Applying Mathematical Thinking: The Role of Mathematicians and Scientists in Equipping the New Generation Scientist

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The ability to make effective use of mathematical and statistical thinking and reasoning within context is an essential skill for graduating science students. The challenge for educators in higher education is to determine how best to foster the development of these skills. Many argue this challenge is becoming greater, given the increasingly diverse student body (often with weaker mathematics backgrounds) and the increasing use of modelling and data in modern science (meaning that the need to be able to apply mathematical and statistical thinking and reasoning is increasing). This paper discusses the implementation of initiatives within four institutions (University of Queensland, James Cook University, University of Maryland and Purdue University) that address these needs. In addition to describing the initiative itself, the change process is described. Therefore each initiative is examined through a framework based on: the need for the change, vision for the change, implementation of the change and evaluation of the change. In particular we explore the role of mathematicians and statisticians in these processes.

Keywords: interdisciplinary; higher education; science; mathematics; educational change

Introduction

Mathematical and statistical thinking and reasoning in science – the need for new curricular approaches

The increasing need for science graduates to achieve competency in the application of mathematical and statistical thinking and reasoning in science contexts has been documented extensively over the last 10 years. Publications representing collective views of modern scientists are perhaps the most powerful in highlighting the uniformity with which this belief is held. For example, *Vision and change in undergraduate biology education: A call to action* published by the American Association for the Advancement of Science in 2009 [1], and the *Learning and Teaching Academic Standards – Draft Science Standards Paper*, published by the Australian Learning and Teaching Council in 2010 [2] are two such documents which were produced after wide consultation with scientists. In each of these documents the need for science students to be competent quantitative thinkers is clearly articulated.

Despite the acknowledgement amongst scientists of the importance of the ability to apply mathematics and statistics in their profession there is a broad range of opinion amongst educators as to how best to foster these skills in school and university students. The challenge for tertiary educators is exacerbated by the downwards trend in general mathematical preparedness of students entering the sector; see Brown [3]. It is difficult to see how this trend can be reversed because of the need for the tertiary education sector to cater for an increasingly diverse range of student backgrounds to satisfy ambitious government targets for participation rates in higher education such as those in the Bradley Report [4]. In addition, there is frequently an expectation amongst entering students that knowledge of mathematics and statistics is not essential in science. One cause of this is the common view that increasing the mathematical content of the school curriculum in disciplines such as biology may diminish their appeal to the student body [5], so that educators lean toward teaching science without emphasising the need for or links to mathematics. This expectation is reinforced in the eyes of students considering study of science beyond secondary school through the absence of mathematics prerequisites requirements for entry into science degrees at many tertiary education institutions in Australia [6]. The default position in many examples of science education at the tertiary level is that "mathematics-rich courses are presented by teaching staff from mathematics departments, and science-rich courses are taught by staff from the various scientific fields," [7]. A more contextualised approach illustrating the application of mathematics is often proposed by secondary educators as a mechanism to motivate students to persevere with the study of mathematics. Students studying science have the perfect context in which to observe the application of mathematics, so illustrating the links between science and mathematics should be an achievable goal in tertiary education. A curriculum that fosters understanding of the intertwined nature of mathematics and science almost certainly requires approaches that are described as *multidisciplinary, interdisciplinary* or *integrated* (among others). The interpretation of these terms varies; see for example Venville et al. [8]. However for the purposes of this article we will assume that the nature of the material taught and the way it is taught requires either some form of collaboration across traditional discipline boundaries, or alternately, requires teachers with deep conceptual knowledge of more than one discipline area.

Implementing and analysing new curricular approaches in science

There is a lack of peer-reviewed literature discussing undergraduate science curricula that illustrate the links between mathematics and science learning outcomes at the level of the degree program [7]. Undoubtedly this situation will change as faculty engage and academic leadership embrace this issue. Factors that lead to success are of great interest to those embarking on this journey, and it is clear there is a high degree of uncertainty as to what governs success in curriculum reform. To illustrate this point it is noteworthy that literature aimed at facilitating reform in Science, Technology, Engineering and Mathematics (STEM) education is readily available at the micro-unit level. A key word search by Henderson et al. [9] revealed 295 journal articles published between 1995 and 2008 (inclusive) describing efforts of change agents to improve undergraduate STEM education. These authors report that despite significant funding for research that led to these publications, there is little evidence of widespread resulting impact. This suggests the need for systematic approaches to the analysis of educational change strategies in STEM at the degree program level within an educational framework, so that future efforts are more likely to provide greater positive impact.

