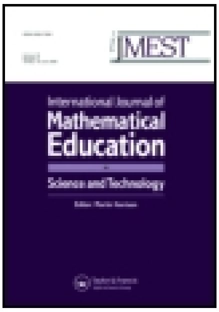

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Infusing quantitative approaches throughout the biological sciences curriculum

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A major curriculum redesign effort at the University of Maryland is infusing all levels of our undergraduate biological sciences curriculum with increased emphasis on interdisciplinary connections and quantitative approaches. The curriculum development efforts have largely been guided by recommendations in the National Research Council's *Bio 2010* report and have resulted in revisions to courses in biology, mathematics, and physics over a period of 10 years. Important components of this effort included (1) developing online modules to infuse more mathematical content into six biology courses taken by biological sciences majors during their first 2 years of study; (2) strengthening the interdisciplinary connections of ancillary courses in mathematics and physics to support the development of quantitative skills in biological contexts; and (3) creating more quantitatively intensive courses for the final 2 years of the bachelors of science programme. These efforts, carried out by a large, multidisciplinary team of faculty, have resulted in increased coherence in the undergraduate biological sciences curriculum, increased quantitative skills in first- and second-year students, and a greater appreciation among graduates for the essential relationship between mathematics and modern biology.

Keywords: biological sciences; quantitative skills; science education; higher education; curriculum; online modules

1. Introduction

There is a growing societal need for individuals with proficiency in the sciences, but it is estimated that fewer than 40% of students who enter college with an interest in a science career successfully complete a science degree.[1] While many factors influence the loss of students from the science education pipeline, there is abundant evidence that poor quantitative skills are a major barrier to success in science curricula.[1,2] The number of students entering colleges and universities with insufficient preparation in math is increasing globally.[3–7] At the same time, biology is evolving rapidly from its historical roots as a largely descriptive field to one that is heavily reliant on quantitative approaches. Undergraduate biological sciences education now faces the challenge of bolstering the

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quantitative skills of under-prepared students while simultaneously strengthening the quantitative emphasis of undergraduate biology coursework to reflect the current nature of the field. This need has inspired a series of reports and essays urging reform of undergraduate biological sciences education to integrate more mathematics into the curriculum.[8–13]

There are many fine examples of courses and curricula that address the need to develop quantitative skills in biology students. Calculus courses with biological emphasis have been developed at several institutions.[14,15] The University of Arizona offers a calculus-based statistics course that focuses on biological applications.[16] Other institutions have created interdisciplinary introductory courses that blend multiple disciplines. For example, the Symbiosis project at East Tennessee State University merges introductory biology and calculus into a single interdisciplinary course.[17] The University of Richmond and the University of Queensland have both created first-year courses that integrate mathematics and computer sciences with the physical and natural sciences.[18,19] A common strategy to strengthen the quantitative emphasis of introductory biology courses is the modular approach, where discrete units focusing on computation, modelling or problem solving are incorporated into the existing curriculum [20] and a variety of online tools are available for this purpose (e.g., ESTEEM, http://bioquest.org/esteem/; Numb3r5 Count, http://bioquest.org/numberscount/). The challenge is not lack of consensus, ideas, and materials so much as developing a coherent programme that helps students build on their prior knowledge and skills.

We report here on a long-term (10 years) effort to increase quantitative rigour and interdisciplinary emphasis across the biological sciences curriculum at the University of Maryland – a large, public university in the United States. This overview describes several different but interlinked initiatives that share the common goal of strengthening the quantitative skills of undergraduate students. Published data supporting the success of individual initiatives is cited where available, while in other cases comprehensive evaluation is still underway. Our experiences provide a model for course and curriculum revision.

2. Institutional context: building a shared vision

The University of Maryland is a research-intensive university with an undergraduate enrolment of more than 26,000 students. About 2500 of these students are pursuing majors in the biological sciences. The biological sciences curriculum consists of a four-year programme during which students complete basic coursework in biology, chemistry, calculus, and physics, followed by advanced coursework in a particular specialization area (cell biology and genetics, ecology and evolution, microbiology, physiology, and neurobiology) or broad training across several areas (general biology). The curriculum prepares students for graduate study, entrance to medical school, and jobs in industry.

