines (usually taught as separate subjects in a curriculum),
is also weakened; again there is a necessary integration of disciplines as they are applied to the contextual problem.

2.1 Design's challenge to pedagogy

The social realist argument in the sociology of education suggests that in order to disrupt the reproduction of social inequality through education requires broadening access to 'powerful knowledge' and the practices for its production. This, they argue, is best achieved through disciplinary separation (+C) in order to immerse students in disciplinary knowledge and practices of particular disciplines, and explicit pedagogy (+F) in order to make the requirements of the various disciplines clear. The analysis presented above suggests that the mechanical engineering design course under investigation integrates disciplines and weakens the boundary with the everyday and the contextual (-C) and has an ambiguous pedagogy with strong framing (+F) of the regulative discourse but weak framing of the instructional discourse (-F). Elsewhere I have argued that although this makes teaching and learning design difficult, it is necessary (Wolmarans, 2013). The point is that this is not a badly run course with poor course objectives, but rather that it is a typical engineering design course with particular challenges necessary to induct students into the discourse of design. The intension of this research is to gain more insight into how students successfully (and less successfully) navigate this difficult pedagogy in order to assist instructors to help all students to make this transition.

2.2 Research questions

Following three design teams in a mechanical engineering capstone design course, this study attempts to unravel some of the factors contributing to why some students are successful and others not as they navigate the various ambiguities and contradictions inherent in a weakly classified and weakly framed pedagogy. The specific focus is the disciplinary knowledge that students select and use in their design, and how that knowledge is transformed into a prototype artefact. But since this is a pedagogic setting, not a professional setting, it is also important to consider the way in which the instructor intervenes to clarify the evaluative criteria, or what really matters in their design.

• How can we make sense of the different ways in which students more/less successfully navigate the disciplinary boundaries and specialise knowledge in the concrete but complex context set up by each design challenge?

• What is necessary in order to successfully apply scientific knowledge to solve design problems?

3. Methodology

In this study, the data selected from the full data set (Adams & Siddiqui, 2013) was that provided for the three teams in the mechanical engineering group are analysed. The data include the course prospectus (labelled CP in the analysis and discussion); a preliminary design report (PDR) from each team in the form of PowerPoint slides; a video recording and transcription of the critical design review (CDR) along with the slides that support the presentation; a video recording and transcription of the final design review (FDR),
which included a presentation of a working prototype. The CDR shows a formal presentation of the design by the team, with interspersed questions from the instructor and in one case a fellow student. The FDR is a more informal discussion between the students and the instructor, where the physical prototype is discussed and demonstrated. There is additional data for the group that won the innovation competition, including a video and transcription of the team presentation and question and answer session at the competition, which were not considered at all in this study.

The analysis is qualitative, but theoretically informed by Bernstein's code theory and Legitimation Code Theory (LCT). That means that the data are read using conceptual tools defined by LCT and interpreted against a backdrop of Bernstein's theory of pedagogic transmission and acquisition. For a detailed description of this dialectic relation between the theory and the data see Maton and Chen (forthcoming, 2015). While Bernstein's code theory was used to illuminate the nature of a design course as weakly classified and weakly framed, it is inadequate for investigating the details particularly of the weak classification. Consequently I have turned to LCT, a theory that emerged from Bernstein's theoretical foundation and is thus consistent with it. LCT includes five conceptual couplets for analysing various aspects of knowledge relations. In this analysis LCT (semantics) has been used to address the two elements that weaken the classification of design, crossing the boundary between disciplinary knowledge and the concrete particulars of the everyday; and crossing the boundaries between multiple disciplines as they are drawn together in their application to a single contextual problem.

The analysis is presented as a qualitative description of insights gained from a deep immersion in the data, but always with a battery of theoretical concepts in the background. The first stage was to recognise within the data those theoretical concepts that are likely to shed light on the significant aspects of the data itself. These concepts were then specialised to the data, or developed in ways that lend themselves to identification within the data, and rigorous description and comparison. With an 'external language of description' (Bernstein, 2000) in place to translate theoretical concepts onto the data, the manner in which each team dealt with knowledge was analysed and described with a view to understanding what is required for success.

4. Introducing the teams and elaborating the course

In this mechanical engineering design course, we follow three design teams through three review events including the final evaluation in the form of the FDR. The three teams perform quite differently in the course. The first team, let us call them the 'Prop Team' ('PT'), can be considered the most successful team. They were assigned an unequivocal A for the project; were selected to participate in the final round of the innovation competition, and went on to win it. The second team, the 'Robot Fish Team' ('RFT') also scored an A on the project, although the instructor clearly indicated that they were close to a B+. While they did get selected into the top 10 projects, they did not make it into the final round of five in the competition. The third team, the 'Cap Team' ('CT'), did not produce a working prototype and the data implies that they failed the course.
The earlier analysis of the course structure and evaluative criteria in terms of classification and framing showed some of the ambiguities inherent in a course of this nature. Yet some teams navigate these ambiguities seemingly without difficulties, others, for whatever reason, do not. The following sections look at the nature of the weakening of classification (between theory and context; and between disciplines), and the way in which the instructor contributes to clarifying the ambiguous evaluative criteria.

