# *Inferential reasoning in design: Relations between material product and specialised disciplinary knowledge*

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*This study investigated how students* use *knowledge in a mechanical engineering design course. The findings suggest that the structural relations that students construct between the designed artefact and the knowledge recruited are more important than just the content knowledge. Using the semantics dimension of Legitimation Code Theory, LCT (Semantics), as the analytical lens, the findings suggests that students need to be able to shift fluently up and down a range of relative abstraction and concretisation, but always rooted in the concrete. In design, when the evaluation often lies in the performance of the artefact, an increase in the technical and functional requirements of the artefact drive the requirement for a more abstract and integrated use of the knowledge recruited.*


*Keywords: design knowledge, disciplinary knowledge, logic of design, reasoning*

Attempts to characterise the nature of design, and consequently what should be taught and learned in design courses has been a consistent challenge to the design research community. What has generally become evident from this broad ranging, but potentially fragmented research is the complexity of what it means to design (Dorst & van Overveld, 2009). As the design research community grapples with design processes, creativity, design thinking and the skills needed to design, underlying concepts of 'reflective practice' (Schon, 1984) and the notion of 'being' or 'becoming' (see for example Adams, Daly, Mann & Dall'Alba, 2011), have tended to dominate the research. In this collection of papers that analyse design review conversations between students and instructors from a range of perspectives, the general focus is on understanding the nature of reasoning as it is articulated throughout the design process.

The contribution of this paper is a study of the nature of reasoning using specialised disciplinary knowledge to design, specifically the way in which students mobilise disciplinary knowledge to design a material artefact in a simulated professional context. Where many design education researchers propose mimicking authentic practice in order to better develop design skills (see for example Bucciarelli, 2003), sociology of education theorists in the social realist

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www.elsevier.com/locate/destud
0142-694X *Design Studies* ■■ (2015) ■■–■■
http://dx.doi.org/10.1016/j.destud.2015.12.003

tradition (Moore, 2012) after Bernstein (2000) have argued that the context of education sets up particular knowledge and social relations that change or 're-contextualise' the discourse itself. The ambiguity that arises as a result of these conflicting social relations, and implications for assessment are developed in a companion paper to this one, based on the same empirical data (Wolmarans, in press). In this paper, the focus is on the structural relations that students construct as they work with specialised knowledge to design. While social realists have raised the importance of *knowledge* as an object of study, they have tended to focus on abstract generalisable knowledge. Design offers an interesting addition to that research because it requires the specialisation and concretisation of knowledge.

In taking a knowledge perspective on design this paper perhaps represents one extreme, very different than the more constructivist perspective taken by Adams, Forin, Chua, and Radcliffe (2016) at the other. However, there are traces of specialised disciplinary knowledge in the other papers, for example as the basis of deep reasoning (Adams et al., 2016), developing a balance between a "command of technical matters and the norms of practice" and "their own sensibilities" (McDonnell, 2016); and within the evaluative logic of functional originality (Christensen & Ball, 2016). The papers by Dong, Garbuio, and Lovallo (2016) and (Yilmaz & Dally, 2016) in this volume also look at how instructors influence shifts in the nature of reasoning, as cycles of abductive and deductive reasoning in the former and between convergent and divergent reasoning in the latter.

As part of the DTRS10 symposium, this paper draws on the shared data set generated for the symposium (Adams & Siddique, 2015) and develops an aspect of a paper presented at the symposium (Wolmarans, 2014). This study follows three mechanical engineering design teams through their Preliminary Design Review, Critical Design Review and into their Final Design Review and evaluation as they design and build a prototype device. The analysis uses one of the five dimensions of Legitimation Code Theory (LCT), LCT (Semantics) (Maton, 2014), to investigate the way in which students need to work with multiple disciplinary traditions while simultaneously moving between abstract theoretical knowledge and the material context of its application. The findings suggest that some students are less successful than others, not because of the knowledge they use, but because of how they use it.