Since the 1990s, University of Maryland faculty and administrators in the biological sciences had been exploring the relationship between quantitative skills and academic success. There was clear evidence that students entering the University with weak math preparation were likely to encounter difficulties in their science course-work – in 1995 only 58% of biology majors entering the University in need of remediation in mathematics completed their first semester in good academic standing.[21] These analyses of students' achievement led to a mathematics prerequisite for enrolment in introductory biology and chemistry and an intensive summer math programme for entering freshmen with weak mathematics preparation.[2]

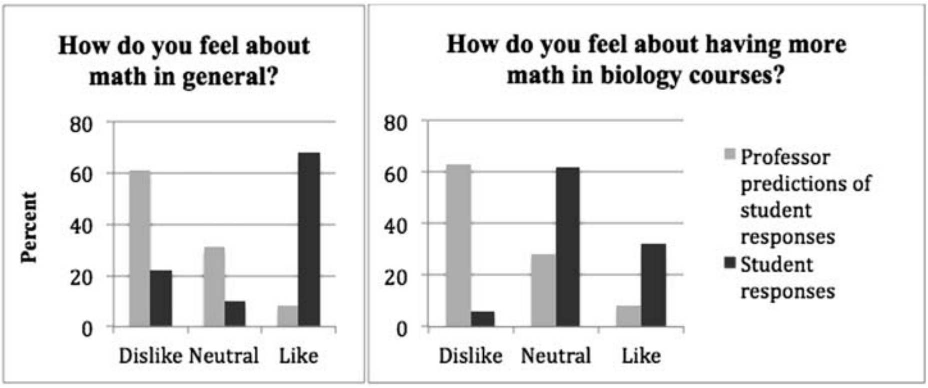

Figure 1. Faculty perceptions and student reports of students' attitudes toward mathematics.

Despite this recognition of the important relationship between mathematics and success in the biological sciences, and the growing role of mathematics in modern bioscience research, there was no coordinated effort to strengthen the linkage between the disciplines. The curriculum lacked coherence in the eyes of the students – although they had substantial exposure to quantitative subjects through coursework in calculus, physics, and statistics, many struggled to apply the skills developed in those courses to new, biologically relevant contexts. The lack of curricular emphasis on the linkages between mathematics and biology stemmed at least in part from a feeling on the part of many biology faculty members that students would resist an increased emphasis on quantitative material in their biology courses. However, an informal poll of faculty and their students revealed a disconnect between faculty perceptions of how students felt about math and the students' self-reported feelings (Figure 1).

The push to strengthen the quantitative emphasis of the undergraduate biological sciences curriculum was spurred in part by the growing number of the biological sciences faculty who felt that students enrolled in upper-level courses were much less adept at quantitative reasoning than would be expected given their previous coursework in mathematics and statistics. At the same time, the College had begun hiring a cadre of faculty members in emerging, quantitatively intensive scientific fields such as bioinformatics, theoretical ecology, and computational neuroscience who wanted to develop advanced courses that were in closer alignment with the direction of modern bioscience research. This increasing emphasis on interdisciplinary research in biology was mirrored in the departments of mathematics and physics, where growing numbers of faculty focused on biological problems. This shifting local environment coincided with the release of the National Research Council's report *Bio 2010: Transforming Undergraduate Education For Future Research Biologists*,[11] which urged a shift towards interdisciplinary and quantitatively rigorous undergraduate biology curricula. This became a guiding force for our early efforts and was reinforced by subsequent reports that echoed these sentiments, e.g., *Scientific Foundations for Future Physicians* [22] and *Vision and Change*.[13]

Concurrent with faculty discussions, the University began establishing a system of learning outcomes assessment [23] whereby the faculty within each discipline would establish specific, programme-level goals for their students, assess student learning with respect to these goals, and use these data to improve the curricula and instruction. There were six programme outcomes established for the biological sciences, two of which related to quantitative skills. These two outcomes are as follows.

- Students should demonstrate an ability to use and apply quantitative methods, especially, interpretation of graphical or tabular data; expression of physical, chemical, or biological process in mathematical form; and solving equations to determine the value of physical, chemical, or biological variables.
- Students at the lower level should have a basic understanding of how to express questions as a hypothesis, how to design a test of a hypothesis, and how to gather and analyse simple data.