4.1 Theorising the relation between theory and context (semantic gravity)

The classification analysis of the course shows us that the boundary between the various engineering science disciplines and the 'everyday' context, which provides the design problems, is weakened. But it does not tell us much more about the relation between the theoretical knowledge and its context of application. Distinctions between abstract and concrete, or theoretical and practical knowledge, have been dealt with in different ways by theorists. Semantic gravity, a concept developed within Legitimation Code Theory (LCT) rather than categorising knowledge types looks at the relationship between knowledge and its object of knowledge; "the degree to which meaning relates to its context" (Maton, 2014, p. 110). Semantic gravity suggests that the relation between knowledge and object of knowledge varies along a continuum. "One can also describe processes of strengthening semantic gravity, such as moving from abstract or generalized ideas towards more concrete and delimited cases, and weakening semantic gravity, such as moving from the concrete particulars of a specific case towards generalisations and abstractions whose meanings are less dependent on that context." (Maton, 2014, p. 110). This is useful in two ways. Firstly, rather than categorising knowledge as concrete or abstract, semantic gravity relates the level of abstraction to the material object of knowledge. And secondly, semantic gravity allows for a continuum of relative abstraction, and suggests a natural movement up and down this continuum.

Applying the theoretical construct of semantic gravity to the analysis of the Course Prospectus and the Final Design Review suggests a code clash between the two. The Course Prospectus foregrounds the application of "various engineering sciences" that are needed to inform the design, while the material prototype is only mentioned. This suggests weaker semantic gravity (SG-). Although the theory is intended to be specialised to the context, it is the basket of available theory, abstracted for use in any context, that is the focus of the Course Prospectus. During the evaluation, the FDR backgrounds the theory in favour of the complete assembly and operation of the prototype. Meaning is based on the performance of the material product itself, not the theory used to do the design. The semantic gravity is substantially stronger (SG+).

4.2 Developing the semantic gravity range (external language of description)

In order to understand how the students negotiated this code clash, a scale of semantic gravity was developed in conjunction with the data to provide a basis of comparison between the three teams. Here meaning refers to the manner in which students' reason about the decisions they make in relation to the material product. A scale of four qualitatively different strengths of the relation between knowledge and object of knowledge is developed in order to investigate changes in the semantic gravity of the
student reasoning during the design process. The scale is tabulated below with illustrated examples from the student data. An important methodological point is that this external language of description is not a categorisation of the teams, but rather an illustration of the scale of semantic gravity that informs the discussion of the teams' various performances.

Table 1. Developing a scale of semantic gravity

<table>
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<tr>
<th>Semantic gravity (relation between theoretical and material considerations.) (abstraction/concretisation)</th>
<th>Example in data</th>
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<tbody>
<tr>
<td>SG-- Theoretically abstracted or idealised, but disconnected from product of design or neglects material realities. Reasoning remains in abstracted or idealised form.</td>
<td>S: &quot;...plugging all the materials into Solidworks and the known weights of the motors and chain, we were able to come up with a total weight that needs to be lifted by the motor, about 26, pounds... working through the, torque equations ... we'll be running it at about ... one and a half rotations per second, which comes out to be about 32, ah, pound inches. ...gives us, some playing room to make sure that we can lift...&quot; ('CT'-CDR:t10)</td>
</tr>
<tr>
<td>SG+ Reasoning is lead by practical considerations (abstracted or idealised models), but knowledge is specialised to the product based on material realities. Abstract reasoning directly linked to material practicalities</td>
<td>&quot;This shows the basic motion of the caudal fin. As you can see, you have to first initiate it. And once you initiate it, it kind of works in steps, so create a sine wave depending on how compliant the tail fin is. This will create the vortices and it does, because the speed of the fish is dependent on the vortices itself to swim, it's gonna take a little bit of time to build up speed, but eventually, it will get, within a few seconds, the max speed for the fish.&quot; ('RFT'-CDR:t3)...we also have done a drag simulation in Ansys, it's about 0.28. It is a little higher than a normal fish.... And this is the video that we done some testing on the fin... But we didn't get to maximum speed...Based on what we used, we just had to see how it move.&quot; ('RFT'-CDR:t19)</td>
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| SG+ Reasoning is lead by practical considerations (empirical tests or "...we were able to find this motor.... The torque's a little low, but ... since we have a little bit of buffer with the speed, we're planning on driving a little bit more amps, bringing it down to a slower speed in there for a little bit higher torque out of there. Since motors move along a torque speed
material limitations) but informed by theoretical or conceptual considerations. curve. (PT'-CDR:t8-9)

In contrast to the two previous categories, here practical necessities lead the conceptual reasoning. The practicalities of motor selection lead the reasoning, but the reasoning is linked back to a conceptual understanding of the operation of motors.

