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Engineering science and pure science: do disciplinary differences matter in engineering education?

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BACKGROUND

The traditional engineering curriculum takes engineering students from foundation courses in the basic sciences and mathematics to engineering science courses that form the core of the qualification and the resource students draw on in their capstone design courses. An unproblematic transition from the science courses to the engineering sciences is often assumed, and what little consideration is given to student difficulties usually focuses on teaching techniques and novel classroom practice. Scant attention is given to something more deep-seated: fundamental differences in the disciplines.

In his seminal study in the early 1970s Biglan (1973) developed two sets of binaries to describe disciplinary differences: hard/soft and pure/applied. In these terms basic sciences can be described as hard-pure and engineering sciences as hard-applied. However, there are those (de Figueiredo, 2008; Johnston, 1999; Layton, 1986; Vincenti, 1990) who would argue that engineering knowledge is more than applied science: it has different purposes, uses different methods to produce distinctly different knowledge with different outcomes. However, the work done in this area tends to remain at the level of conjecture about fairly superficial differences in the content of the disciplines.

The work of British sociologist Basil Bernstein is extensively used in the sociology of education in general and in the sociology of knowledge in particular. Bernstein (2000) describes the pure sciences as examples of singulars: fields of study that have appropriated spaces for themselves with clear maintenance of disciplinary boundary. Engineering is described as an example of a region, with orientations towards both the singulars from which it draws, and the world of practice. The Bernsteinian theory provides us with a language to describe disciplinary difference and to differentiate between knowledge-as-research and knowledge-as-curriculum.

PURPOSE

This study draws on Bernsteinian theory to grapple with underlying structural issues around disciplinary difference and the possible implications of these for teaching and learning in engineering. The study also attempts to contribute to the conversation about the nature of engineering knowledge.

DESIGN/METHOD

In order to explore differences in the disciplinary knowledge structures that go beyond dissimilarities in content, the study looks at how the same knowledge (First and Second Law of Thermodynamics) is approached in an undergraduate physics and mechanical engineering course at a research-intensive South African university. Using Bernstein's theory involves the development of a robust external language of description which starts off with the high level abstract concepts of the theory and 'translates' these into the empirical setting of the study (the physics and mechanical engineering classes).

RESULTS

Significant differences were found in the way thermodynamics knowledge is structured in the physics curriculum compared to the way it is structured in mechanical engineering. The paper reports specifically on the notion of 'useful' knowledge and the relation between theory and context in the different disciplines.

CONCLUSIONS

The underlying structural differences between pure science knowledge and engineering science knowledge have implications for the way in which courses are taught in undergraduate programmes. Students have to negotiate these fundamental differences as they progress in their academic career, and foregrounding the differences explicitly in the pedagogic practice is likely to assist students. In addition it is anticipated that the theorised approach adopted in this study will contribute to the scholarly discourse around the nature of engineering science knowledge.

KEYWORDS
Engineering knowledge, knowledge structures, disciplinary difference

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> *"If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations — then so much the worse for Maxwell's equations. If it is found to be contradicted by observation — well, these experimentalists do bungle things sometimes. But if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation." — Arthur Eddington*

The data presented in the paper is part of a larger study in engineering education concerned with the nature of disciplinary knowledge, and in particular the different kinds of knowledge engineering students have to negotiate as they progress through their academic career. For engineering students the earlier part of their professional education focuses on the basic sciences, and courses in mathematics, physics and chemistry typically form the bulk of their first year curriculum. From their second year onward the focus of the curriculum shifts towards courses in the engineering sciences determined by the particular branch of engineering in which they specialise. A clearer understanding of differences in the knowledge structures might give insights into implications for the professional education of engineers.

The study draws on the theory of British sociologist of education, Basil Bernstein, and explores the use of concepts from a Bernsteinian framework to explore knowledge structure differences between pure and engineering science knowledge in the curriculum. As such the study is positioned to contribute to the conversations in the community of Bernsteinian scholars around the nature of professional knowledge and professional education, as well as to conversations in the community of engineering educators on the nature of engineering knowledge and its potential implications for pedagogy.

