Putting it into perspective: Mathematics in the undergraduate science curriculum

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Mathematics and science are tightly interwoven, yet they are often treated as distinct disciplines in the educational context. This study details the development, implementation and outcomes of a teaching intervention that highlights the links between mathematics and science, in the form of a first year interdisciplinary course. A mixed method study using surveys and focus groups was employed to investigate undergraduate science students' perceptions of their experiences. Findings reveal that students bring strong beliefs about the nature of mathematics and science from secondary school, which can impact significantly on the success of interdisciplinary science-mathematics courses at the tertiary level. Despite this, a range of beneficial outcomes can arise from such courses when they are delivered within a framework of analysing real-world issues. However, students with weak mathematical skills derived little benefit from an interdisciplinary approach and are likely to disengage from learning, in comparison with students who enter university with a solid foundation in mathematics.

Keywords: interdisciplinary; integration; mathematics education; science education; higher education; curriculum

AMS Subject Classifications: 92B99; 97B40; 97D30; 97M10

1. Introduction

The origins and nature of mathematics and science are tightly interwoven, so much so that it is difficult to distinguish whether Newton was acting more as a scientist or a mathematician when he developed calculus [1]. However, in the educational setting, boundaries between science and mathematics are typically very clearly defined. In the context of primary and secondary school, students take distinct mathematics classes and science classes. In many cases, while the same person might teach both science and mathematics, these subjects are still delivered as separate entities. For most students who enter post-secondary education the apparent boundaries between mathematics and science remain, and are often strengthened.

The relationship between mathematics and science in the educational context is a source of on-going debate and confusion. This debate has gained more attention in the secondary sector over the past few decades, particularly in the United States. The declining performance of students in mathematics and science prompted a new focus on primary and secondary curricula, in particular, a call for mathematics and science

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to be linked in schools [2]. Indeed, one such proposal urged research scientists to take up the challenge and design relevant mathematics curricula for schools that integrate the applications of mathematics within science [3]. In the 1990s, the debate focused on the 'integration' of mathematics and science curricula in schools as a means to reinvigorate student interest and increase student learning in mathematics and science [4]. While some visualised mathematics and science at opposite ends of a spectrum with 'integration' occurring somewhere in the middle [5, 6], others conceptualised the 'integration' of mathematics and science within social contexts and real life problems and issues [7, 8]. The debate about the meaning of 'integrated curriculum' versus 'interdisciplinary curriculum' is continuing. For the purposes of this paper, the term 'integrated' refers to curricula in which the boundaries between science and mathematics are indistinguishable, while 'interdisciplinary' refers to curricula in which there is a mixture of science and mathematics although the boundaries of the two disciplines remain visible [9]. Czerniak *et al* [10] and Venville *et al* [11] give in-depth explorations of the language of the debate around integrating mathematics and science, and issues of integrated science curricula in schools.

Traditional concerns of what mathematics was being taught in school science classrooms shifted in the 1980s towards a 'de-mathematisation' of the science curriculum [12]. This has resulted in two profound problems for universities: first-year undergraduate science students who often lack the necessary mathematical skills, and commencing university students who hold the misguided belief that mathematics is not needed, or even irrelevant, in science [13]. Thus, the science-mathematics debate that was previously limited to primary and secondary schooling has moved into the university sector, albeit with a somewhat different form and language to that of pre-tertiary schooling. While the science-mathematics debate is a broad-brush term for the school sector, at the tertiary level the discussion has focussed on more specific attributes (such as quantitative skills/reasoning/literacy) that students should gain through the undergraduate science curriculum [14, 15].

The need to graduate more students from university who are ready to enter the science, mathematics and/or engineering workforce is well-acknowledged globally [16-23]. Quite rightly, graduate employability is increasingly influencing university curricula. Furthermore, in recent years the rapidly changing nature of science, strongly driven by (and leading to) technological advances, has resulted in numerous calls for review and renewal of how science and mathematics are taught to undergraduate students; for example, see the landmark report [24], and [13]. Clearly, empirical research is required to identify mechanisms which are effective in overcoming the well-entrenched negative belief systems of many students.