<table>
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<tr>
<th>SG++</th>
<th>Practical reasoning based on empirical testing or material considerations, but (apparently) devoid of theoretical or conceptual considerations.</th>
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<td></td>
<td>&quot;And in terms of functionality, ... the lifting motor and the rotating motor will not lift or rotate, they kind of just vibrate in place. ... We were able to get it to lift and rotate separately.&quot; (CT'-FDR:t2)</td>
</tr>
<tr>
<td></td>
<td>Here the concrete problem is described, but there is no evidence of recourse to theoretical reasoning to make sense of and address the problem.</td>
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4.3 Reading the data in terms of semantic gravity

'CT' appears to skip between SG-- and SG++, but without moving through the intermediate categories. They developed an idealised CAD model of their mechanism, but fail to theorise the nature of the idealisation and the possible implications for a real model. The understanding of the design is held completely in the idealised model (SG--). This exchange with a student in the audience (Sₐ), illustrates the point. The student is trying to draw their (Sₐ) attention to the potential practical problem of synchronising two independent motors, something that the idealised model can't show (the reasoning would require the strengthening of semantic gravity):

Sₐ: "I was just wondering, so you’re rotating and lifting at the same time? |
Sₐ: "... how you're co-ordinating the two – rotating with lift - " |
Sₐ: "... that is done with two different motors. ... both of them are stepper motors. So once the stepper motor starts rotating, the other one would get out of signals like this much steps has been completed. So lift this much... that had to come from the experimental data." (CT'-CDR:t:13)

Despite this prompting when the material realities emerge in the FDR the team focuses on the concrete particulars of the prototype apparently (at least in the available data) devoid of theoretical or conceptual reasoning (SG++).

Sₐ: "And in terms of functionality, the machining is good, but the lifting motor and the rotating motor will not lift or rotate. Um, they kind of just vibrate in place. ... We were able to get it to lift and rotate separately." (CT'-FDR:t2)

An example of weakening the semantic gravity would be to recognise that the motors vibrating in place might suggest they were stalling as a result of an overload. That they operated individually might suggest that when operating together the load somehow increases, so perhaps the motors are working against each other. This might indicate the problem the other student was alluding to in the previous exchange. However neither the instructor nor the students engage in this kind of more inferential reasoning; they remain in the material context (SG++).
In this problem, which appears to be the critical problem in their design, and which they were unable to resolve, we see a separation between theory and the material product, either completely abstracted or completely material. The team appears to struggle to relate the idealisations of theoretical concepts to their problem, or to abstract the material realities using theoretical concepts. This inability to abstract ideas is also evident in that this was the only team not to present conceptual alternatives. It is almost as though they are unable to abstract concepts adequately to provide a basis for principled comparison. Rather they are focused on a 'material' solution, and present the idealised model or theoretical equations as separate and hardly related to the material solution.

'PT' also build a CAD model of their mechanism. But they seem to use the model to inform design decisions more effectively, for example, "we did several analyses to determine the size of the angle lead piece, and, ah, added a brace at the end to change... the key here is that the right where the left motor is, the back plate was deflecting the rear quite a bit, but now it's in a range which is acceptable to us. The maximum displacement here is 19-1,000ths of an inch, which is in the location where the, the plane actually stands on the sub-assembly. " (PT-CDR:t4-5) Here we see theoretical knowledge in the stress analysis leads the reasoning, but the knowledge is used to inform practical decisions, and make changes to the material product (SG-).

Like 'CT', 'PT' is very concerned with material practicalities of their problem (SG++), the bulk of their research into their design relates to benchmarking other similar models, which are then compared in terms of size, weight and cost, quite material considerations. However there are also many illustrations of their practical reasoning being informed by theoretical concepts (SG+). For example:

S_\text{PT}: "Our drive motor is now a geared motor, and instead of using a worm gear, we're using two bevel gears to power our front steering wheel. ... We're using a geared motor also to direct drive a ball screw, which is... along the axis of our slider, instead of above it now. ... this will give us a little bit better mechanical advantage ...a little bit simpler assembly." (PT-CDR:t2)

The data shows that while SG+ and SG++ dominate the mode of reasoning used by 'PT', they do also at times weaken the semantic gravity to SG-, where theoretical rather than material considerations lead the reasoning, but always in explicit relation to the material product of design. In contrast 'CT' skip between SG-- and SG++, either completely idealised and unrelated to the material realities of the product, or completely absorbed with the product itself, with nothing in the middle.