Purpose of Study

It is clear that the lack of certainty about how best to develop the ability to apply mathematical and statistical thinking and reasoning in the context of science means this is an area in need of urgent attention. We present initiatives that have been used to develop these skills in science programs in each of four tertiary institutions. Whilst certainly not comprehensive, they are indicative of some current approaches in the sector, and will be of interest to those considering curriculum reform in this area.

More importantly, through these examples we aim to contribute to the body of knowledge on the implementation of new curricular approaches that facilitate the development of in-context mathematical thinking in undergraduate science students. In particular we wish to gain insight into the working relationship between academics in mathematics and statistics and those in the science disciplines (such as biology) in the implementation of such initiatives. We aim to explore the research question:

> How do cross discipline collaborations amongst mathematicians, statisticians and scientists contribute to the application of mathematical thinking of science students?

Through this publication we hope to foster interest in the discussion on how the relationship between mathematicians, statisticians and scientists can evolve to better meet the need of modern science graduates in their chosen career path.

Fullan's Model

In order to distil useful information regarding educational change it is advantageous to have access to a model that allows the complex process to be understood both in its component parts and in its entirety. This also allows for systematic comparison of different initiatives, thereby offering increased opportunity for understanding the scope for generalising to achieve educational change across context. In this article we will use a framework for analysis based on Fullan's 1982 publication [10] that examines large scale educational change. The model is presented below, in a linear form, although in reality the process is iterative. At each stage we use guiding questions to focus attention on aspects that facilitate comparison across initiatives.

1. Initiation of change. Who prompts the change and why is it needed?
2. Vision for change. What does the change look like?
3. Implementing for change. How is the change translated into practice?
4. Evaluating the change. How effective is the change?

While the model is comprehensive in its form, not all initiatives presented in this article are at the same point in their development. Hence, the analysis will focus on those areas where sufficient information exists to enable useful conclusions to be drawn. It is also important to note that the initiatives vary in target audience and intended purpose. Although this makes comparison difficult, it is still possible to comment on trends observed in the analysis.

The Institutional Initiatives

Background of the institutions

The four institutions forming the study are listed in Table 1 and are composed of public multi-campus universities in Australia and the USA. They all have a research focus; three fairly broadly, with the exception being James Cook University where research tends to be located in selected niche areas in science.

Table 1. Background data of the institutions

University	Founded	Under-graduates	Post-graduates	QS Ranking[#1]	THE Ranking[#2]
University of Queensland	1909	29,226	10,643	43	81
James Cook University	1970	12,093	3663	354	-
University of	1856	26,542	10,653	104	98

Maryland					
Purdue University	1869	31,145	7639	87	87

#1 – This is the Quacquarelli Symonds ranking: http://www.qs.com/

#2 – This is the Times Higher Education ranking: http://www.timeshighereducation.co.uk/world-university-rankings/

University of Maryland

The University of Maryland case study is centred on initiatives to meet the needs of students pursuing majors in the biological sciences.

Initiation of change

Efforts to increase the quantitative training of biological sciences students arose from the changing landscape of scientific research. Many of the newly hired biological sciences faculty members reflected the increased quantitative emphasis of modern biology. Simultaneously there was a growing feeling among biological sciences faculty that students enrolled in upper-level courses did not show the degree of sophistication in quantitative reasoning that would be expected given the students' previous mathematical coursework. Also the department of mathematics had recruited a cohort of faculty members who were focused on biological problems.

Vision for change

Informal discussion among University of Maryland biological sciences faculty members resulted in a unified vision to infuse mathematics more deeply into the biology curriculum at all levels. The approach had three major components: (1) imbed basic mathematical content into introductory biology subjects for both majors and non-majors, (2) revise the mathematics sequence taken by biology students to be more biologically relevant, and (3) create an upper-level, quantitatively intensive subject in mathematical biology. The overarching goals of this coordinated approach were to help students appreciate the importance of mathematics and statistics for modern biology and allow students to more readily apply their quantitative knowledge to biological problems.

Implementing for change

The main strategy to imbed mathematical and statistical content into introductory biology subjects was to create the series of online modules called MathBench; see Nelson, et al. [11].