# 1 Literature

## 1.1 Engineering design: science, design and professional skills

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. For this reason



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design plays an important role in engineering curricula. From the perspective of learning to design, there are three competing aspects to seeing design as the determining aspect of engineering practice. Firstly, design in a science-based profession takes the form of the application of scientific principles to solve design problems, but access to and the nature of application of scientific principles is often assumed to be unproblematic. This model of engineering design is evident in the reports on engineering curricula in the Anglo-American countries over the years. The Mann (1918) and Grinter (1955) Reports calls for strengthening the scientific foundation of engineering, but by the 1990s there was a growing concern that engineering science so dominated engineering curricula that students could not competently use the knowledge outside of the courses they learned it in. The solution was seen as increasing design in the curriculum (Harris, Grogan, Peden, & Whinnery, 1994; Seely, 1999). However, the complaint persists 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 …" (King, 2007, p. 7).

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. 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 …". The statement relates to the many skills needed to design, but also to the difficulty of taking knowledge learned in its abstracted and insulated form in engineering science courses, and recontextualising it within the complexity of a real context requiring both the recognition of appropriate disciplinary knowledge and the recontextualisation of that knowledge for application to a specific material artefact. And thirdly, design as practice becomes a mixture of knowledge, process and the enabling skills or graduate attributes needed for successful professional practice, a multitude of requirements that significantly detracts from the intellectual challenge of learning to design (Dym, Agogino, Eris, Frey, & Leifer, 2005). The specialised knowledge and the expertise required to use this knowledge seems often to be either assumed or ignored.

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 difficulty of recontextualising knowledge and the limitations for practicing



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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 Specialised disciplinary knowledge and design

All design disciplines draw to some extent on various bodies of specialised disciplinary knowledge, but in engineering design, the role of this knowledge tends to be more explicit than in some of the other design disciplines. Carvalho, Dong, and Maton (2009), using another of the five LCT dimensions, LCT (Specialization), label engineering a ‘knowledge code’, where the design discipline is legitimated on the basis of the power of predictive scientific knowledge. This does not mean that there are not important knowledge relations in all design disciplines, only that they might be expected to be more easily recognisable in an engineering design discipline (Dong, Maton, & Carvalho, 2015). Therefore, this study focuses on mechanical engineering design, as a paradigmatic case (Flyvbjerg, 2001) of design most likely to offer insights into the knowledge relations in design.

The role of disciplinary knowledge in design is not straightforward. There is plenty of critique of design presented as the application of scientific knowledge following a linear problem solving process (Dorst & Dijkhuis, 1995; Lawson, 2004; Visser, 2009). The alternatives, probably most notably design as a ‘reflective practice’ (Schon, 1984), tend to background specialised disciplinary knowledge in favour of the skills needed to design and a disposition of design, what is being called the ontological side of design (Adams, et al., 2011). While these aspects of design are critical, in this paper I want to lift disciplinary knowledge and the ways in which this knowledge is used from the many other aspects of design. Certainly the common sense notion of design as the application of scientific knowledge is far too simplistic, as Bucciarelli (2003) notes. On the other hand Cross (2003) studied the work of three expert designers and points out that one of the things they all have in common is that they tend to think from ‘first principles’, or foundational disciplinary knowledge. This is by no means an instrumental application of scientific knowledge, rather it is a form of inferential reasoning articulated with slightly different emphases by Winch (2010) and Abbott (1988).

Abbott (1988) introduces inference as a mode of professional reasoning intended to link problems with potential solutions through chains of coherent abstract relations, usually based on specialised disciplinary knowledge. He notes that specialised disciplinary knowledge is organised differently than



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either the problems encountered by professionals, or the cases that have served as solutions previously. However, as this study shows, linking abstract knowledge, organised by coherent conceptual structures, to material contexts, organised by problem or solution types (Abbott, 1988), is not necessarily intuitive for all students. Winch (2010) also works with inferential reasoning to develop a model of vocational expertise. Like Abbott he sees the importance of chains of reasoning within a coherent framework defined within a particular profession or vocation. But he recognises the framework as a network of relations of 'know how' and 'know what', where coherence is built up though experience over time. One of the challenges design students face is that they typically do not have an extensive catalogue of past problems and typical solutions to draw on, and are consequently more dependent on inferential reasoning to find design solutions than experienced professionals might be.