3. Quantitative initiatives

It was within this context that University of Maryland faculty launched a coordinated effort to strengthen the interdisciplinary linkages throughout the biological sciences curriculum (Figure 2). The approach consisted of several interlinked components: (1) infusing more mathematical content in the fundamental biology courses taken by the biological sciences majors, pre-medical students, and non-science majors; (2) revising ancillary courses in mathematics and physics to support the development of quantitative skills and reinforce their utility in the biological sciences; and (3) creating more quantitatively intensive courses at the upper level (e.g., a course in mathematical modelling for biology). Our objectives were to help students appreciate the utility of quantitative approaches in modern biology

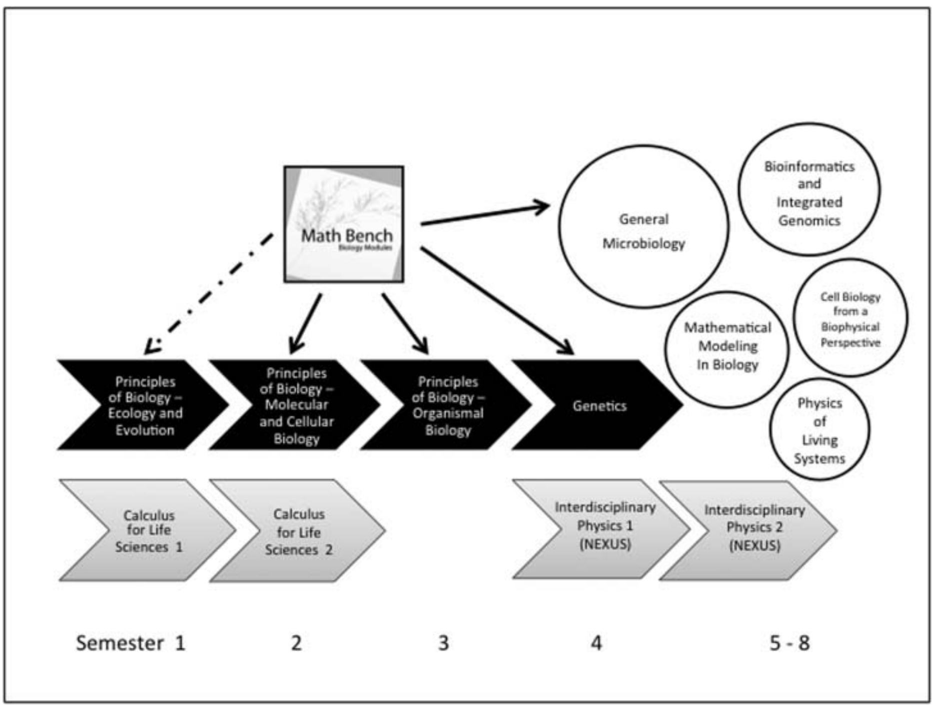

Figure 2. Components of the University of Maryland's effort to strengthen the quantitative skills of the biological sciences students.

and become adept at applying quantitative approaches to solving biological problems. The various components of this coordinated approach were developed and introduced in phases over the course of nearly 10 years.

We used multiple measures to evaluate the impact of these reforms and guide subsequent curriculum revisions, including pre- and post-tests of quantitative skills, concept inventories, attitude surveys, student and faculty focus groups, and academic achievement in subsequent courses. A discussion of the key facets of the effort follows.

3.1. Infusing more mathematical content in fundamental biology courses

3.1.1. MathBench

A major strategy for increasing mathematical and statistical content in introductory biology courses was the development of a suite of interactive, online modules (MathBench Biology Modules, mathbench.umd.edu).[24,25] Several modules were designed to supplement existing course content in each of six fundamental biology courses. Four of these courses (Principles of Biology I, II, and III and Principles of Genetics) are required of all the biological sciences majors and are typically completed during the first 2 years of study. The fifth course (General Microbiology) is optional for most of the biological sciences degree programmes but is commonly taken by students intending to apply to medical schools and is the prerequisite for several advanced microbiology courses. The sixth course (Environmental Biology) is designed for non-science majors and is also offered in the summer to advanced high school students.

