Identifying common thresholds in learning for students working in the 'hard' discipline of Science

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Abstract: *Biglan (1973) divides academic disciplines into hard and soft, with subcategories of pure and applied, and life and non-life. We have conducted a study spanning these sub-categories in the 'hard' discipline of science, focused on looking for common factors that impede student learning. A survey of second year undergraduate courses in Thermal Physics, Quality of Medical Practice and Molecular Biology was conducted. A common theme identified was the students' struggle with numeracy skills. Our survey results suggest this has less to do with a real weakness in mathematics, the students in these courses generally have strong mathematical backgrounds, and is more related to two factors – lack of relevance, which reduces their willingness to engage with the challenging aspects of the mathematics, and difficulties in transforming their 'pure' mathematical training into a form that allows them to use it effectively in their chosen courses.*

Introduction

The interplay between a discipline and how we teach it has been the focus of much discussion. Biglan's work is seminal to this discussion. Biglan (1973) characterises academic disciplines as hard or soft, with numerous subcategories within these disciplines, including whether or not the discipline is 'applied' (e.g. medicine and engineering) or 'pure' (mathematics, physics, chemistry, biology), and whether or not there is focus on 'life' (e.g. hard disciplines include medicine and biology; soft disciplines included education in this category) or 'non-life' (e.g. physics). Biglan goes on to propose that a practice shared by those in hard disciplines is *team work* and a *collegiate approach* to research, whereas soft disciplines are characterised by researchers conducting work largely on their own. These descriptions are useful when we make comparisons of shared approaches relating to our discipline and teaching practices, and recognising these discipline-specific differences facilitates better trans-discipline understanding.

An interesting question is how these categories relate to our teaching practices, and ultimately to student learning. In terms of practice, it is clear that our professional practice as scientists is mimicked in how we teach undergraduate science in laboratory classes, where there is frequently an emphasis on team work with students working together to perform experiments and gather data. However, less is known regarding the resulting learning and we were interested in identifying the factors that may be impeding students' abilities in the hard sciences to correctly present and explain scientific data derived from measurements of phenomena important to the subject. Once these factors are identified, we aim to target those points where students are stumbling by implementing teaching and learning interventions to bridge the gaps in their process of translating and explaining their observations.

The work we present here covers the perceptions of students regarding the difficulties they have in learning in hard disciplines and highlights the discipline area differences as perceived by our students and how these relate to assessment tasks. Within the hard disciplines we selected students from Physics, Medicine and Biology so that we could compare across pure and applied, life and non-life sub-disciplines (see Figure 1). By comparing students in different areas of science, we expect to be able to identify area-specific problem areas, as well as processes/concepts that are problematic across subject areas, such as academic numeracy.

Our previous work on threshold concepts (Quinnell & Thompson, 2009) focused on the typical experimental process of science (see Figure 2), moving from observing a phenomenon, to taking measurements, to calculating data into results, and finally to explaining the pattern in those data in relation to the prevailing theories. This is the process that we normally seek to transfer to students in hard disciplines, and particularly in laboratory-based courses. The black arrows in Figure 2 indicate the moments when students commonly experience obstacles to learning. These obstacles are not identified as being exclusively around threshold concepts, but instead appear to be at points where concepts are linked and where the numerical and quantitative aspects play a major role. In this paper, we begin to map students' obstacles to learning onto this generalized model of the scientific method. In doing so, our main aim is to investigate how robust this model for student learning in the sciences (i.e., hard disciplines) is as we make shifts across the sub-category space defined by Biglan, and to look for difficulties and roadblocks to student learning that might be common across what are normally considered to be quite different scientific disciplines.