The purpose of the study is to explore the underlying structural issues around disciplinary knowledge differences in an attempt to answer the question of whether differences in disciplinary knowledge structures are significant in engineering education, and if so, what possible implications this could have for teaching and learning in engineering.

Student transitions and the nature of knowledge

Engineering students face a number of transitions in the course of their professional education. The transition from secondary school into university has received much attention in recent years. Massification of higher education across the world has brought an increasing conviction that the gap between the typical school leaving qualification and the demand posed by first year university education has widened - see for example Baillie (1998) in Australia, Pascarella et al. (1996) in North America and Harvey et al. (2006) in the UK.

Engineering educators are also aware that students find the transition into engineering design problematic: the capstone design courses pose particular challenges with their demand to integrate knowledge from different subject areas to synthesise solutions to ill-defined, complex and open-ended design problems. This has received attention in some engineering education research projects (see, for example Christie & Maton, 2011; Kotta, 2011; Marin,Armstrong & Kays, 1999).

However, I would argue that there is yet another transition that engineering students with which have to contend: the traditional engineering curriculum moves engineering students from foundation courses in the basic sciences and mathematics to engineering science courses that form the core of the qualification and the resource students have to draw on in their capstone design courses. An unproblematic transition from the science courses to the engineering sciences is often assumed, and what little consideration is given to student difficulties in these courses usually focuses on teaching techniques and novel classroom practice. Scant attention is given to something much more deep-seated: fundamental differences in the disciplines.

In his seminal study in the early 1970s Biglan (1973) developed two sets of binaries to describe disciplinary differences: hard/soft and pure/applied. Others (Becher, 1994; Kolb, 1981) have built on this work. Biglan proposed three dimensions (characteristics) for distinguishing between different disciplines, two of which have relevance for this study: the extent to which a paradigm exists in the discipline, and the extent to which there is a concern with application. He used the term paradigm in the Kuhnian sense (1962) to refer to the consensus around theory (what is known), and to what constitute suitable methods to investigate problems appropriate to the discipline. Subject areas with a high degree of paradigmacity are associated with the term 'hard', and those without, with the term 'soft'. The second dimension enabled Biglan to distinguish between 'pure' and 'applied' disciplines: those, like education and engineering, with a concern for application, and those, like physics and english, with much less concern for application of the knowledge.

In these terms basic sciences can be described as hard-pure and engineering sciences as hard-applied. However, is engineering science mere applied science? There are those (de Figueiredo, 2008; Johnston, 1999; Layton, 1986; Vincenti, 1990) who argue that engineering knowledge is more than applied science: it has different purposes, uses different methods to produce distinctly different knowledge with different outcomes. However, the work done in this area tends to remain at the level of conjecture about fairly superficial differences in the content of the disciplines. In addition no distinction is made between knowledge generated by experts in the field and knowledge as it is taught to students in undergraduate curricula.

Theoretical framework from the sociology of education

Much current research in higher education focuses on constructivist and positivist approaches with little attempt to move beyond fairly superficial descriptive accounts. Ashwin (2009) insists that these approaches either ignore issues of structure and agency, or at best emphasise student agency (eg. approaches to learning), while neglecting the effect of structural issues in teaching-learning interactions.

The work and theory of Basil Bernstein is widely used in the sociology of education and in the sociology of knowledge in particular (Ashwin, 2009; Maton, 2008; Moore & Young, 2001; Muller, 2009; Sadovnik, 2001; Wheelahan, 2006; Young & Muller, 2007).The Bernsteinian theory provides a language of description that is powerful enough to allow us to grapple substantively with issues around disciplinary knowledge structures. Its conceptual tools also allow for a distinction to be made between the knowledge constructed in research by discipline specialists (in what Bernstein calls the Field of Production), and how that knowledge is adapted (recontextualised) into curriculum knowledge (Bernstein's Field of Recontextualisation). It further allows us insight into what constitutes pedagogic practice (since the intended curriculum does not materialise unproblematically into classroom practice).