2. Purpose of study

As the science-mathematics debate in the university sector intensifies, new approaches to teaching interdisciplinary mathematics and science will need to be developed and implemented in an attempt to better prepare undergraduate students for a future in science. This study does not intend to address this large scale issue directly. Instead, it is reporting on a specific intervention (the implementation of a new subject in a science curriculum) and is exploring students' beliefs and understanding about the links between mathematics and science. This study is situated within a larger research project exploring the quantitative skills of undergraduate science students through a comparison of students graduating from an established, unstructured science curriculum and a newly implemented, more structured science curriculum. Given the lack of research in the tertiary sector for those seeking evidence-based practical approaches or models for developing undergraduate science curricula that instil greater appreciation of the fundamental links between mathematics and science, we aim to contribute in this area. Within the framework of the science-mathematics debate, this paper explores the following research question:

> How are students' perceptions and beliefs affected by an interdisciplinary science and mathematics course?

The findings of this study should be of interest to both mathematics and science departments. Usually, mathematics-rich courses are presented by teaching staff from mathematics departments, and science-rich courses are taught by staff from the various scientific fields. In order for science students to develop an appreciation of the strong links between mathematics and science, it is crucial for mathematicians to better understand the skills, interests and requirements of the student audience, who are generally not studying mathematics for its own sake. It is equally crucial for scientists to recognise and understand the scope, relevance and usage of mathematics in science.

3. Background

3.1. Institutional context

The University of Queensland (UQ) is a large, research-intensive university in Brisbane, Australia, with over 37,000 students drawn from more than 100 countries across both undergraduate and post-graduate programs. In 2006, the research income for the university reached $215 million dollars (AUD). The Bachelor of Science (BSc) is a large, generalist degree program, with more than 3,000 undergraduate students. Applicants are required to have completed high school level English and Mathematics B (study of functions, sequences and series, an introduction to calculus, and probability and statistics), along with either chemistry or physics. Full-time students can complete the BSc in 3 years, with an optional Honours year.

3.2. SCIE1000: Theory and Practice in Science

In 2006, the BSc curriculum was reviewed and a new first year course was developed as a result, named *SCIE1000: Theory and Practice in Science.* Two learning goals for SCIE1000 are of particular relevance for this paper: (i) to instil an appreciation of the quantitative skills required for the practice of modern science, regardless of discipline, by involving students in the analysis of real world issues and (ii) to improve students' mathematical skills in the context of scientific problems and issues.

SCIE1000 was designed as a gateway course for BSc students regardless of major. While all students had completed Mathematics B or equivalent upon entering the BSc, the inevitable disparity in their high school mathematics classroom experiences [25] ensured that students' mathematical abilities were as wide-ranging as their interests. The course design process was informed by the Mathematics B curriculum, and aimed to build on the mathematical skills that students were expected to bring to university. In fact, relatively few new mathematical concepts were introduced in SCIE1000. This was a deliberate decision as SCIE1000 was not intended to be a course focused on mathematics; instead, its aim was to demonstrate how mathematics underpins and connects various disciplines in science.

SCIE1000 was developed as an interdisciplinary course more than an integrated science-mathematics course, as the discipline boundaries were intended to remain distinguishable. Indeed, the interdisciplinary nature of this course was reinforced by the chosen teaching process. There were three hours of lectures and two hours of tutorials per week over a 13 week semester. A team-teaching approach was adopted across both the lectures and tutorials, with a mathematician and a scientist jointly delivering all of the lectures, and two tutors teaching each tutorial, one with a mathematics background and the other with a computing or science background. Ultimately, the mathematician took the lead in developing the course and identifying the larger issues where mathematics and science intersected in a meaningful and relevant way (Table 1). SCIE1000 was first implemented in 2008 as a highly recommended, but not compulsory, course to all new BSc students.

<INSERT TABLE 1 HERE>

4. Methodology

The research methodology for this study was framed within Howe's concept of pragmatism [26] and adopted the principles of Patton's utilisation-focused evaluation [27]. A mixed-methods research design was used to investigate the research questions [28], specifically a sequential or two-phased study [29]. First, a survey was administered online to all students in SCIE1000 and their responses analysed, and the second phase involved a series of focus groups. The project was granted ethical clearance through the University's Behavioural and Social Science Ethical Review Committee.

4.1. Participants

In semester 1 2008, the SCIE1000 course enrolment was 569 students across 13 degree programs, including the BSc, Bachelor of Biomedical Science and Bachelor of Biotechnology. The gender of students enrolled in the course slightly favoured females (54%) with students between the ages of 16-19 representing 89% of the enrolments, and 99% of SCIE1000 students in the first year of their degree program. Students were asked to identify which specific area of science interested them most: the major areas were 39.2% biomedical science, 29% biology, 7% chemistry, 6.1% physics, 6.1% mathematics, 4.6% psychology and 1.5% earth sciences.