During the first stages of the development process, the development team met with biology faculty members to develop a list of quantitative skills necessary to develop a deep understanding of biological phenomena (Table 1). Each module introduces or reinforces these basic quantitative skills. The tone of the modules is informal and the degree of mathematical sophistication within the modules builds gradually, which makes the modules accessible to those with weak math preparation as well as those who approach quantitative content with trepidation.[24] Each module consists of approximately 10–20 pages of text, thought questions, and quantitative problems. Interactive elements with contextually appropriate feedback are imbedded throughout. The modules are typically completed outside of class and require a half hour to 2 hours to complete, depending on their complexity and the student's need for repetition to achieve mastery. An individual class might use between 5 and 10 modules over the course of a semester, with each module typically keyed to specific content in the lecture or laboratory (Table 2). A freshman taking the entire required

Table 1. Key quantitative skills and concepts reinforced by MathBench modules.

1. Distil mathematical equations from a verbal description
2. Understand equilibria and rates of change
3. Understand types and structures of mathematical models (e.g., discrete vs. continuous, stochastic vs. deterministic)
4. Understand and use statistical tests
5. Make simple probability calculations
6. Convert units and use unit analysis to check answers
7. Scale up or down, using magnitude and significant digits
8. Use elementary functions (linear and quadratic, exponents and logs)
9. Manipulate graphs (e.g., graph equations, interpret intercepts and asymptotes)
10. Manipulate equations (e.g., solve for a variable)

Table 2. MathBench modules and the courses for which they were developed.

Course	Modules	Focus
Principles of Biology I: Cellular and Molecular Biology	Basic lab techniques	Measurement
	Straight lines/ standard curves	
	Logs and pH	
	Calculating molar weight	
	The size of things	
	A graphing primer	Visualization
	Log transformations	
	3D becomes 2D	
	Chopping up plasmids	
	Normal distributions and the scientific method	Probability and statistics
	Bar graphs and standard errors	
	BLAST and (im)probability	
Principles of Biology II: Ecology and Evolution	Basic rules of probability	Probability and statistics
	Intro to Punnett squares	
	Testing differences with the *t*-test	Statistical tests
	Testing goodness of fit with the chi-square	
	Exponential growth and decay	Population dynamics
	Logistic growth: the case of the missing housefly	
Principles of Biology III: Organismal Biology	Introduction to diffusion	Cell processes
	Diffusion through a membrane	
	Osmosis	
	The Nernst potential	
	The 3/4 scaling law	Miscellaneous
Principles of Genetics	Intro to Punnett squares	Probability and statistics
	Intermediate Punnett squares	
	Linked genes and recombination: advanced Punnett squares	
	Testing goodness of fit with the chi-square	Statistical tests
	Simulating goodness of fit tests	
	Mutation and equilibrium	Population dynamics
General Microbiology	Frank's football fiasco: exploring growth rate and meningitis	Microbiology
	Serial dilution: measuring meningococcal populations	
	Methods of measuring bacterial populations	
	Experimenting with meningitis	
Environmental Biology	Exponential growth and decay	Population dynamics
	Sampling	Environmental science
	Tragedy of the commons	
	Evolved immunity	
	What's in your watershed?	
	The case of the missing mountaintop	
	Iconic graphs of climate change	
	Keeling nails carbon dioxide	
	Mann builds a hockey team	

sequence of the coursework would encounter about 20 of these modules over the course of their first 2 years.

As MathBench has been phased into courses over a period of several years, the percentage of the biological sciences graduates who have used the modules in at least one of their courses has increased steadily from 24% in 2007 to 65% in 2012. This value has not reached 100% because each required course is taught by multiple faculty members, who are given the freedom to teach the required content in their own way. Many have adopted MathBench, but others have not. Students who enter the University with Advanced Placement credit from high school or who have completed the fundamental biology coursework at other institutions before transferring to the University of Maryland are less likely to encounter MathBench in their coursework. Nevertheless, a large number of students, both science majors and non-science majors, have used MathBench to augment their quantitative skills.