## 1.3 Social realism in the sociology of education: broadening access to 'powerful knowledge'

One of the more prevalent recommendations for improving design teaching is to simulate a professional design context in the classroom in an attempt to reproduce the logic of 'authentic' professional practice. For example, Bucciarelli (2003) identified the shift from convergent, well-defined problems in typical engineering science courses to ill-defined divergent problems in design as the principle challenge to learning to design. He attributed this to a 'disjuncture' in contexts between the logic of the academy and the logic of practice. Although there has been little research specifically applying Bernsteinian concepts to design, there is a growing body of literature on professional expertise and professional education in the social realist school of sociology of educations, see for example a collection of papers in Young and Muller (2014). This research tradition takes knowledge as the object of study, but also recognises that social relations have causal affects on the production and transmission of 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. The argument 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



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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 theoretical tradition and subjected to tests of empirical and descriptive accuracy defined by particular disciplinary practices (Young, 2000). 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 reasoning suggests that access to 'powerful knowledge' (abstract, generalisable theory) is best achieved through disciplinary separation in order to immerse students in disciplinary knowledge and practices of particular disciplines, and explicit pedagogy in order to make the requirements of the various disciplines clear. However, design necessarily works with multiple disciplinary traditions simultaneously and between theory and context, requiring a different structure of knowledge, more concrete and specific. The purpose of this study is therefore to look specifically at what students need to do in order to recontextualise the abstract, generalisable theory learned in other courses as they navigate disciplinary boundaries, and the boundary between theory and context.

### 1.3.1 LCT (semantics): design as multidisciplinarity in context

Legitimation Code Theory (LCT) is a conceptual framework developed in the Bernsteinian tradition to explore meaning from a knowledge perspective (Maton, 2013, 2014). Here, meaning will be taken to be 'how we make sense' of something, an idea or an object. LCT (Semantics), one of the five dimensions of LCT, consists of a pair of related concepts that analytically separate the relation of meaning to its context (semantic gravity) and the relative complexity of meaning condensed into terms, symbols, gestures etc (semantic density). In the analysis that follows, LCT (Semantics) provides a lens to investigate what it means to successfully 'apply theoretical knowledge to solve real world problems'. It helps to make more explicit some of the tacit dimensions of knowledge selection and application during design. Semantic gravity highlights shifts between abstraction (theoretical inferences) and concretisation (material prototype), and semantic density deals with the integration (multidisciplinary) of multiple disciplinary 'knowledges'. From an educational perspective, this framework provides design instructors with one way to think about helping their students learn to design using theoretical knowledge, in addition to the other skills and ways of being required.

Semantic gravity describes "the degree to which meaning relates to its context" (Maton, 2014, p. 110). Theorists have dealt with distinctions between abstract and concrete, or theoretical and practical knowledge, in different ways, but the analysis usually involves categorising something as either concrete or abstract (or a similar dichotomy). Semantic gravity, on the other hand, rather than categorising knowledge types looks at the relationship between knowledge and its object. This is a recognition that abstract meanings refer back to their concrete object; that an abstraction is relative to a concrete manifestation. Semantic gravity is usually characterised as stronger (SG+) or weaker (SG−), where SG+ suggests meaning relies strongly on its context and SG− suggests that meaning has been abstracted out of its immediate context of discovery or application. Seeing semantic gravity varying along a continuum allows one to "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 enables research to follow shifts in reasoning between the abstraction and concretisation, or inferences between the concrete prototype and abstracted concepts that inform design decisions.