4.2. Phase 1: Quantitative study

The design of the survey was adapted from the Student Assessment of Learning Gains instrument [30]. The survey was administered online to all students in the last two weeks of the semester, and was incorporated into the final assignment where students could take the survey for a bonus mark. Of the 569 students enrolled in the course, 546 completed the online survey, giving a 96% response rate. The findings of the survey informed the development of the focus group questions. While the survey explored a range of topics and included the standard course evaluation questions mandated by the university, only those relevant to the study are being reported in this paper.

4.3. Phase 2: Qualitative study

Four independent, semi-structured focus groups were held in the middle of the semester following the offering of SCIE1000. The first three focus groups centred on the overall BSc curriculum in first year, although a substantial component of the discussion focused on SCIE1000. To control observed effects, these focus groups were created for low GPA (0.00-3.99), medium GPA (4.00-5.99) and high GPA (6.00-7.00) students enrolled in the first year of a science program (BSc, BSc dual degree, Bachelor of Biomedical Science, Bachelor of Biotechnology). Each GPA group was comprised of roughly equal numbers of males and females, and in each group there were students who had, and had not, completed SCIE1000. Initial analysis of feedback from the other groups informed the conduct of the fourth focus group, which solely discussed aspects of SCIE1000. The sampling strategy in forming this final focus group was to identify and invite students who had completed SCIE1000 and who had a GPA between 4.0 and 7.0. All participants in this group were females, but as gender was not a consideration in the sampling strategy this was not considered to be a problem affecting interpretation of findings. In total, 25 students participated in the four focus groups with 17 in the general BSc focus groups and eight in the SCIE1000-specific focus group.

5. Results and discussion

Survey results on the overall student perception of SCIE1000 are discussed first. Then both quantitative and qualitative results of this study are presented in relation to the two learning goals previously stated for SCIE1000, in the context of the science-mathematics debate. Finally, unanticipated findings are revealed.

5.1. SCIE1000 overall course rating

SCIE1000 polarised students more than any other first year course in the BSc offered in the same semester of 2008. As part of the standard course evaluation, students were asked on the survey, “Overall, how would you rate this course?”. The results across a five-point Likert scale are: very poor (3.1%), not so good (11.5%), satisfactory (22.9%), good (49.1%) and outstanding (13.4%). The mean value and standard deviation was 3.58 ±0.96. In another first year (biology) course running simultaneously with SCIE1000, the mean and standard deviation to the same question was 3.83 ±0.67. Overall, on this question students rated SCIE1000 higher than the two chemistry courses and the statistics course, but lower than the three biology courses, which are core subjects in the first year BSc curriculum.

5.2. First learning goal: “To instil an appreciation of the quantitative skills required for the practice of modern science, regardless of discipline, by involving students in the analysis of real world issues.”

The survey probed students’ beliefs about the role of mathematics in science. Only 3.3% of respondents believed that mathematics is not important in science. When asked about the relationships between ideas in science and mathematics, 10% of respondents believed there is “little relationship” between the two. While the vast majority of students recognised that mathematics is important in science, fewer acknowledged the relationship between the two. The focus groups further explored students’ beliefs about the interdisciplinary nature of mathematics and science. In the SCIE1000-specific focus group, all students responded affirmatively when asked whether SCIE1000 was successful in introducing and instilling an appreciation of the interdisciplinary nature of science and mathematics.

Two themes emerged which are related to achievement of this learning goal: (i) students' abilities to draw connections between the disciplines and to broader world issues; and (ii) the challenge and frustration of learning within an interdisciplinary context.

5.2.1. Connection Across all of the focus groups, students were generally positive about the emphasis being placed on connecting science and mathematics through real world issues.

> "SCIE1000 is a course that uses mathematics and science in an everyday sort of context so that you can appreciate what you're learning in a science degree applies to the rest of the world."

Students in the high GPA, general BSc focus group could provide specific examples of the interdisciplinary nature of science and mathematics. In addition to connecting what they learned in SCIE1000 to other courses in their degree program, they also expressed the most satisfaction with being able to apply their learning "to the rest of the world".

> "Everything was actually related to real life. Every piece of magazine or everything that you read, you're kind of like, you've got a feeling that you understand it based on the knowledge that you got from SCIE1000. So yeah, it's pretty good."

This is in stark contrast to the students in the low GPA, general BSc focus group. Not one of the students in this group could identify how this course was helping them. Some students could describe the intended purpose of the course ("they think mathematics is integral") and how it "sort of related to biology and chemistry". However, their experiences in SCIE1000 had not convinced them of the interdisciplinary nature of mathematics and science or how this connects to world issues.