According to Bernstein, physics and chemistry are examples of *singulars* with strong hierarchical knowledge structures. He describes a singular as a knowledge structure comprising "a specialised discrete discourse with its own intellectual field..." (Bernstein, 2000, p. 52) with few references to other external fields. Singulars are protected by strong boundaries and characterised by a certain "inwardness" (Young, 2008, p. 156).

Engineering, like medicine and architecture, is an example of a *region* because of its relation to the field of practice. The study uses a finer grained approach to 'engineering' as a field of study by using one of the engineering sciences as a starting point. The engineering sciences are applied fields of study with their roots in the pure sciences, but with a strong orientation towards the engineering profession. Therefore the various engineering sciences (rather than 'engineering') can be described as regions, because of their explicit reference to the world of practice, in addition to their orientation to the singulars like physics and chemistry.

Bernstein uses the concept of *classification* to describe the nature of the boundedness of categories. Singulars with their strong "degree of insulation" (Bernstein, 2000, p. 99) have stronger boundaries, and are therefore described as having strong classification. With their orientation towards practice, regions have weaker insulation, resulting in more permeable boundaries, and therefore weaker classification. The recontextualising of regions from singulars would then always result in a weakening of classification. The question is how the weakening of classification works in practice.

Project design and operationalising the theory

The project was designed to allow the researcher to look at the same knowledge as it is recontextualised in two different disciplines, both of them with strongly hierarchical knowledge structures, one a singular, the other a region. The data was collected in a mechanical engineering science course (thermofluids) and a section of a physics course, addressing the same knowledge, namely thermodynamics. The focus is on how the curriculum knowledge is embodied in the classroom. Data was collected in lectures by taking detailed notes alongside course notes and audio-recording lectures.

The study describes attempts to operationalise this process of regionalisation. It seems reasonable to expect to see evidence of the essential difference between singulars and regions (the macro context of knowledge structures) in the recontextualised micro context of the enacted curriculum in the lecture room.

The empirical setting of the study is a contained set of laws and concepts in thermodynamics as it is taught in physics as an example of a singular, and in the engineering science course as an example of a region.

An early indication of what follows in the two disciplines can be seen in the way in which the field of thermodynamics is introduced. In the physics course thermodynamics is combined with statistical mechanics, and the overall approach to thermal physics is a statistical one. The physics class notes describes thermodynamics as [the field of study that] describes macroscopic properties of a system in equilibrium and the relationships between them (eg. pressure, temperature, volume, internal energy etc.) without any consideration of microscopic interactions. Statistical mechanics provides the connection between thermodynamics and the statistical behaviour of microscopic constituents.

The mechanical engineering textbook gives the following description: "The name thermodynamics stem from the Greek words *therme* (heat) and *dynamis* (power), which is most descriptive of the early efforts to convert heat into power" (Cengel & Boles, 2011, p. 2). The regionality of the engineering description with its reference to the field of practice and its concern with useful energy is signalled early on.

Thermodynamics is a particularly interesting field to explore in the context of singulars and regions, as the Field of Production of the body of thermodynamics knowledge currently taught in undergraduate university courses clearly shows traces of the influence of both the pure science singulars as well as the typical engineering applications. A clear illustration of this can be found in the work done by James Watt and Sadi Carnot on early heat engines: Watt is remembered as someone with an 'engineering bent' because of his work to improve the efficiency of one of the earliest versions of the steam engine, whereas Carnot exemplified the work of the physicist in his theoretical and mathematical explanation for the improvement. This two-pronged stimulus to knowledge growth in the Field of Production of thermodynamics knowledge is rather emblematic in the history of the development of thermodynamics.

We now turn to the slice of data selected for the purpose of this paper.

Results and analysis

"Work done by the system is positive – it is good for us!"

One formulation of the First Law of thermodynamics states that energy cannot be created or destroyed, but can be transformed from one form into another; the total amount of energy in a system and its surroundings is therefore constant. This can be stated mathematically in different ways, and involves stating a sign convention. In this case it has an impact upon the formula used for calculating energy.