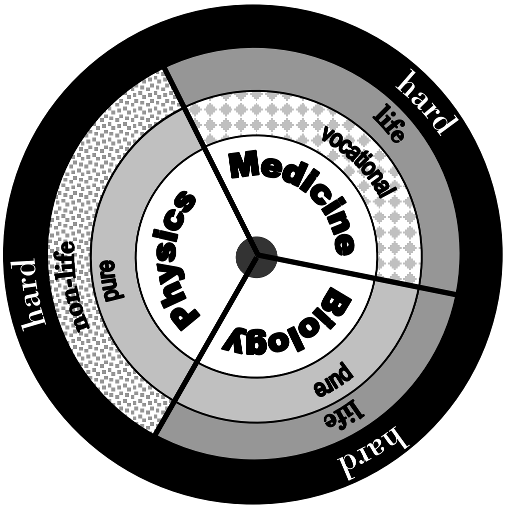
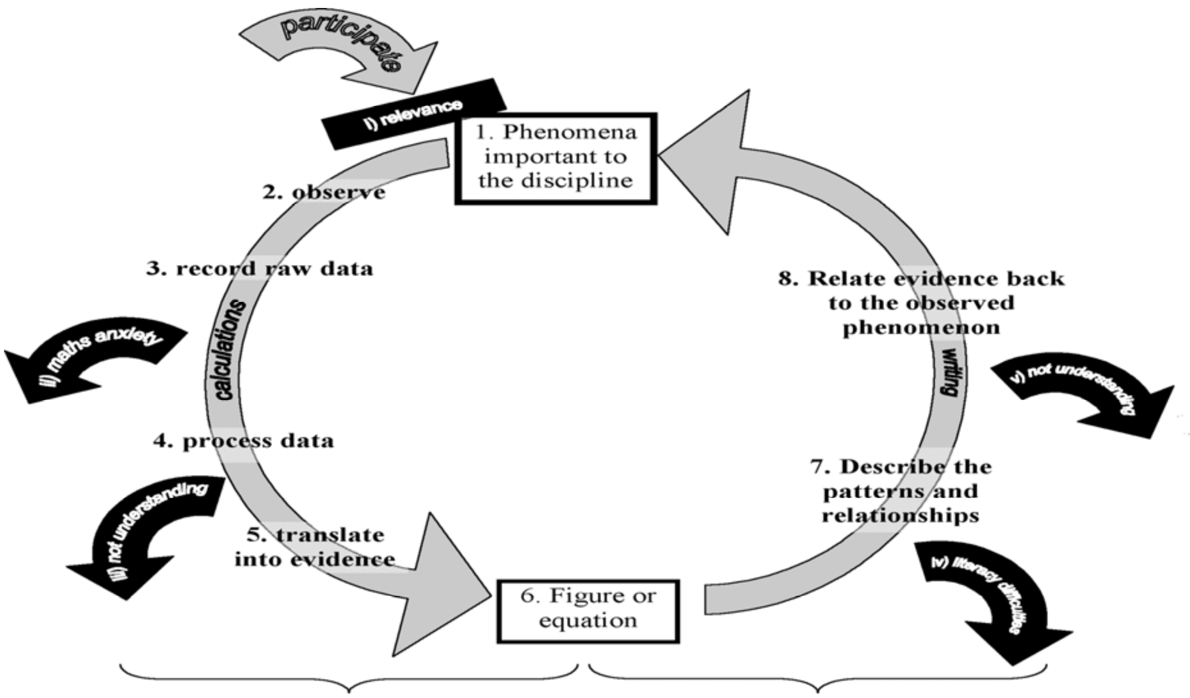


Figure 1: Discipline map of science hard disciplines: Physics, Medicine and Biology (categories after Biglan, 1973). Medicine is a vocational (applied) life discipline. Physics is pure non-life discipline. Biology is a pure life discipline.



A. Experimental process: translating observations into data summary

B. Interpreting process: translating evidence into an explanation

Figure 2: Generalised process in teaching science using experiments and demonstrations.

Method

We recruited students enrolled in the following second year undergraduate courses: a) Thermal Physics (a hard, pure, non-life discipline), b) Quality of Medical Practice (a hard, applied, life discipline), and c) Molecular Biology (a hard, pure, life discipline). (Note: Quality of Medical Practice is offered to first and second year medical students concurrently.) Students were surveyed at the end of the semester as to the perceived relevance of the subject to their degree (Likert-scale) and given an open response question asking them 'what is it about learning Thermal Physics/Quality of Medical Practice/Molecular Biology that you have found to be problematic?'. Themes in the students' open-ended responses were identified by looking for comments that were common to each cohort. The data presented here are part of that collected from this survey. This study was approved (08/2008/20) by the Human Research Ethics Committee of the University of New South Wales.

Results

Cohort profiles

The class cohort profiles for this study are given in Table 1. Both Thermal Physics and Quality of Medical Practice are closely tailored to the needs of the cohort being taught and there is little diversity in terms of the academic pathways of the students in these courses. Molecular Biology, on the other hand, has a more academically diverse student-base. Table 1 shows the student responses to the statement: 'I can see how this subject relates to my degree'. In terms of the proportion of the cohorts that *strongly agreed* or *agreed* with this statement, Thermal Physics was the highest at 100%, with 78% in Quality of Medical Practice, and 65% in Molecular Biology. These data align to the statement made about diversity in these respective cohorts. Molecular Biology is the most diverse, and by corollary, has the least agreement with regard to relatedness of the subject to the diverse degree programs of the students enrolled. The academic in charge of the Molecular Biology course has provided a statement about how the course aligns to the degree program of the study participants, and a statement as to whether the assessments directly or indirectly require students to undertake calculations, and/or make written inferences from these calculations that demonstrates understanding of the discipline theories and concepts. Additionally, the Molecular Biology course is non-continuing i.e. students cannot use it to progress to third year Molecular Biology courses, and this probably impacts on student opinions of its relevance to their degree.