Dong et al. (2015) have used semantic gravity, in conjunction with LCT (Specialization), to address on-going debates about what matters in design. Within their broader discussion, they argue that design needs to encompass a range of semantic gravity, from the weaker semantic gravity of, for example, general design principles to the stronger semantic gravity of specific design cases. They also associate a wider range of semantic gravity with the idea of cumulative learning (Maton, 2013), as a means of assisting students to transfer knowledge into new contexts. Georgiou, Maton, and Sharma (2014) present an interesting analysis of students working in physics, and the importance of retaining a connection with the concrete object under discussion.

Semantic density sets up a continuum of relative condensation or elaboration of meaning (Maton, 2014). Stronger semantic density (SD+) implies the integration of multiple ideas, condensed into a more complex, but coherent, idea. Weaker semantic density (SD−) implies simpler ideas, or the elaboration of complex ideas into component parts. Semantic density thus enables us to track the relation of theoretical concepts to one another, an element of inferential reasoning that can deal to some extent with the multidisciplinary inherent in design reasoning.

Semantic gravity and semantic density are usually (although not exclusively) considered together. Represented on a Cartesian plane with semantic gravity on the vertical axis and semantic density on the horizontal axis, trajectories in reasoning can be traced. For example Shay and Steyn (2014) use LCT



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(Semantics) to develop a coherent trajectory for learning in a design curriculum. But the four quadrants also suggest four distinct modalities of reasoning. The dominant modalities studied to date are the shift between SG+/SD− and SG−/SD + often referred to as a semantic wave (Maton, 2013) and associated with 'cumulative' learning (Maton, 2009). The semantic wave has been used in educational research across a range of disciplines (for example Blackie, 2014 in chemistry; Macnaught, Maton, Martin, & Matruglio, 2013 in teacher education). Semantic waves tend to suggest that elaborating complex meanings in terms of simpler concepts (SD−) is associated with concrete examples (SG+) and condensing meanings into symbolic form (SD+) is associated with abstracted meanings (SG−). However, it is important to remember the other two theoretically possible modalities SG−/SD− and SG+/SD+ (for example Shay (2013) uses the four modalities to interrogate curriculum differentiation in on going curriculum policy debates). I will go on to argue that SG+/SD+ is particularly important in design where much of the complexity can lie in the context, rather than in abstracted principles.

In the analysis that follows, semantic gravity is analysed first, followed by an analysis of semantic density. However, where most analyses of semantic density see the condensation of meaning in the abstracted form (SG−/SD+), the complexity in design tends to reside in the concrete form, which condenses the meaning of the device (SG+/SD+). In order to show this phenomenon more clearly, semantic density will be extended for application in material contexts.

## 2 Introducing the data: the course, the students and their designs

This study followed three teams of mechanical engineering students in their capstone design project through the design process to the final evaluative event. The course is a typical capstone design course in which teams of students design and build a prototype device in response to a perceived user need. But the teams performed with variable success in the course, and the research question directing this study was, within the complexity and ambiguity of design, how do the different teams use disciplinary knowledge in a way that might account for their differential success in the design course? Table 1 summarises the data used in the analysis. The study has implications for how we might understand design assignments, and how design instructors might assist more students to work successfully with disciplinary knowledge.

The CDR was a formal presentation of the design by the team, with interspersed questions from the instructor and in one case a fellow student. The FDR was a more informal discussion between the students and the instructor, where the material prototype was discussed and demonstrated.

**Table 1 Data sources analysed in the study**

| *Code* | *Event/document/s* | *Contents of data* |
|---|---|---|
| CP | Course prospectus | A hand-out provided to students at the beginning of the course detailing the course content and expectations. |
| PDR | Preliminary design review | A Preliminary design report from each team in the form of PowerPoint slides. |
| CDR | Critical design review | A video recording and transcription of the team presentation of the proposed artefact for budget approval along with the slides that supported the presentation. |
| FDR | Final design review | A video recording and transcription of the evaluation of the completed design, which included a presentation of a working prototype. |

The three teams performed quite differently in the course. The first team, let us call them the 'Prop Team' ('PT'), can be considered the most successful team. Their device was conceptualised as a battery operated mechanism for towing a light aircraft. The device was designed to sequentially secure, then lift the nose wheel of the aircraft. Once the nose wheel has been lifted above the ground, the operator initiates the drive train to tow the aircraft while manually controlling the direction. This team was assigned an unequivocal A for the project; was selected to participate in the final round of an innovation competition, and went on to win it.