'RFT' begins their design with a strong theoretical bias, however it is always theorised in terms of their contextual problem (SG-). It is most interesting that in both their CDR and FDR their instructor is usually trying to strengthen the semantic gravity, probing them on practical issues. One might see this as the instructor attempting to clarify the ambiguous evaluative criteria. In the CDR we have the following exchange:

I: Is that the vertical position of the center of buoyancy? ... So doesn't that mean that there's a fairly low margin to keep the fish upright?
S_{RFT}: As far – well, it is weighted downward, so it should orient itself in this way, but it just won’t right itself as quickly. So the center of gravity is lower than that of buoyancy the moment will actually correct itself, right?
I: Right. What is that distance between the two? ...
S_{RFT}: It was half-inch vertical distance.
I: Okay. So technically, that should right itself, right? But it's gonna be really slow ... So we might want to think about trying to increase that distance, that moment arm. ("RFT"-CDR:t14-15)

And in the FDR, watching a video of the robotic fish in a pool the instructor sounds surprised:

I: There it is on its side, rights itself well. Wow. That worked nice. Apparently, the calculations are good, too." ("RFT"-FDR:t2)

The dominance of the SG- mode of reasoning in 'RFT' team is evident in both their research around the problem and their concept development. For example the team researches biological aspects of fish in order to determine their design criteria, and do detailed research into fluid dynamics to establish that "because the speed of the fish is dependent on the vortices itself to swim, it's gonna take a little bit of time to build up speed, but eventually, it will get, within a few seconds, the max speed for the fish" ("RFT"-CDR:t3). However, the theoretical knowledge is always specialised to the material design. This same theorised reasoning is applied sequentially to each of the decisions about which possible form each subsystem or component should take as they conceptualise their candidate solution. Even when they refer to planned empirical testing, coded (SG+) because the results pertain to the particular context of the test, there is evidence of theoretical reasoning. Explaining how they determined the proposed dimensions of the caudal (driving) fin:

S_{RFT}: "And then the 1.6 you see above, is the wake. So during testing, this is gonna be one of the things we look for is actual wake that you see behind the fish. And this will show how we should get our approximate length of 11 inches." ("RFT"-CDR:t4)

Perhaps partially under the influence of the instructor, and partially as a result of the shift from conceptual design to operationalizing the prototype, we see a distinct strengthening of the semantic gravity through the various stages of their design.

4.4 Evaluative criteria - what really matters

As mentioned previously, the final evaluation is based on the extent to which the prototype is assembled and functions, with no expectation of reference to any form of theoretical abstracted reasoning that lead to the material product, on this scale SG++. There might be the potential of weakening the semantic gravity slightly in explaining why things may have changed or how they could be improved. But, the lack of any form of inferential reasoning to account for the failure of the mechanism designed by 'CT', either under probing by the instructor, or lead by the students, suggests theoretical
understanding was not actually relevant to grading. The mechanism did not function, the students failed. If they could have got the mechanism functioning, they would have passed. This same logic is evident, though slightly more subtly in 'PT' team's FDR.

As proof of operation 'PT' provide video footage of their mechanism capturing the nose wheel of a light aircraft and towing it. The towing speed is extremely slow and the instructor asks what speed it is in relation to their design criteria:

I: And what did our top speed end up being in this?
S_{PT1}: We did not measure it.
I: What do we think it is? ...
S_{PT1}: Roughly two miles an hour, or –
S_{PT2}: 2 miles an hour.
I: What did we plan? 3.5, or something?
S_{PT1}: We had aimed for ... two miles an hour.
I: Okay. All right. Anything else? ('PT'-FDR:t6)

Two miles an hour is about 3 feet per second (or $1\text{ms}^{-1}$), a moderate walking pace. The video shows that the airplane is towed less than three feet in more than 10 seconds (an order of magnitude slower than claimed). It may take some time for the mechanism to get up to towing speed, but it is significant that the instructor does not query this or further engage; he merely accepts their assertion. A similar social dynamic is evident in the exchange over the omission of the phototransistors from the assembly. The students confidently declare, "No, we don't need more time. It was not a critical function of our design." ('PT'-FDR:t2) And the mechanism is considered fully assembled. The students are graded an A, and go on to win the innovation competition.

Both these examples are presented as concrete statements of fact (SG++). There is certainly no theoretical inferential reasoning involved. Rather, I would argue that the student statements are made in response to the very concrete need to have a fully assembled, fully functional prototype, a requirement that this team of students appears to understand. In contrast, 'RFT' are far more tentative about their claims of performance, and the instructor suggests the design is worth a B+ because although they have a fish that is sealed, swims (with neutral buoyancy, depth control and roll stability) turns and responds to avoid obstacles (although far slower than desired), it does not have the tracking system initially conceptualised. By reducing the scope of the design, to exclude tracking, the instructor does concede an A to the team. It is notable that 'RFT' do attempt to explain the slow turn response to obstacle avoidance, both in terms of the change of IR range in water and the size of the dorsal fin. But this weakening of the semantic gravity does not appear to carry as much significance in the evaluation as the stronger semantic gravity of the claims made by 'PT'.