Evaluation of the effectiveness of the modules has focused primarily on the introductory biology course that focuses on cellular and molecular biology, which incorporates the largest number of modules (10). In this course, students show increases in quantitative skills that are independent of their previous math coursework.[25] They also show an increase in their willingness to tackle quantitative problems and a better appreciation for the importance of mathematics to the field of biology.[25] Preliminary analyses show more modest increases in quantitative skills following MathBench use in sophomore-level Principles of Biology III: Organismal Biology and Principles of Genetics courses (Figure 3). We are currently partnering with 32 institutions of differing type, size, and demographics to gather data on the effectiveness of MathBench in diverse educational contexts. This process has given us insight into the factors that encourage the adoption of teaching innovations and will serve as the basis for creating a faculty development framework that supports wider dissemination.

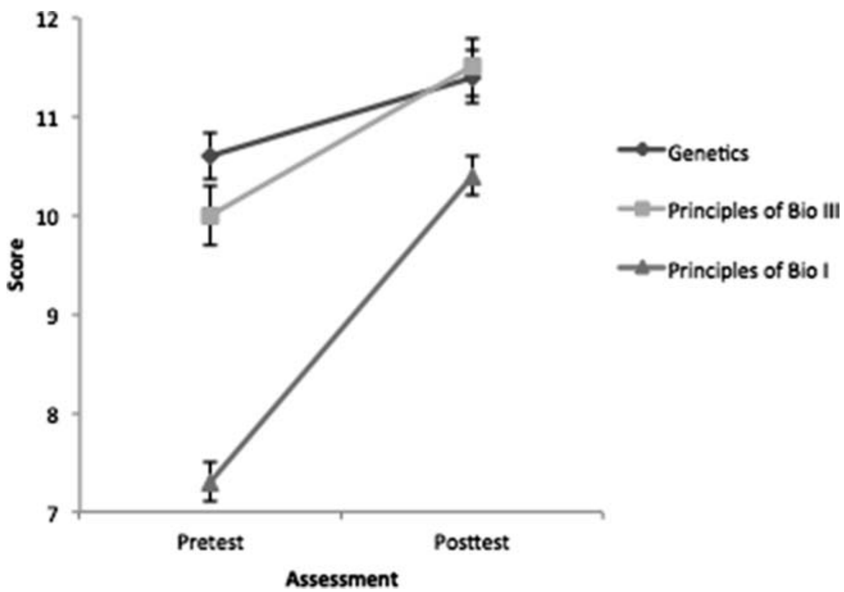

Figure 3. Scores (mean ± SE) on the MathBench pre- and post-tests of quantitative skills for students enrolled in Principles of Biology I: Cellular and Molecular Biology (Fall 2009, $N = 206$), Principles of Biology III: Organismal Biology (Fall 2012, $N = 90$), and Principles of Genetics (Fall 2011, $N = 144$).

3.1.2. Organismal Biology

Organismal Biology was created to fill a gap in the introductory biology curriculum. In the original curriculum, students completed one introductory course focusing on cells and molecules and a second on evolution and ecology. The new course was designed by an interdisciplinary faculty team and was intended to help students develop an integrated perspective on the universal mathematical, physical, and chemical principles that underlie the structure, function, and diversity of life.

Despite its principles-based emphasis, early versions of the course did little to dissuade students from their firmly held belief that success in the course could be achieved solely by memorizing facts. Interviews with students indicated that many found the course difficult and resisted the instructors' attempts to incorporate mathematical and physics approaches.[26] In response, a modified version of the course was offered, in which one of the three weekly lectures was replaced by small group activities that facilitated active student engagement. These group active engagement exercises prompted students to generate quantitative, physical, or conceptual models of biological phenomena. Group homework assignments reinforced this by asking students to apply the mathematical, physical, and chemical principles they had learned to novel problems.

Evaluation of this course, which is ongoing, has drawn from faculty field notes and reflections, surveys of student attitudes, qualitative analysis of classroom interactions, and interviews with individual students. While many students appreciate the value of the principles-based approach in helping them achieve a deeper understanding of Organismal Biology, others view this material as no more than additional facts to be memorized.[26,27] This observation has raised faculty's awareness of the need to understand the epistemological ideas held by students, since their expectations strongly influence their receptivity to new pedagogical approaches and can thwart our well-intentioned attempts to enhance learning. This ultimately led to the development of a tool for measuring student expectations in the interdisciplinary science courses (the MPEX Interdisciplinary Cluster) which is now being used to evaluate student attitudes and student expectations within specific courses and the biological sciences degree programme as a whole.