The second team, the 'Robot Fish Team' ('RFT') conceptualised their design as a "bio-inspired aquatic robot that can observe and interact with its surroundings while following a signal through water." ('RFT'-PDR:p81). The prototype built was a complex robotic device that was simultaneously sealed from the environment and interacted with the environment, was neutrally buoyant, and automatically stabilised itself, read electronic inputs and responded intelligently to them. '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'), conceptualised their product as a mechanism to open jars remotely. The device needed to simultaneously twist and lift the lid of a sealed glass jar, potentially containing hazardous materials. This required 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 was a complex mechanism of multiple motors and drive trains electronically synchronised within a frame that provided the geometry for the mechanism.



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# 3 Analysing knowledge relations

## 3.1 Analysis of a code clash: course objectives vs evaluative criteria

In order to understand the knowledge requirements of the course, a comparison of the course presented in the course prospectus (CP) (course objectives) and enacted in the Final Design Review (FDR) (evaluative criteria) was made. The analysis suggests different priorities between the two. These conflicting principles of legitimation are what in LCT is referred to as a code clash. The course was presented as a typical engineering design course: "[T]he purpose of this course is to offer guided practice in integrating various engineering sciences into practical engineering design projects" (CP:p1). The CP tends to foreground the role of theoretical knowledge, for example "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). While details of the material prototype were limited to "Prototype assembly will occur in rooms in the … laboratory " and "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). Although the theory was intended to be used to design, it was the basket of available theory rather than the performance of the material prototype that was the focus of the Course Prospectus; this suggests weaker semantic gravity (SG−).

In contrast, during the evaluation, students were required to demonstrate their prototype device. The instructor in the role of assessor presented 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). Although the students were invited to elaborate any reasons for deviations or limited functionality, this was not in fact pursued in the FDR. The FDR backgrounds the theory in favour of the complete assembly and operation of the prototype. Meaning was dependant on the performance of the material product itself (in that it defined what it meant to pass or fail), not the theory used to do the design. The semantic gravity was substantially stronger (SG+).

In terms of semantic density, no indication of the complexity of either the prototype device or the theoretical requirements was given in the CP. Typically the direction taken by the designed artefact would dictate both what theory and to what depth it is required. But the students are left to make these interpretations themselves. In comparison to disciplinary subjects, where the theoretical complexity is defined by the lecturer (within curriculum choices), here



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the theoretical complexity is defined by the requirements of the prototype as the design emerges.

The brief comparison of the CP and the FDR indicates conflicting principles of legitimation (*what appears to matter* in the CP is different to *what really matters* in the FDR), a 'code clash'. In order to investigate how students navigate these code clashes with differential success, finer-grained scales of semantic gravity and semantic density were developed in conjunction with the data to provide a basis of comparison between the three teams. The analysis of semantic gravity is presented first, followed by semantic density.

## 3.2 Semantic gravity: reasoning in relation to the material prototype

In order to investigate the patterns of inference students appear to be using as they make decisions about their design, semantic gravity offers a lens to focus on the relationship between abstracted theory and the material prototype. A four-point scale was developed; with the first distinction being whether theoretical or material considerations led the reasoning, and the second on the connection between the theoretical and material considerations (Table 2).