Problematic learning

Open-ended responses in both Thermal Physics and Quality of Medical Practice (statistics) highlighted numeracy as an issue. Interestingly, Molecular Biology students were more focused on understanding the concepts. The difference in assessment tasks in each of the courses explains this. Most of the assessments in both Thermal Physics and Quality of Medical Practice were calculation-based, more so than the assessments in Molecular Biology, where students were required to submit written laboratory reports. This is not to say that Molecular Biology students do not have an issue with numeracy. We expect that had students in Molecular Biology been asked how confident they were with their results when they were doing their calculations (as in the study by Quinnell & Wong, 2007) these students too may have uncovered numeracy as a problematic area.

In pure disciplines, such as molecular biology and physics, students specified particular aspects, such as demonstrations, or particular topics that engaged them when asked what they enjoyed most, for example "I like learning about how proteins are made and their structures. I like learning how knowledge can help cure disease".

In ***Thermal Physics*** students' open-ended responses indicated that entropy, and particularly micro-entropy and canonical ensembles were problematic concepts primarily because they were so abstract. Numeracy also came up as a problem, particularly when students were called upon to transfer knowledge from earlier lectures towards solving new problems either in class or in assignments and problem sets. Thus a key problem in the non-life discipline of physics appears to not so much be the numeracy itself, but in linking it to the concepts, particularly the more abstract ones. In many senses, the issue appears to be the struggle to make the intangible become tangible.

	Course details	Alignment to degree Convener's statement	Students' perception
Thermal physics	Second year undergraduate Enrolment : 42 (20 survey responses) Degree program diversity: 17 BSc with Physics major, 3 BEng.	For BSc physics major students, the course is extremely relevant, thermodynamics is one of the core courses in our 2nd year program and underpins much of the physics they learn in later years. For the engineers, the course is relevant but more for seeing contrasting approaches and seeing the science that supports the more applied versions of the subject that they will see as engineers.	100% *strongly agreed/agreed* that the course related to their degree
Quality of Medical Practice	First and second year undergraduate (~1:1) Enrolment : 523 (86 survey responses) Degree program diversity: almost exclusively 3802 Medical Program	The course is statistics, which is highly relevant but it is not immediately obvious to students that this is key to clinical practice. Students see the value of statistics in year 3 or 4 when they do their Independent Learning Project (32 week research period) and as they progress through their clinical placements.	78% *strongly agreed/agreed* that the course related to their degree
Fundamentals of Molecular Biology	Second year undergraduate Enrolment : 101 (71 survey responses) Degree program diversity: Mainly BSc, some BSc (Adv). Course is required for BSc (Food Technology) and an option for BSc (nanotechnology).	Complements all programs, although does not offer options for students to address topics more specific to their program. This course is non-continuing, with students needing to take an advanced course if they want to study Molecular Biology at third year level. Assessments require calculations, but these involve basic numeric skills and not higher mathematics.	65% *strongly agreed/agreed* that the course related to their degree

Table 1: Course profile of Thermal Physics, Medicine and Molecular Biology: degree diversity, alignment to cohorts academic program.

In ***Quality of Medical Practice*** students' comments focused on concepts such as risk and degrees of freedom and how to select the appropriate statistical test for a given problem. A few students commented that there were "too many tests". Several students made suggestions how to teach the course better e.g. that there is too much work online. Some students failed to see the relevance although most did. These students are well motivated and high achieving, and most have high level mathematics from high school. But despite this, there were several comments indicating that numeracy was an issue e.g, "numbers freak me out". As we would expect for an applied discipline, the students appeared focused on what they believed would be most useful. For example, these medicine students could acknowledge their lack of engagement with a topic (in this instance 'statistics') (Thompson, 2008), while at the same time appreciating its relevance. This common response is typified by the statements "The dryness of the topic. i.e. Maths is not fun." and "It is very relevant to the degree that I'm studying. It is very useful when trying to read articles and studies."

In ***Molecular Biology***, students struggled with the number of definitions and the number of "parts" and were overwhelmed with information. Language and definitions were problematic and some students were trying to memorise the content. Others used the terms "understanding" and "conceptualising the theory" which indicates that they were not rote learning. Biological concepts included: "understanding many of the processes involved in recombinant DNA", and complex process such as gene regulation, transcription and translation and the detail and complexity of these biological process. So, in the life-discipline, students are grappling with complexity.