Shortly after initiating MathBench, faculty members in biological sciences began meeting with colleagues in mathematics to discuss the creation of a calculus sequence that would focus specifically on the types of mathematics that are most valuable for biologists and demonstrate the critical role of mathematics in understanding biological phenomena. To demonstrate the essential linkages between the fields of biology and mathematics, the subject has two problem-solving sessions per week in addition to lectures, one led by a mathematics teaching assistant and one led by a biology teaching assistant. The biology teaching assistants were also integral in the development of group problem-solving exercises that involve authentic biological problems. The subject was piloted with a small group of students in Spring 2008 and was instituted as a requirement for biology majors the following semester.

The third strategy to strengthen quantitative skills in biology students consisted of an upper-level Mathematical Biology subject that allowed students to develop sophisticated quantitative approaches to authentic biological problems. The chief developer of the new subject was a biology faculty member with formal graduate training in physics and research interests in computational neuroscience. Using a variety of tools (Excel and Matlab) and mathematical approaches (non-linear difference equations, eigenvector analysis, multidimensional stability), the subject asks students to develop models to investigate important phenomena in diverse biological disciplines, including population dynamics, molecular evolution, phylogenetics, and infectious disease. The subject has been offered several times to very small numbers of students. It will soon reach a larger, broader audience as the capstone course of a new Honours program in Interdisciplinary Life Sciences, which enrolls approximately 75 students per year.

Key in the development and implementation of these reforms has been a reliance on an interdisciplinary faculty team consisting of biologists and mathematicians; within each discipline there were individuals who worked across disciplines as well as individuals with specific expertise in science education and curriculum development.

Evaluating the change

Multiple measures are used to evaluate the impact of these reforms, including pre- and post-tests of quantitative skill, student and faculty focus groups, surveying attitudes of graduating seniors, and tracking student grades. Students using MathBench show increases in critical quantitative skills that are independent of mathematical background and only slightly influenced by concurrent enrolment in a mathematics course [12]. A formal assessment of the impact of the revised calculus sequence on student performance in subsequent quantitatively-intensive coursework is underway. More informally, faculty members teaching the introductory physics sequence taken by biology students and those teaching upper-level biology subjects have noted a higher level of preparation of students since the implementation of this subject.

James Cook University

The initiative under discussion was delivered for the first time in the second half of 2010. It was introduced as one of a number of initiatives in curriculum reform, both across the Faculty of Science and Engineering and the university.

Initiation of change

The campus-wide curriculum reform agenda was seen as an opportunity to address deficiencies in student learning. In science, many students were observed to struggle when asked to use mathematics or statistics in a science context, demonstrating a lack of ability, willingness and confidence. Even more alarmingly, there was a perception amongst staff that the requirement to use mathematics or statistics in context was sufficiently unpalatable for some students to cause them to withdraw from the science program.

Vision for change

Discussions amongst the staff of the faculty revealed a belief that if the benefits of using mathematics and statistics to gain insight into problems in science could be demonstrated to students early in the program, they would engage with problems requiring these skills elsewhere in the science program in a more enthusiastic manner. As a result, a compulsory first year subject “Systems modelling and visualisation” was introduced. In order to demonstrate the relevance of mathematics and statistics to the entire science cohort it was anticipated that each of the three schools within the faculty would provide high-profile staff for prominent teaching roles in the subject.

Implementing for change

A statistician within the discipline of mathematics and statistics was chosen as the coordinator. She formed a committee consisting of representatives from information technology, biological sciences and physics to oversee the development of the subject. Her committee also had input from the Associate Dean Teaching and Learning who was overseeing the curriculum renewal process across the faculty. A second biologist, prominent and highly regarded in her field and with extensive experience in the application of statistics was also brought in to the project. She and the coordinator of the subject were ultimately responsible for ensuring content alignment.

It is important to note that a significant number of students enter the subject through the university's alternate pathway in the Diploma of Science in which students study the prerequisite secondary school mathematics content in an accelerated form. Concerns over the mathematical ability of the cohort led the team to a case study approach in which six lectures at a time were devoted to a single study, the mathematics for which was not too extensive. The aim was to highlight methods of modelling and visualisation in each of the studies.

Case studies came from biological science, physics and climate change, reflecting the high-profile areas of research within the university that uses mathematics and/or statistics. There was considerable debate around the programming platform to be used, because many experienced staff believed that the hurdle associated with learning software is at least as challenging as learning the discipline content. Excel was chosen as the software tool because of the belief that students were likely to have seen it before.

Evaluating the change

The coordinating committee consulted with a science education specialist from within the university to develop ways of evaluating the effectiveness of the subject. This involved a questionnaire, follow-on focus group interviews and the perceptions of staff in follow-on subjects as to the ability of students in using mathematical and statistical thinking and reasoning in context. The results of this analysis will be published elsewhere.