What matters is that meaning is condensed into the operation of the prototype, regardless of the abstract theoretical reasoning that informs (or not) that operation. However, although SG++ is the criterion for success, it is also clear that in order to realise the working prototype, students do need to be able to move up and down the semantic gravity.
range. Although practical reasoning trumped theoretical reasoning, the inability move up and down the scale smoothly appears to have significantly contributed to 'CT's failure.

4.5 Theorising the relation between disciplines (semantic density)

Where semantic gravity provided some insight into the relation between knowledge and the material object to which it is being applied, semantic density, its partner concept in LCT, will be used to explore the relations between concepts as disciplinary boundaries are crossed (or not) (Maton, 2014). Where semantic gravity sets up a range of relative abstraction or concretisation of meaning in relation to an object of knowledge, semantic density sets up a range of relative condensation or elaboration of meaning. Stronger semantic density implies the integration of multiple ideas, condensed into a more complex idea, weaker semantic density implies less complex ideas, or the elaboration of complex ideas into parts. A similar scale for semantic density as was created as that for semantic gravity.

Table 2. Developing a scale of semantic density: `discursive relation'

<table>
<thead>
<tr>
<th>Semantic density (integration/separation)</th>
<th>Example in data</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD++ Condensation of theoretical concepts built on a coherently integrated conceptual body of knowledge.</td>
<td>There is little in the way of developing complex ideas through the integration of simpler ideas. The development of the CAD and AnSys modelling tools might be considered to have very strong semantic density, as the integration of numerical modelling and either solid mechanics principles or fluid dynamics principles with a related graphical output. However the students merely use these tools, rather than contributing to their development.</td>
</tr>
<tr>
<td>SD+ Sequential application of discursive concepts, but with clear conceptual links between multiple concepts with interdependent consequences.</td>
<td>&quot;This shows the basic motion of the caudal fin. As you can see, you have to first initiate it. And once you initiate it, it kind of works in steps, so create a sine wave depending on how compliant the tail fin is. This will create the vortices and it does, because the speed of the fish is dependent on the vortices itself to swim, it's gonna take a little bit of time to build up speed, but eventually, it will get, within a few seconds, the max speed for the fish.&quot; (RFT-CDR:t19) The design of the mechanism that creates the fish's motion draws on links between biological understanding of fish swimming, material properties of the fin material; fluid dynamics principles; rigid body dynamics and matching of motors, all drawn together simultaneously to develop a mechanism to meet the design goals.</td>
</tr>
<tr>
<td>SD- Sequential application of discursive concepts, but applied independently of each other without explicit links between multiple concepts</td>
<td>&quot;Ah, the reason for that is to lower the friction and, therefore, the forces on this slider component so we don't have to have quite as big a lift motor.&quot; (PT'-CDR:t9) Students are drawing on conceptual reasoning, but in relation to small parts of the overall design, in this case a loading analysis to size one of the motors. There is no need to consider multiple theoretical implications in relation to each other.</td>
</tr>
<tr>
<td>SD-- Separation of meaning evident in disparate bits used as facts.</td>
<td>&quot;...we saw several risks ...we were afraid that since we’re machining a lot of these parts are not exactly to the size we need, ... there's gonna be an error so we'll have to re-machine them. ... properties changing because of machining due to, ... a lot of heat being transferred to parts that might change it. &quot; (CT'-CDR:t11) Although a number of ideas are considered, each potential source of 'error' is treated independently of the others.</td>
</tr>
</tbody>
</table>
Using this scale of semantic density, the dominant mode of reasoning in terms of semantic density was determined for each team.

Table 3. Categorising the dominant mode of semantic density

<table>
<thead>
<tr>
<th>Team</th>
<th>Dominant mode of theoretical integration or relations</th>
<th>code</th>
</tr>
</thead>
<tbody>
<tr>
<td>'CT'</td>
<td>Application of basic torque, force, pressure relations and some basic strength calculations. But students appear to apply equations rather than concepts as individual components. There is little evidence of the development of integrated coherent conceptual reasoning.</td>
<td>SD-- (DR)</td>
</tr>
<tr>
<td>'RFT'</td>
<td>Biological attributes of different fish (shape, locomotion, etc) linked explicitly with engineering sciences (buoyancy, fluid dynamic, aerodynamics, strength). Alternative solutions to robotic fish linked to project requirement. Electronic devices (alternative possibilities evaluated wrt project) Materials (alternative possibilities evaluated wrt project) In most cases the theoretical insights from multiple disciplines are considered in relation to each other.</td>
<td>SD+ (DR)</td>
</tr>
<tr>
<td>'PT'</td>
<td>Students do some FEM modelling of strength and deflection, and draw on conceptual understandings of motor characteristics matching. But the use of theoretical concepts tends to be sequential and only related in a linear chain of consequence.</td>
<td>SD-(DR)</td>
</tr>
</tbody>
</table>