The internal energy of a system may change by either transfer of heat (Q) or by work (W) being done. In physics (the science singular) the formula used is $\Delta E = Q + W$, with ΔE the total change in internal energy of the system, Q the energy transferred as heat, and W the amount of work done. According to the sign convention used in the physics course, work done on the system is taken as positive ($W_{on\ system} > 0$) , and work done by the system is negative ($W_{by\ system} < 0$). Physics displays its singular characteristics here in the very careful way in which concepts are defined, and in the reasonable and perfectly logical appeal of defining the total change in internal energy of a system in the form of a sum of quantities. One of the consequences of defining the work done by the system as negative in this way, is that when the system does work, energy is 'lost' from the system to the surroundings.

In the mechanical engineering course (the engineering science region) the formula used by the lecturer to calculate the total internal energy is $\Delta E = Q - W$. This is because of the definition of the terms Q and W: Q is 'the net heat input' into the system (similar to the definition used in physics) and W is the 'net work output' of the system(arguably the terms 'input' and 'output' could already be seen to be signalling an engineering rather than pure science environment!). For an engineer the purpose of a heat engine is to produce useful work, and so in the engineering lectures the sign convention employed is such that the work done by the system is defined as a positive quantity ($W_{by\ system} > 0$), or, in the words of the engineering lecturer: "Work done by the system is positive – it is good for us!" . The engineering science's disciplinary logic insists that (desirable) work produced by the system is a positive quantity, even if it means an arguably more idiosyncratic formula has to be used.

There is an arbitrariness fundamental to the nature of a convention as described here, and it is therefore conceivable that somewhere engineering students might be taught that $\Delta E = Q + W$, but the international textbooks used in the courses seem to confirm the notion that the difference between the science course and the engineering science course might be significant.

"Entropy scares ... an engineer!"

In the course of the discussions of the Second Law of thermodynamics and its effects, the concept of entropy is introduced, defined and derived, starting, in both courses with reference to the irreversibility of some processes: a cup of hot coffee cools down, heating a metal wire will not produce electricity, etc. It is in the approach to entropy and the Second Law of Thermodynamics that the differences between the physics singular and the engineering science region are most pronounced.

In physics the Second Law is approached from statistical thermodynamics: the average behaviour of large groups of individual particles is introduced, and the point is made that irreversible processes are not inevitable, but just overwhelmingly improbable. This is done at an abstract mathematical level: the numbers of ways in which energy quanta can be distributed amongst atomic oscillators is calculated and proving that the most probable macrostate of atomic oscillators is the only likely one. The Second Law of thermodynamics is stated in terms of the tendency of a closed system towards maximum entropy. It is emphasised that (as stated in the First Law of thermodynamics) even though the total energy of an isolated system remains constant, the distribution of energy changes: spontaneous processes lead to a more disorderly dispersal of the total energy, and that entropy is a measure of the macrostate disorder of the system. These are theoretical concepts that apply to the whole of the cosmos in a similar way as they apply to a cup of coffee cooling down. This is an example of the high value is placed on generalised and generalisable knowledge in the physics singular.

In the engineering science there is very little need for a probabilistic approach to the Second Law, and classical thermodynamics is used. For the solving of typical engineering problems a macroscopic approach is sufficient and no knowledge of the behaviour of individual particles of systems is required. Empirical properties such as volume, temperature, pressure and composition of fluids are important in the engineering context and examples covered involve consideration of the internal combustion engine, steam turbines in power plants, flow mixtures in reactors etc. That these bulk matter properties arise from microscopic properties of individual particles is of very little interest in the engineering course.

The classical thermodynamics approach to the notion of dispersed energy as a result of processes a system undergoes is rather different in engineering science. It is pointed out that one of the implications of the Second Law is that energy has quality as well as quantity. The First Law is concerned with the quantity of energy and the transformations of energy from one form to another with no regard to its quality. The Second Law provides the necessary means to determine the quality as well as the degree of degradation of energy during a process. This notion of degrading of energy again speaks to the practical concern of engineers with usefulness of processes ('degradation' of energy carries a near normative connotation, compared to the more neutral terminology of dispersal of energy in physics). In engineering science the Second Law of thermodynamics is also used to determine the theoretical limits for the performance of commonly used engineering systems: efficiency of a heat engine is a central concern for the engineers. This was vividly underscored in the colourful comment of the mechanical engineering lecturer: "Entropy scares the hell out of an engineer!"