> "It is like it is just mathematics and then they try to make it into life and they can't. I couldn't relate it seriously."

Students in the middle GPA, general BSc focus group could identify interdisciplinary connections, such as "action potentials in biology and concentrations in chemistry", although all of their examples were limited to courses in their degree program.

5.2.2. Challenge and frustration While some students in the high GPA, general BSc focus group described frustration with SCIE1000, such as "I absolutely hated SCIE1000 while I was doing it", in many cases the challenge of the course appeared to centre on the workload and their poor time-management skills. They acknowledged the value in "refreshing" their high school mathematics and believed that this would assist them as they progress through the degree program. In contrast, the students in the low GPA, general BSc focus group constantly referred to a lack of preparation for the mathematical requirements of SCIE1000. They believed that the course moved too quickly for them and "it got worse" as the semester progressed. The challenge of SCIE1000 became "too much", turning into frustration because "it's never fun when you don't understand something". Students described a cycle of disengagement where lack of understanding led to difficulty in learning, which resulted in boredom and disinterest.

5.3. Second learning goal: "Improving students' mathematical skills in the context of scientific problems"

The survey probed student gains in their understanding as a result of SCIE1000. Around 80% of students felt that as a result of completing SCIE1000, they made substantial gains in connecting how mathematics can be used to solve scientific problems. Roughly half of the students attributed substantial gains in applying knowledge from SCIE1000 to other courses in their degree program or to using critical approaches in daily life. The survey also explored students' attitudes towards mathematics and science and how they might transfer these skills into other contexts. While 80% of students indicated that mathematics serves a greater purpose in science than basic memorisation of facts, their attitudes towards relating mathematics to other courses was more divided, with only 50% of the students attempting to relate mathematics to what they learned in other courses.

Two themes relating to achievement of this learning goal emerged from the focus group analysis: (i) students' prior mathematical knowledge; and (ii) students' increased recognition of the relevance of mathematics.

5.3.1. Prior mathematical knowledge The focus groups found that students perceived that SCIE1000 had helped them to improve their mathematical skills in the context of scientific problem-solving. Students viewed SCIE1000 as a "leveller", bringing all students up to speed with the mathematical knowledge required for a science degree. Students recognised the diversity in the academic preparedness of students within the science degree programs and as such, SCIE1000 is "giving you a basic knowledge in mathematics that you can use in a whole bunch of different scientific areas". At the same time, students believed the course favoured students with a stronger mathematical background as it moved quickly through concepts. Although the prerequisite requirement of Mathematics B was well-known, several students judged that Mathematics C (a more advanced high school course) would be an ideal prerequisite. Regardless, students acknowledged that mastery of Mathematics B is crucial, as simply passing Mathematics B in high school is "not enough" for success in SCIE1000. Again, differences between the high and low GPA, general focus groups were evident. The high GPA group appreciated the opportunity to revise "forgotten" high school mathematics, and even those students in the high GPA group who had taken more advanced mathematics in high school valued the opportunity to practise mathematics. Conversely, students in the low GPA group resented having to take an "extra subject". Lack of adequate prerequisite mathematical knowledge was a major factor influencing their responses. Most of these students believed Mathematics C, a subject they had not taken, was a prerequisite for SCIE1000.

5.3.2. New relevance SCIE1000 was viewed as a "refresher course" that also contextualised mathematics in the world of science and issues affecting society. Although there was a sense that much of the abstract mathematical content had been covered in high school, it was "made new" in the sense that the course "brings to life" mathematical theory. Again, there was a substantial difference amongst the high and low GPA, general BSc focus groups. While students in the low GPA group could not identify any relevance for the mathematics presented in SCIE1000, the high GPA group revelled in a new understanding of mathematics as "relevant", as one student described.

> "It's very focused on practical applications. It walks through everything and the mathematics in it is really good because it's the same mathematics as school but the way you learn it is just completely different. It's just so much more relevant."

In the SCIE1000-specific focus group, students defended the mathematics presented in the course. It was seen to weave in and out of the entire course, and as such was integral to the course itself. These students believed that SCIE1000 had resulted in an improvement in their mathematical skills. As one student explained, "It definitely did improve your mathematics regardless of being near to Mathematics B or anything".

5.4. Unanticipated finding

While SCIE1000 was developed to bridge the gap between high school mathematics and university science, it was not anticipated that students would recognise this as strongly as they did. A clear theme emerged across the focus groups regarding how mathematics was taught in high school and how this influenced their beliefs. Interestingly, no focus groups were explicitly asked about high school mathematics, but students in the SCIE1000-specific focus group started their own discussion outlining their experiences of mathematics at high school.