Semantic density considered in relation to the relative success of the three teams suggests that while students do need to draw on conceptual reasoning founded in theoretical knowledge, the complexity of the reasoning, and theoretical justification for decisions is not as important as getting the prototype working. Rather than developing and integrating complex understandings, relatively basic theoretical constructs, applied in sequence could be adequate. But what is less clear, when looking at theoretical complexity in isolation from the product of design, is the dependence of theoretical complexity on the inherent complexity of the material product.

4.6 Complexity in terms of the material prototype

Expending the idea of semantic density to the material product provides an additional layer of insight into the designs. The idea introduced by semantic density, of increasing complexity as the integration of multiple sub-parts into a coherent whole does resonate with observations of the material prototype developed. So while semantic density was developed in terms of 'meaning' and has usually been used to analyse the condensation of ideas in to more complex ideas, here, meaning resides in the assembled mechanism and its operation. Exploring the idea of semantic density in terms of material relations between parts and their operation, the scale developed for the discursive relations (the relations between theories used) of semantic density was translated into an equivalent scale for the material relations of the parts that were integrated in the material prototypes of each team. This scale was used to code the prototypes produced by each team. The distinction between discursive relations and material relations is akin to, but not quite the same as Maton's distinction between discursive relations and ontic relations, because he uses ontic relations to describe the relations between the knowledge practices "and that part of the world towards which they are oriented" (Maton, 2014, p. 175); whereas I am looking at the relations between the actual material parts that comprise the designed artefact. Discursive relations are the relations between various knowledge and knowledge practices.
Table 4. Developing an equivalent material relation for semantic density

<table>
<thead>
<tr>
<th>Code</th>
<th>Code</th>
<th>Discursive Relations</th>
<th>Material Relations</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD++</td>
<td>SD++</td>
<td>Condensation of theoretical concepts built on a coherently integrated conceptual body of knowledge.</td>
<td>Complex material product integrates multiple subsystems operating simultaneously and requiring synchronisation.</td>
</tr>
<tr>
<td>SD+</td>
<td>SD+</td>
<td>Sequential application of discursive concepts, but with clear conceptual links between multiple concepts with interdependent consequences.</td>
<td>Complex material product integrates multiple subsystems linked dependently to one another, but operating sequentially.</td>
</tr>
<tr>
<td>SD-</td>
<td>SD-</td>
<td>Sequential application of discursive concepts, but applied independently of each other without explicit links between multiple concepts</td>
<td>Simple material product essentially a single subsystem without any dependency on other subsystems.</td>
</tr>
<tr>
<td>SD--</td>
<td>SD--</td>
<td>Separation of meaning evident in disparate bits used as facts.</td>
<td>Collection of individual material parts that do not (need to) work together.</td>
</tr>
</tbody>
</table>

As with the discursive relations of semantic density, the prototype designed by each team was categorised in terms of the material relations of semantic density.

Table 5. Categorising the semantic density of each artefact

<table>
<thead>
<tr>
<th>Team</th>
<th>Description of artefact</th>
<th>code</th>
</tr>
</thead>
<tbody>
<tr>
<td>'CT'</td>
<td>The solution is conceptualised as an &quot;aesthetically pleasing&quot; ('CT'-PDR:p5) mechanism to simultaneously twist the lid and lift it. This requires a means of clamping a jar with sufficient force to resist the load applied to open the lid without breaking the jar; a drive train strong enough to transfer the load developed by a motor and selecting a motor large enough to transmit the torque required to twist the lid. The design solution is a complex mechanism of multiple motors and drive trains electronically synchronised within a frame that provides the geometry for the mechanism.</td>
<td>SD++</td>
</tr>
<tr>
<td>'RFT'</td>
<td>The solution is conceptualised as an &quot;aesthetically pleasing&quot;, &quot;bio-inspired aquatic robot that can observe and interact with its surroundings while following a signal through water. (RFT'-PDR:p81). This requires an artefact that operates in an aquatic environment, mimics a fish's locomotion, can recognise and avoid objects. Since the project is motivated as a research tool to track real fish, it must also follow a signal. The solution is a complex robotic device that is simultaneously sealed from the environment and interacts with the environment, is neutrally buoyant, and automatically stabilises while responding to the environment, reads electronic inputs and responds intelligently to them.</td>
<td>SD++</td>
</tr>
<tr>
<td>'PT'</td>
<td>The product is conceptualised as an &quot;aesthetically pleasing&quot; (PT'-PDR:p4) battery operated mechanism for towing a light aircraft. The solution will first secure and then lift the nose wheel of the aircraft. Once the nose wheel is lifted above the ground the operator initiates the drive train to pull the aircraft while manually controlling the direction. The operation is primarily manual and sequential; although there were intended to be automated stops these were not included in the prototype.</td>
<td>SD+</td>
</tr>
</tbody>
</table>