Discussion

How do we now talk about the data described above in terms of the theory tools provided by the Bernsteinian theoretical framework?

The "epistemic destiny" (Muller, 2009, p.209) of knowledge in science is the pursuit of increasingly abstract and general propositions. This is a consequence of the inward orientation of singulars – they have "very few external references other than in terms of themselves" (Bernstein, 2000, p. 9). Singulars like physics relate to the external world by way of empirical validation of knowledge: knowledge claims can be refuted or verified by empirical means. This is also seen in the way in which mathematics is often handled in the singulars in the development of derivations and proofs, which becomes the way a singular like physics will 'argue its case'. This was illustrated in the data in the careful definitions and neutral sign convention chosen. The point was made powerfully by the use of the statistical mechanical approach to account for the microscopic properties that give rise to macroscopic properties of matter.

Regions, like engineering science, are different: "Regions face inwards towards singulars and outwards towards external fields of practice" (Bernstein, 2000, p. 55). There is a certain tension in the inward and outward orientation of regions (Young, 2008), and the strong link with the external world is very different in nature: the engineering profession deals with a particular type of problem-solving in a 'real world context'. Applied knowledge like that of the engineering sciences has a strong focus on utility. Following Muller one could describe the epistemic destiny of engineering science knowledge as the pursuit of fitness for purpose. It is in this particular relation to the external world that classification is weakened and regionalisation results.

Implications for teaching and learning in engineering: some speculation

The results from the study seem to hint at some fundamental differences in the way in which the same knowledge (First & Second Laws of thermodynamics) is structured in different disciplines. The study itself was not designed to look at the impact of these differences on teaching and learning in the disciplines, and further research is needed.

However, an argument could be made that engineering students who have to negotiate moving from pure science courses into engineering science courses might find the transition problematic because of the different demands made by the structural differences in the valued knowledge in the different disciplines. It is possible that quite different thinking skills are required for the abstract generalised approach of the pure sciences compare to the highly situatedness of the engineering sciences. Good pedagogic practice would require the teacher to induct students into the significantly different orientation that is required, and foregrounding the differences explicitly in the pedagogic practice is likely to assist students. How this should best be done lies beyond the scope of the study described.

Conclusions

The study described in the paper attempts to describe a way to theorise differences in closely related, but distinctly different disciplines. In this an attempt was made to contribute to the scholarly discourse around the nature of engineering science knowledge. The data collected contributes empirical referents to aspects of Basil Bernstein's theory of knowledge: it provides a way in which regionalisation of knowledge can be understood.

The most significant finding from the study is the demonstration of the different way in which the same knowledge is recruited for different purposes in the two disciplines. Both disciplines with their hierarchical knowledge structures have empirical referents in the external world, and therefore a 'context' they refer to. The way physics as a singular deals with the empirical world is to enlist an idealised version, because of the value it places on abstract generalisable theoretical knowledge. The context is often the laboratory, or an idealised account of an every-day-life context. This was illustrated in the data in the precise definitions of quantities and the universal abstract form of the equation, in the strong emphasis on the explanatory power of theoretical models and molecular theory for macroscopic behaviour. In these the inward orientation of the singular with its strong classification was clearly evident. The engineering science region, on the other hand, unmistakably drew on a real/realistic working environment where the task of the engineer is the solving of real-world problems. The data exemplified the emphasis on working definitions that embody the priorities of efficiency and performance and quality. Context, for the engineer, is not so much a place as it is a purposefulness. Theoretical knowledge in engineering science is always a means to an end, and the end is frequently a pressing real-world problem. The regionalised nature of the knowledge in the engineering science is evident in the permeable interface with the world of engineering practice.

The study was able to give an intriguing insight into one possible way to look at the motivation behind a process of regionalisation of knowledge, as well as what the product of such regionalisation might look like: the engineering profession's passionate insistence on usefulness of knowledge becomes the driver for a recontextualisation of principles, laws and concepts shared with science singulars, and results in a body of knowledge with a discernibly altered orientation.

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