> "It (SCIE1000) shows you that you actually need mathematics. Like when I left high school and they tell you that you will probably never need mathematics again. But you need it."

> "I had a good mathematics teacher and he actually told us you will need this. In any course you do, you will need this for business and science and everything, so I was expecting it."

Students in the high GPA, general focus groups also held a discussion about high school mathematics, again without any explicit prompting. While they acknowledged similar experiences of high school mathematics and being "amazed" to discover that mathematics is relevant in science, they went a step further and concluded that this approach to teaching mathematics should be adopted at the high school level.

> "SCIE1000 was good. Now that I think about it, it's probably something that should all be incorporated into the high school curriculum so you have that basis by the time you come to uni."

For many students, SCIE1000 was an eye-opener, helping to connect abstract problem solving with real world problems. For those students in the middle and low GPA, general focus groups, there was no mention of any high school teachers or any defining moments where mathematics came under the lens of a new perspective.

6. Conclusion

This study is important for its heuristic contribution to the science-mathematics debate that is now entering higher education, bringing attention to a phenomenon that requires further discussion and exploration [31]. While this study is limited to an investigation of student perceptions of a single course at a single institution, further research into academic staff perceptions and beliefs, both in the disciplines of science and mathematics, would be valuable in addition to a deeper exploration of student behaviours and learning outcomes as a result of interdisciplinary course curricula in higher education.

Findings of this study reveal that an interdisciplinary science and mathematics course can be beneficial in introducing students to the interdisciplinary nature of science and mathematics through analysis of real world issues, while improving students' mathematical skills. However, the benefits of this curricular approach are not evenly distributed across students. Those students with a weaker foundation in mathematics gain little benefit from this approach. This is a problem that requires further exploration, as the number of students entering tertiary study with limited mathematical skills is increasing [32, 33].

Developing and delivering an effective interdisciplinary science-mathematics experience to large numbers of first year students presents a substantial challenge. Universities are typically organised around traditional disciplinary boundaries, which can be a hindrance to cross-disciplinary collaborations in regards to curriculum development and teaching. For students to encounter a genuine interdisciplinary learning experience, we believe that responsibility for developing and teaching the course must be shared between mathematics and science disciplines/departments, rather than be viewed as purely a problem in either field. Scientists and mathematicians both have a great deal to add to the process, and indeed can learn substantially from each other. The logical, sequential and exact nature of mathematics compliments hypothesis-driven science, which is typically much less exact, yet perhaps more creative.

Finally, our findings provide further evidence regarding the impact of high school mathematics teachers on students' beliefs about the nature of mathematics, and in particular, beliefs about the relevance, applicability, and role of mathematics in university studies and daily life. Early on, university science curricula should challenge any misguided beliefs about the role of mathematics in science. Undergraduate science curricula must demonstrate the interdisciplinary nature of science and mathematics, particularly as school curricula are modified to better link these disciplines. Otherwise, universities run the risk of perpetuating misguided beliefs that modern science does not require mathematical skill amongst university graduates.

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Table 1: SCIE1000 framework

Social, real-world problem	**Mathematical concepts**	**Scientific context**
Heart disease	Modelling (discrete versus continuous)	Biology and Physics: Fluid flow of blood
Media reporting	Quantitative reasoning and units	Scientific literacy
Climate change	Basic mathematical functions (linear, quadratic, power)	Geographical sciences and Ecology: Temperature, wind chill, climate, impacts on species and diversity
	Periodic functions	Geographical sciences and Biology: Daytimes and seasons
	Exponentials and logarithms	Biology and Chemistry: Algal blooms, radioactive decay, pH scale
	Matrices and matrix operations	Geographical Sciences: Greenhouse gases and carbon trading schemes
Populations	Discrete models, geometric models, matrix models	Microbiology, Ecology and Psychology: Bacterial growth, stage-structured population models, behaviourism
Drugs, sex and depression	Average rates of change, derivatives, Newton's algorithm for finding roots	Pharmacology: Pharmacokinetics
Hypersonic flight	Antiderivatives and integration	Physics: Motion
Populations and change	Differential equations (exponential and logistic)	Ecology and Epidemiology: Unconstrained and constrained growth
	Lotka-Volterra model	Ecology: Predator/prey relationships
	Euler's method	
Pandemics and catastrophes	SIR model, systems of Differential equations	Microbiology and Epidemiology: Infectious disease

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