### 3.2.1 'Cap Team' remote jar opener

'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 failed to theorise the nature of the idealisation and the possible implications for a real model. The understanding of the design seemed to be held completely in the idealised model (SG−−) in the earlier stages of the design. This exchange with a student in the audience ($S_a$), illustrates the point. The student is trying to draw their ($S_{'CT'}$) 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?"
> S'CT': "Yeah, there'll be a … slight lift … once we start rotating the top."
> Sa: " … how you're co-ordinating the two − rotating with lift - "

**Table 2 Semantic gravity (relation between theoretical and material considerations; abstraction/concretisation)**

| | | |
|---|---|---|
| SG−− | Reasoning is led by theoretical considerations | Theoretically abstracted or idealised, but disconnected from product of design or neglects material realities. Reasoning remains in abstracted or idealised form. |
| SG− | | Reasoning is led by theoretical considerations (abstracted or idealised models), but knowledge is specialised to the product based on material realities. Abstract reasoning is directly linked to material practicalities. |
| SG+ | Reasoning is led by material considerations | Reasoning is led by practical considerations (empirical tests or material limitations) but informed by theoretical or conceptual considerations. |
| SG++ | | Practical reasoning based on empirical testing or material considerations, but (apparently) devoid of theoretical or conceptual considerations. |



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> S'CT': " … 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++).

> $S_{'CT'}$: "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 the theoretical idealisation of the prototype in the CAD model and the practical implications inherent in the material product, either completely idealised (SG−−) or completely material (SG++). The team appears to struggle to relate the idealisations or theoretical concepts to their prototype, or to abstract the material realities using theoretical concepts.

This inability to abstract ideas *might* account to some extent for the fact that this is the only team not to present any conceptual alternatives. A conceptual analysis between solutions requires some level of abstraction if comparisons are made on a principled basis. The focus exclusively on a 'material' solution, suggests limited appreciation for the power of principled reasoning. This is consistent with their presentation of the idealised model and theoretical equations as separate from and barely related to the material prototype.

### *3.2.2 'Prop Team': light aircraft tow*

In contrast, 'PT' also built a CAD model of their mechanism, but they seemed to use the model to inform design decisions more effectively. They are able to link the idealisation to the material implications more explicitly. For example,



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> "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 that theoretical knowledge (in the form of continuum mechanics) leads the reasoning, but the knowledge is used to inform practical decisions, and make changes to the material product (SG−).

Like 'CT', 'PT' was very concerned with material practicalities of their problem (SG++), the bulk of their research into their design relates to benchmarking other similar models, which were 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:

> $S_{'PT'}$: "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++ dominated the mode of reasoning used by 'PT', they also at times weakened 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' skipped 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 between.

### 3.2.3 *'Robot Fish Team': robotic fish*

'RFT' began their design with a strong theoretical bias, however it was always theorised in terms of their material artefact (SG−). It is most interesting that in both their CDR and FDR their instructor tried 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 is 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? …



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$S_{'RFT'}$: 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 researched biological aspects of fish in order to determine their design criteria, and did 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 was always specialised to the material prototype. This same theorised reasoning was applied sequentially to each of the decisions about which possible form each subsystem or component should take as they conceptualise their 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.

### 3.2.4 Implications for assessment

Although each of the teams tended to favour a different mode of reasoning, the final evaluation was based on the extent to which the prototype was assembled and functional, with no expectation of reference to any form of theoretical abstracted reasoning that led to the material product (SG++). There might have been 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 led by the students, suggests theoretical understanding was



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not actually relevant to grading in this case. 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 was extremely slow and the instructor asked about the speed in relation to their design criteria:

I: And what did our top speed end up being in this?
S'PT'1: We did not measure it.
I: What do we think it is? …
S'PT'1: Roughly two miles an hour, or –
S'PT'2: 2 miles an hour.
I: What did we plan, 3.5, or something?
S'PT'1: 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 $ms^{-1}$), a moderate walking pace. The video shows that the airplane was towed less than three feet in more than 10 s (an order of magnitude slower than claimed). It may take some time for the motor to get up to towing speed, but it is significant that the instructor did not query this or further engage; he merely accepted their assertion. A similar social dynamic is evident in the exchange over the omission of the phototransistors from the assembly (a safety feature intended to stop the mechanism from overrunning). The students confidently declared, "No, we don't need more time. It was not a critical function of our design." ('PT'-FDR:t2) And the prototype was considered fully assembled. The students were graded an A, and went on to win the innovation competition.