The University of Queensland

The University of Queensland has introduced a range of activities directed at increasing the mathematical abilities of science students, in the contexts of each individual science discipline. This case study focuses on a capstone subject (BIOM 3200) for students in the biomedical science major of the Bachelor of Science, and how that subject builds on an introductory statistics subject.

Initiation of change

A recent review of the Bachelor of Science program identified a substantial lack of integration between mathematics, statistics and a range of science disciplines. As a result, a compulsory introductory statistics subject was introduced, taken by around 1000 science students each year. However, it became apparent that in many cases, the material covered in this subject was not reinforced in later subjects. Students typically lost confidence in their statistics ability, forgot how to apply their knowledge, and even came to believe that mathematics and statistics are unimportant in science. Faculty in biomedical science decided that it was essential to further build the quantitative skills of their students by integrating data analysis in the capstone subject. This was initiated by the subject coordinator, and included close collaboration with a discipline-based statistician.

Vision for change

The vision for the compulsory introductory subject was to cover statistical material regarded as essential for all science students. This subject was taught by a discipline-based statistician, and also included components of ethics, writing and quantitative communication. The goal for the capstone subject for approximately 250 students majoring in biomedical science was to provide an integrative learning experience bringing together biomedical science and statistics, and to further develop students' skills in ethics and communication. The importance of this integration was expressed by a senior biomedical science academic, who identified that the highlight of the subject was the way in which the contextualised integration of science and mathematics would produce ‘very different and confident students’.

Implementing for change

The capstone subject was presented in three modules, with each module based on a biomedical problem. Students worked in groups, assisted by tutors, building on prior disciplinary learning and connecting biomedical science with statistics, ethics and communication to enhancing their biomedical science knowledge. In the data analysis activities, each group of students was provided with a set of raw data derived from published biomedical science research by the statistician. Students undertook analysis, interpretation, presentation of results and report writing, treating the data as an integral component of the process by which the underlying research problems were analysed, interpreted, understood and communicated to a diverse audience.

It rapidly became apparent that biomedical science tutors would be unable to facilitate understanding of the statistics, because they lacked the insight or expertise in using and explaining statistics. To assist in overcoming this challenge, two tutors were present in each class, one from biomedical science and the other with expertise in statistics. To further facilitate understanding, the discipline-based statistician provided the following additional support:

- students were given a series of application-based lectures before they commenced data analysis;
- biomedical science tutors received a training session for each module; and
- the discipline-based statistics tutors attended a workshop on what they could reasonably expect students to know, and the most appropriate approaches to use.

Evaluating the change

The capstone subject was evaluated using a tailor-made survey to explore the effectiveness of the initiative. Questions focused on whether students increased their confidence in data analysis, improved their quantitative skills, and developed new insights into how to approach scientific data analysis. The majority of the students appreciated the value of disciplinary and interdisciplinary integration that occurred in the subject, and also identified that there was integration of their prior learning, from both biomedical science and statistics.

Purdue University

At Purdue University, an understanding of the synergy between statistics and science is achieved through a process of writing tasks and peer review.

Initiation of change

As with other case studies presented in this report, faculty members in biology recognized that the ability to apply mathematical and statistical thinking is becoming increasingly important because of the changing nature of scientific research. At the same time, there was evidence that students enrolling in bioscience programs were often substantially underprepared in understanding and appreciating the roles that probability and statistics play in dealing with the inherent variation of biological systems.

Vision for change

Despite a range of previous initiatives aimed at developing links between mathematics, statistics and biology, a significant gap in required knowledge was seen to remain. Several recent efforts have been explicitly designed by faculty to further prepare bioscience students to apply mathematical and statistical reasoning and also describe natural phenomena, and validate scientific knowledge.

Implementing for change

A recent National Science Foundation award entitled *Teaching Ethical, Experimental, and Quantitative (TEEQ) Biology through Problem-Based Writing with Peer Review* was initiated at Purdue University by collaboration between a biologist and a statistician in response to the need for students to understand the role of probability and statistics in analyzing variation in biological systems. The project adapted the Calibrated Peer Review (CPR) process, developed at the University of California at Los Angeles, as a mechanism for increasing student understanding of experimental methods and quantitative approaches in biology.