It is immediately clear that the 'semantic density' of the prototypes is generally higher than the semantic density of the engineering theory used. This is evident in the fairly sequential application of various concepts, not intended to build coherent theoretical meaning, nor requiring coherent integration. The theory is drawn on in bits and pieces, used and then left for the next bit of theory. In contrast the material relations tend to be more complex. The prototypes conceptualised by 'RFT' and 'CT' teams require the integration of multiple parts all working in synchronicity to function. On the other hand 'PT' were quite intentional about simplifying their solution:
S: "... being a fairly small, fairly efficient design, we don't anticipate assembly or machining to take that long on our part, and so we're hoping to be able to get to test this within maybe three weeks or so." (PT-CDR:t12)

The results of the course clearly indicate that simplifying the solution was highly valued, something 'PT' seemed to understand better than either of the other teams. By conceptualising a solution that sequentially captures, then lifts then tows the light aircraft, 'PT' were able to avoid complications that arise with the integration of subsystems. In contrast, by conceptualising a solution that simultaneously lifts and twists the cap of a jar, 'CT' ran up against potential synchronisation problems. But what are the implications when a solution is necessarily complex? 'RFT's solution needed to integrate problems of buoyancy with those of sealing, an electronics system that responded to inputs in intelligent ways, and coding that involved multiple decision paths. 'RFT' produced a highly complex (I would argue necessarily complex) prototype. And while the instructor may have had sympathy for this as evidenced by his manipulation of the grading algorithm, the simpler solution was still more highly rewarded, even when it is not in fact fully assembled nor was it operational at the level specified in the design requirements.

4.6 Putting the analysis back together

LCT (semantics) was used to develop an understanding of what weakening classification means for design. The two distinct boundaries that were weakened were those between theoretical, abstracted disciplinary knowledge and the messiness of the everyday context in which the knowledge was applied; and the boundaries between distinct engineering disciplines as they are applied in various sequences and with various implications to the context. Semantic gravity is one useful concept for analysing the first boundary crossing and its partner, semantic density for the second boundary. However, because the ambiguous evaluative criteria condensed into the assembly and performance of the material product, with little recourse to discursive reasoning, or very strong semantic gravity, a second aspect of semantic density was introduced to account for the relative complexity of the material prototype. This final element points to the importance of simplifying the material design as far as possible, seen as weakening the semantic density. However, although analysed separately, it makes sense that these concepts are deeply entwined with one another. A simplified prototype reduces the need to draw on multiple theoretical disciplines simultaneously. An ability to move up and down semantic gravity, theorising and drawing the theory back to the material problem, or starting with concrete problems and abstracting principles in order to theorise the implications of potential solutions, gives the theory meaning and allows a strengthening of the discursive relations of semantic density.

If we compare the more complex prototypes (SD++), we see that the one team ('RFT') was able to consider and relate conceptual ideas from multiple disciplines simultaneously (SD+), and relate these conceptual ideas to the material implications of their product (SG-). The other team ('CT') did not appear able to either conceptualise in terms of multiple conceptual ideas simultaneously (SD--), nor to relate the conceptual ideas to the material implications (SG++/SG--). This suggests that even though the evaluative criteria
are based on very strong semantic gravity, in order to realise this students need to move smoothly up and down the semantic scale.

5. Implications for design thinking and learning

5.1 Knowledge matters

This research attempts to bring disciplinary engineering knowledge explicitly into the discussions on design thinking, and especially learning to design. The focus is on the shift required of students from conceptually organised disciplinary subjects, to knowledge organised by the context set up by a design problem. This goes some way to addressing the concern raised in engineering education reports over at least the last century, that despite courses in fundamental theoretical disciplines, many engineering graduates lack the skill to apply this knowledge in the complex problems encountered in the workplace (Grinner, 1955; J. King, 2007; Mann, 1918).

5.2 Shifting complexity to context

Some of the previous discussion may suggest that this is a bad course, or unusually poor pedagogy. This is not really the issue; these are fairly standard challenges faced in any mechanical engineering design course. In these kinds of design challenges, meaning resides in the performance of a prototype, or in LCT (Semantics) terms, in very strong semantic gravity. Similarly, simplifying the design concept as far as possible in order to reduce risk is an important, if perhaps somewhat tacit, goal of engineering design. Typically in engineering science courses the complexity lies in building complex conceptual relations within a particular disciplinary tradition. By contrast, in design, the complexity lies in holding together multiple disciplinary concepts in relation to the material object of design, sometimes sequentially, but sometimes also simultaneously. The semantic density of the material relations tends to be higher than that of the discursive relations, but as the complexity of the designed artefact increases, it makes sense that it is likely to force an increase in the requirements of semantic density of the discursive relations too.