Both these examples were presented as concrete statements of fact (SG++). There was 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 have understaood. In contrast, 'RFT' were far more tentative about their claims of performance, and the instructor suggested the design was worth a B+ because although their fish was sealed, swam (with neutral buoyancy, depth control and roll stability) turned and responded to avoid obstacles (although far slower than desired), it did not have the tracking system initially conceptualised. By reducing the scope of the design, to exclude tracking, the instructor did concede an A to the team. It is notable that 'RFT' did 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 using explicit theoretical inferences



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did not appear to carry as much significance in this evaluation as the stronger semantic gravity of the claims made by 'PT'.

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

## *3.3 Semantic density (discursive relations): reasoning in relation to multiple theoretical disciplines*

In addition to a process of reasoning that shifts smoothly between abstracted principles and concrete particulars, design has a sense of integration about it. Semantic density provides a lens for sharpening our focus on the aspect of integration of meanings. As with semantic gravity, a scale of semantic density is developed below. In this scale, the form of the inferential relations between the various disciplinary 'knowledges' recruited is described. The first distinction relates to whether or not the disciplinary implications are considered in relation to one another, and the second distinction relates to the level of integration or separation of the disciplines. It should be noted that this is a slightly different operationalising of semantic density than is seen in terms of condensation of meaning, rather it looks to integration of meaning (Table 3).

There is little in the way of evidence of SD++ in the data. The development of the CAD and AnSys modelling tools might be considered SD++, 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. This is consistent with design as application of abstract concepts rather than design as the development of abstract concepts. But it is a different code than what might be experienced in other senior engineering science courses.

'RFT' are the only group that appeared to explicitly draw inferences across multiple disciplines (SD+). For example,

**Table 3 Semantic density (relation between multiple theoretical disciplines)**

| | | |
|---|---|---|
| SD++ | Multiple disciplines considered in relation to one other | Integration of concepts spanning multiple disciplines into a coherent complex whole. |
| SD+ | | Sequential application of concepts spanning multiple disciplines, but with consideration of implications from other disciplines. |
| SD− | Disciplines considered in isolation from one other | Sequential application of concepts spanning multiple disciplines, but with no apparent consideration of implications from other disciplines. |
| SD−− | | Separation of meaning evident in disparate bits used as facts. |



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"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." ('RFT'-CDR:t19).

The design of the mechanism that creates the fish's motion draws on links between a 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. In fact in most cases this team appeared to consider the theoretical insights from multiple disciplines in relation to each other.

In contrast, although 'PT' used theoretical concepts from multiple disciplines to make inferences about their design, they tended to consider the theoretical concepts sequentially and only related in a linear chain of consequence. "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." ('PT'-CDR:t9). Students were 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 was no need to consider multiple theoretical implications in relation to each other.

'CT' do apply of torque, force, pressure and some basic strength calculations. But the students appeared to apply equations rather than concepts as individual components. There was little evidence of the development of integrated or coherent conceptual reasoning.

" … 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. " ('CT'-CDR:t11).

Although a number of ideas were considered, each potential source of 'error' is treated independently of the others.

In terms of getting a working prototype, it is clear that integrating complex meanings across multiple disciplines simultaneously was not a requirement for success in this particular course. Rather than developing and integrating complex understandings, relatively basic theoretical constructs, applied in sequence could be adequate. But separating meaning from the concepts, as seemed to be that case for 'CT' limits their capacity to make meaningful theoretical inferences about their device.



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### 3.4 Semantic density (material relations): implications of complex material devices

What is less clear, when looking at theoretical complexity (the relations between multiple theoretical ideas) in isolation from the product of design, is the dependence of theoretical complexity on the inherent complexity of the material product (the number of components that fit together and the relations between them as the artefact operates).