3.2. Revising ancillary courses in mathematics and physics

3.2.1. Calculus for the life sciences

Two semesters of calculus are required for the biological sciences BS degree. Historically, biology majors could complete this requirement by enrolling in a theoretical calculus sequence developed for engineering and physical sciences students or a less rigorous applied calculus sequence designed for business and social sciences majors. Neither sequence was designed to help students understand how calculus could be applied to biological problems and most students opted to take the less rigorous course sequence. When surveyed, only 47% of students who graduated in 2010 reported that they had sufficient preparation in calculus courses for their subsequent coursework in biology.

In response to this deficiency in the biology curriculum, faculty members from mathematics and the biological sciences worked together to develop a new calculus sequence focusing specifically on the mathematics most relevant to modern bioscience research. The development team included both biologists with mathematically intensive research foci and mathematicians whose research addressed biological problems. The course development process was simplified by the availability of several potential textbooks [28,29] and the existence of similar efforts at other institutions.[14,15] After being piloted with a small group of students in Spring 2008, the course was instituted as a requirement for the biological sciences majors the following semester. It now serves over 600 students per semester.

The course is taught in a large lecture format (150–200 students) that meets twice per week. In addition, the students break up into smaller groups of 20–30 students for twice-weekly recitation sessions. In these 50-minute recitation sessions, students work in groups on problems that demonstrate the utility of mathematical approaches to solving biological problems. One of the recitations sessions is led by a graduate student from mathematics while the other is led by a graduate student from the biological sciences. Inclusion of a biology-teaching assistant in a course sequence previously taught exclusively by mathematicians provides students with credible evidence of the importance of quantitative approaches in biology. The biology graduate students have also played a leading role in developing the problem sets used in the recitation sessions, often basing them on their own research disciplines. Over time this has resulted in a large bank of problem sets focusing on a broad range of biologically important topics (Table 3; hhmi.umd.edu/teachinglearning/calculusforthelifesciences).

Anecdotal evidence from faculty members teaching introductory physics and upper-level biology courses suggests that students who have taken the revised course are better prepared for subsequent quantitatively intensive coursework than those who took the previous sequence, but quantitative evidence of the benefits of the revised course has been elusive. We used three different measures of student achievement to compare students who had taken the former, applied calculus course with those who had taken the newly revised calculus for the life sciences course: (1) scores on the MathBench quantitative skills pre-test assessment in second-year Organismal Biology and Principles of Genetics courses, (2) final grades in quantitatively intensive upper-level Cell Biology, Evolutionary Biology and Molecular Genetics courses, and (3) scores on individual test items (complex, quantitative problems) from a subset of these courses. No statistically significant differences were found for any measure after controlling for other factors that were thought to be predictive of student academic performance, such as quantitative SAT score and cumulative grade point average. It is likely that either our metrics were not sensitive enough to detect a difference in the student performance or the subsequent courses had not yet increased their quantitative rigour enough to make differences in student preparation apparent.

Table 3. Examples of topics covered in Calculus for Life Sciences I and the corresponding biological contexts for recitation problem sets.

Math topic	Biological context
Exponential functions	Bacterial cell division
Trigonometric functions	Circadian rhythms
Limits	Plant/insect interactions
Instantaneous and average rates of change	Spread of a virus
The derivative	Bird reproduction and distance functions
Derivatives of trigonometric functions	Fish morphology
Graphs and the derivative: relative extrema	Free potential of a cell membrane
Graphs and the derivative: increasing and decreasing functions	Pollination
Absolute extrema	Darwin's finches
Implicit differentiation	Invasive species
Integration: anti-derivatives	Modelling bacterial growth
Definite integrals; fundamental theorem of calculus	Blood flow
Integration: the fundamental theorem of calculus	Cell division

It is possible that students benefit from the course in ways that we did not measure, such as by bolstering their confidence in their quantitative skills, increasing their interest in taking additional quantitatively rigorous courses, or giving them problem-solving skills that increased their competency as undergraduate researchers. Our graduation surveys provide encouraging data on student perspectives towards the new course: 89% of 2012 biological sciences graduates who completed the revised calculus sequence felt it prepared them sufficiently or well for their subsequent coursework, compared to 47% of 2010 graduates who had completed the previous sequence.