The process works as follows. Each student is presented with a contextualized problem with a substantial quantitative basis, and then asked to write an analysis and discussion. Students are then given guiding questions to build their competence in the scientific review process. Following this, each student receives three peer documents to review using the guiding questions and then assign a score. Finally, the student undertakes a review of their own work. The student's grade is based on both their own writing and their peer reviewing.

New quantitative problem-based writing assignments with peer review have been incorporated into an introductory subject, Biology 131, to help students connect what they learn to both current and historical research endeavors. Biological problems with writing assignments for peer review are also being incorporated in the Statistics 301 subject (a subject also catering for students outside science) to help students understand how new knowledge accumulates in the biosciences. Students also consider what ethical constraints, such as predictions of the expected number of animals for a research study, must be considered. The project targets more than 1300 students annually.

Evaluating the change

A Participant Perception Inventory was developed as a project evaluation tool. This is a questionnaire designed to measure student perception of their own knowledge (cognitive dimension), experience (behavioral dimension), and confidence (affective dimension) about ethical, experimental, and quantitative aspects of research. Results show that the CPR assignments provide a tested method to help students learn by lowering barriers to primary literature. Student responses were examined using a factor analysis method to determine groups of questions that are answered by students in a correlated manner, thus indicating aspects of student thinking that are closely linked. The factor analysis scores were also used to inform teaching by identifying categories that may need to be taught in an explicit manner. For example, results suggest that visualization associated with research is an important skill that may need to be more explicitly addressed.

Discussion and Conclusion

Analysis of the change process

In each of the initiatives presented, the initiation and vision for change was driven by the need for student understanding of some aspect of science to be enhanced by the ability to apply mathematical or statistical thinking or reasoning to that scientific context. In the two cases from the USA, faculty in biology were the initiators, while in the two cases from Australia science faculty were involved in the initiation, but broader teaching and learning agenda also facilitated their initiation.

Considerable variety exists in implementation. In comparing the two USA studies, the initiation for change was almost identical; however the vision and implementation provide a significant contrast. In the Maryland case, a calculus subject for biology students was developed in partnership between faculty in mathematics and biology. Students were exposed to teaching assistants from both mathematics and biology. At Purdue the partnership between a biologist and statistician resulted in a problem-based writing and review task, embedded within a statistics subject catering for the needs of students outside biology as well as within. Thus the links between statistics and science were developed as a goal within a general statistics subject.

Similarly, in comparing the two Australian studies, the initiation for implementing core subjects in the science program was similar; however the specific subjects introduced at the two institutions were quite different in their approach to developing the skills of the students. These contrasts serve to highlight the variety of options available to those grappling with the issue of how to embed the development of mathematical and statistical thinking within science contexts.

In each study significant steps have been taken to evaluate the effectiveness of the changes implemented. While they show considerable success in some areas, there are challenges associated with the interdisciplinary nature of these initiatives. Undoubtedly these challenges were anticipated, as evidenced by the pairing of tutors from differing backgrounds in the Maryland calculus course and the University of Queensland capstone subject. Research around how best to develop relationships between teaching staff of differing discipline backgrounds is needed to overcome these challenges.

The role of mathematicians and statisticians

In all of these initiatives, it is particularly interesting to observe the degree of importance placed on cooperation between mathematicians, statisticians and scientists. It is clear that the four projects presented here involved collaboration across discipline boundaries, some in the formulation of resources and others in the day-to-day teaching. One factor that hasn't been made explicit to this point is the level of support in terms of funding required to allow them to succeed – each of the initiatives involved substantial funding that probably cannot routinely be made available across large numbers of institutions. Whether these collaborations would occur in the absence of funding is a significant question to ponder.

The four case studies present instances in which the default position (science students needing to deduce the links between mathematics and science for themselves) was reconceptualised to better achieve the intended outcomes of contextualising mathematical learning for science students. While the initiation to rethink the default position varied across the case studies, all implementations involved collaboration and cooperation across traditional discipline boundaries, with mathematicians, statisticians and science faculty all teaching in the broader context of quantitative science. The case studies demonstrate that successful collaboration across disciplines is possible and can improve the mathematical skills of science students. This raises broader questions as we move beyond a "single subject" view of teaching the application mathematics to science students: how do we better link the "pure" mathematical knowledge gained in mathematics-rich courses to the contextualised mathematics taught in science-rich courses? How do we create sustainable frameworks that allow for interdisciplinary collaborations with a view to building the mathematical skills of science students across all levels of the degree program? Finally, how do we gather evidence to inform the ongoing efforts of mathematicians and scientists as they work together to achieve these interdisciplinary learning outcomes?

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