Expanding the idea introduced by semantic density to the material product provides an additional layer of insight into the designs. Recognising 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 multiple ideas into 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 (Table 4). 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). The material relations refer to the actual built artefact, regardless of the knowledge underpinning its intentional design. Making sense of the material relations lies in the demonstration of effective construction and performance of the artefact, as a result of the relations between the parts. In social realist terms, meaning is condensed into performance. Discursive relations are the relations between various 'knowledges' and knowledge practices.

All three teams design complex material devices, with multiple subsystems linked dependently on one another. But the prototypes conceptualised by 'RFT' and 'CT' teams require the integration of multiple parts all working in synchronicity to function (SD++). On the other hand 'PT' were quite intentional about simplifying their solution (SD+):

> 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,



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**Table 4 Developing an equivalent material relation for semantic density**

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

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 was not in fact fully assembled nor was it operational at the level specified in the design requirements.

It is immediately clear that the 'semantic density' of the prototypes designed 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, requiring the successful integration of multiple subsystems in order to work.

# 4 Discussion

## 4.1 Contributions of a knowledge account of design to design education

LCT (Semantics) was used to investigate the nature of inferential reasoning in design. In the case of design, knowledge tends to transition across two distinct boundaries, those between theoretical, abstracted disciplinary 'knowledges' and into messiness of the everyday context in which the knowledge is applied.



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LCT (Semantics) allows us to analyse these two boundary crossings separately. Semantic gravity was used to investigate the relation between specialised disciplinary knowledge and its context of application (the designed prototype), and its partner, semantic density was used to investigate the integration of multiple disciplinary specialisations.

The comparison between the course prospectus (motivating the use of specialised disciplinary 'knowledges': SG−) and the evaluative event (dependent on the assembly and function of the prototype device: SG+) highlights one of the ongoing tensions in design. Although the analysis was focused on the manner in which the students articulated their reasoning about their design in relation to this code clash, it also hinted at the role the instructor played in assisting students navigate the ambiguity. This investigation of a single instantiation of evaluation within a single mechanical engineering design course should not be read as either a definitive emergence of an engineering design course and its evaluation, or a specific critique of one instructor. On the contrary, it serves rather to surface some of many elements of ambiguity inherent in design and design teaching. Unless we develop sharper conceptual tools to identify these sorts of ambiguities, they are likely to remain tacit, complicating any efforts to unify evaluation across courses and between instructors, and restricting access to powerful design strategies to those students who intuitively 'get it'.

These are fairly standard challenges faced in any mechanical engineering design course, where the evaluation often resides in the performance of a prototype, or in LCT (Semantics) terms, in very strong semantic gravity. Consequently, simplifying the design concept as far as possible in order to reduce risk is an important, if perhaps somewhat tacit, goal of engineering design. More important, is the significance of the nature of design in relation to engineering science courses students are familiar with. 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.

Because the evaluative criteria in this course were condensed into the assembly and performance of the material product, with less recourse to discursive reasoning, 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. 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



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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 (either SG++ or SG−−). This suggests that even when 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 gravity scale.

This account of the details of inferential reasoning in design goes some way to pointing out the difficulty of applying specialised disciplinary knowledge in order to design a material artefact. It offers a language for design instructors to negotiate and make explicit a range of potential evaluative criteria in a design course. And it provides a way of thinking about different ways of reasoning that might help instructors to assist more students to use 'powerful knowledge' more effectively. It may help instructors to consider the implications of individual designs, where some students design more complex artefacts than others, sometimes necessarily, sometimes not. It is intended to directly address 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 (Grinter, 1955; King, 2007; Mann, 1918).

## 4.2 Speculating beyond the data

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 was made and the ease with which it was 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 of the modern world, and our hopes that they will be addressed by future engineers, should we not be rewarding



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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 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. 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.

## Acknowledgements

I would like to thank the reviewers, and hope that I have done justice to your insightful and constructive suggestions. Thanks to the organisers and participants at DTRS10, it was truly an extraordinary experience. This research was partially funded by a NRF Thuthuka (PhD Track) Grant TTK1206191463 which made my attendance at DTRS10 possible.

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