Discussion

We have found it useful to refer to Biglan's model for characterising academic disciplines as we attempt to see how our own research practice in a hard discipline (the scientific method) relates to both our teaching, and the difficulties students have with their learning in science. Work by Neumann (2001) and Healey (2000) is also relevant, in that it starts to examine what distinguishes disciplines areas from one another for those practicing in those disciplines. When we look to see whether the defining characteristics of our discipline areas – the features that set one area apart from another – are correlated to troublesome knowledge and threshold concepts for students just entering our discipline territory, we see some interesting patterns starting to emerge.

The most common theme is related to numeracy, and in particular making the transition between qualitative and quantitative aspects of a problem or scientific concept. At a surface level, it may appear that this is driven by weakness in mathematics. However, given that there are clearly a number of students who have performed well in traditional mathematics courses in these cohorts (e.g., medicine students are generally in the top 1% of high-school graduates and physics undergraduates also tend to have a strong performances in high-school maths courses), it is clear that this is not the entirety of the problem. Looking deeper, we instead propose that there are two factors driving the numeracy issue that is common across the subjects that we have studied.

Relevance

Looking across our survey results, it is apparent that an underlying factor driving students' struggle with numerical aspects of hard discipline courses is that they don't see the relevance. At first sight, one might ask what relevance has to do with maths, after all, it is easy to think "it's in the syllabus, I told them to learn it, and therefore they should learn it.", but this view ignores students as free-willed individuals facing competing demands on their limited time available for study. What is perceived as most important will always come first, and given this, relevance immediately becomes an item of great importance to learning outcomes for some given concept or material. Support for this comes by comparing the open-ended responses to Likert-scale questions regarding relevance in our survey responses. There is a rough correlation between the courses where the relevance scores were lower and comments related difficulties with mathematics that were very broad and non-specific (e.g., "the maths was the hardest thing to learn", "It was hard to learn some of the maths" ".... graphs, numbers freak me out sooo confusing" etc). In contrast, when the relevance is higher, the difficulties with maths tend to be more specific, and often related to the second factor below (e.g. "Hard to understand a lot of the statistical concepts without any knowledge of the underlying mathematics.")

Using mathematics

Where comments regarding difficulties with mathematics are more specific, they tend to relate less to the struggle with mathematics itself and more to the struggle to apply mathematics to the subject at hand. This may explain why many students who, by all other indicators should be good (or better) at mathematics, claim to struggle with mathematical aspects of the courses that we have studied here. Further, indirect support is provided by some of our experiences with assessment tasks and problem sets in these courses. Students often appear quite strong mathematically on questions where they follow a familiar path or recipe through the numerical aspects of the problem, or where the problem dovetails neatly into the purer forms of the maths they are taught in dedicated mathematics subjects. However, the very same students appear very weak at maths when pushed outside their mathematical "comfort zone" by a question that requires them to be creative with their mathematics or to develop an approach that varies from a path they have followed before.

This suggests that there are some missing aspects to the mathematical education of our students. Traditional mathematics subjects tend to focus more on the maths itself and less on how to use it – under Biglan's framework, these courses are pure. The traditional approach to other subjects is one of assumed knowledge – that the students have learned the maths elsewhere and therefore can use it. Driven by limited time, these courses then focus on the key concepts of the particular course, the problem being that the students never get formally taught how to use maths, and this becomes a struggle for them. This suggests the possible need for additional maths courses, which should be taught by the teachers of the students' particular major to span this gap in their mathematical abilities, and teach them how to do maths within the field of physics or medicine or biology.

We plan to extend our research into obstacles to student learning by directly addressing the threshold concepts we have identified, to avoid students becoming disconnected from the learning process. In physics, some phenomena cannot be taught using demonstrations and practical classes, as typically used and shown to be effective in the hard sciences, for example due to the need for sophisticated equipment or the occurrence of the effects at an atomic scale. We found from our study that physics students often have difficulty making the intangible become tangible. YouTube and similar online video websites have provided a means to visualise such phenomena (Micolich, 2008). In Quality of Medical Practise, changes to the mode of teaching and content have enabled students to encounter basic and threshold concepts associated with numeracy without being presented with a confronting set of formulae (Quinnell & Thompson, 2009). In biology, improving the numeric self-confidence of students performing calculations, by using a diagnostic, has been shown to improve numeracy by reducing students' associated anxiety (Quinnell & Wong, 2007). Taking a blended approach to teaching in molecular biology, by designing and implementing an online learning module accessed by students in the laboratory class, has shown to improve students' numerical skills in a related assessment task (LeBard, unpublished data). Future research into the success of these interventions on threshold concepts and numeracy in the pure, applied, life and non-life areas within the hard discipline of science appears essential to the further development of effective teaching practices.

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