5.3 Strengthening the framing

This understanding of engineering design was not what was presented in the course documentation, which seems to imply a stronger focus on the discursive relations than the material relations, and a weaker semantic gravity than actually enacted in the evaluation. However, the instructor did seem to attempt to strengthen the semantic gravity and draw attention to the artefact in the way in which he probed the students on very practical issues in their presentations throughout the trajectory of the course. There were also moments where he tried to weaken the semantic gravity of the team that got stuck in the material considerations by asking them to draw on theoretical concepts to predict performance. However, his attempts to shift the code was not always successful; those who could read the indicators were successful in their designs, while 'CT' did not seem able to make the shift. We need to find ways to help both those students who rely too
heavily on theoretical concerns and those students who are unable to translate practical concerns into theoretical form to understand what really matters in design. Presenting design in the common sense form of 'the application of sciences to solve practical problems' is inadequate for this more nuanced understanding of the relation between the science and the practical problem.

5.4 Implications beyond the data

However, locating the evaluation of design in only the material performance of the artefact, and more insidiously in apparently concrete claims of performance regardless of their accuracy is of far more concern. While it might not matter that a small aircraft-towing device does not actually tow at the claimed speed, the certainty with which the claim is made and the ease with which it is accepted without analytical justification or conceptual reasoning, is of concern. As a way of engineering 'being', this unreflective certainty seems problematic. It might have been appropriate in the 1950s, where just getting the job done was what mattered. But what about the uncertainty surrounding the complex problems the modern world faces in global warming and widespread poverty? For example, what are the implications for our future when the safety of fracking for gas in an environmentally fragile area like the Karoo is presented with the same level of certainty and lack of conceptual reflection, when in fact there is an extremely uncertain outcome? When we think about of the uncertainty surrounding the problems the modern world, and our hopes that they will be addressed by future engineers, should we not be rewarding those students who show the capacity to be more reflective about their designs than those who are perhaps a little too certain, a little too concrete?

We also need to consider how to distinguish between the necessary complexity of the designed artefact and poor design conceptualisation, against a backdrop that values design simplicity. Again, in the context of the growing complexity of the problems we face, simple solutions may not be adequate, how do we find ways to reward students who take on a necessarily complex design, holding together the multiplicity of disciplines to develop their design.

6. Making links across the DTRS 10 papers

The complex space that is design was amply demonstrated in the range of diverse topics covered in the presentations at the symposium. One theme that could be picked up in the symposium relates to the centrality of integration in various guises in design. Akın and Awomolo (2014) use syntactic analysis to identify dependencies between parts and infer integration. Secules, Gupta, and Elby (2014) use framing to compare messages that contribute to piecemeal versus integrated design approaches, and Ferreira, Christiaans, and Almendra (2014) use the notion of form as the basis of developing rules to investigate unification of an artefact. These are all akin in loose ways to my use of semantic density to analyse different dimensions of integration.

However, in most cases the technical background knowledge drawn on to design is left implicit. None the less, there were papers in the conference that refer to knowledge, for
example in the form of information sharing (Fleming & Coso, 2014); the nature of reasoning (Cardella, Buzzanell, Cummings, Tolbert, & Zoltowski, 2014; Cardoso, Eris, & Badke-Schaub, 2014; Christensen & Ball, 2014; Dong, Garbuio, & Lovallo, 2014; Howard & Gray, 2014; Yilmaz & Daly, 2014); and the role of artefacts in meaning making (McNair, Paretti, & Groen, 2014). However the nature of the knowledge and its direct link to the design artefact often remains tacit.

The focus in design research beyond the knowledge is perhaps an indication of just how different design is to many of the science, engineering or other discipline focused courses in educational programs. On the other hand, background knowledge may be more of a concern in engineering design than in some other disciplines, for example Lande and Oplinger (2014) show how functionality and completeness were primary in the mechanical engineering data, while passion for the product was more significant in the industrial design data. Goldschmidt, Casakin, Avidan, and Ronen (2014), in a comparison of different disciplines, also provide some evidence that in mechanical engineering students are expected to bring knowledge into the context themselves and the focus is perhaps more on theoretical validation than in the other design disciplines that they analysed.

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References


**Biography**

Nicky Wolmarans is an 'Academic Development Lecturer' in the department of Civil Engineering at the University of Cape Town. She holds a BSc and MSc in Mechanical Engineering and is currently registered for a PhD in the School of Education at UCT.