3.2.2. NEXUS Physics

Two semesters of physics are required for the biological sciences BS degree. As with calculus, students have had two options for satisfying this requirement: one calculus-based and the other algebra-based. Both sequences are simplified versions of the courses designed for physics majors and are taught using the traditional Newtonian framework. The courses, particularly the algebra-based version, have long been perceived by students as being irrelevant to their programme of study and only recently have efforts been made to address this shortcoming.

In 2010, the University of Maryland began redesigning its physics for the life sciences course as part of a multi-institutional effort, sponsored by the Howard Hughes Medical Institute, to create a model premedical student curriculum. This project, known as the National Experiment in Undergraduate Science Education (NEXUS), was inspired by the Howard Hughes Medical Institute (HHMI)–Association of American Medical Colleges (AAMC) report *Scientific Foundations for Future Physicians*,[22] which urged a shift in premedical student preparation from a narrow list of specific coursework to a more flexible, interdisciplinary curriculum that helps students develop broad scientific competencies. These recommendations have been echoed by the AAMC's new preview guide [27] for the heavily revised admission test that will debut in 2015. Quantitative reasoning skills are a central component of the new expectations for entering medical students.[29,30]

NEXUS Physics is conceived of as being for all biology majors and is designed to be taken in the student's second year. It has as prerequisites one year of calculus, a semester of introductory biology, and a semester of general chemistry. Numerous examples from chemistry and biology form the sinews of the class, and we have made a strong attempt to have these examples highlight scientific challenges that require a convergence of thinking of multiple sciences: problems that have both physical and chemical or physical and biological authenticity. Building on 15 years of research into how students learn physics,[31] the course is reformed in both content and pedagogy. In terms of pedagogy, the course follows an active engagement model where students read and reflect on new topics before class meetings, then spend most of their class time engaged in problem solving. The content of the reformed course more closely reflects the directions of modern biological research and differs from traditional introductory physics courses by (1) including atoms, molecules, and chemistry; (2) expanding the discussion of fluids; (3) treating random as well as coherent motion; and (4) teaching students to 'think physically' with math. It directly addresses a deficiency that has been noted by both physics and biology faculty members – that students can carry out calculations if they are presented as calculations but have great difficulty creating the calculation needed for a physical situation or extracting from a solution the implications of the multiple parametric dependencies. In NEXUS Physics, students not only learn to solve problems but explain equations and generate qualitative inferences from them.

The course is organized into a series of topical 'threads', several of which help students gain competency in 'thinking with math' (e.g., mathematical modelling, quantification, and scaling). All resources are being developed and organized in a wiki format so that they can be piloted by others during the development process.

The course was first piloted in a small class (∼20 students) format, taught by a single, experienced instructor. In the subsequent year it was offered in two small sections, taught by two different instructors, with plans to scale it up to serve 300 students per year in the following year.

The process of developing NEXUS Physics has differed in many respects from our typical course redesign process. Like previous curriculum reform efforts, we assembled a group of faculty members representing the relevant disciplines and sought input from faculty teaching upstream and downstream courses. However, the project also relied heavily on the contributions of a team of three postdoctoral associates and five graduate teaching assistants who were supported with grant funding from the HHMI and the National Science Foundation. There were no existing textbooks or appropriate models at other institutions on which we could base our new course, which necessitated the development of readings, homework problems, in-class discussion (clicker) questions, and summative assessments. The postdoctoral associates and graduate students were heavily involved in the development and formative assessment of these new teaching resources. Moreover, the development and assessment of the course was the focus of their postdoctoral and dissertation research in postsecondary science education, allowing a depth and thoroughness of assessment that had been unattainable in previous curriculum reform efforts. This has enabled us to gain a deeper understanding of the dynamics of interdisciplinary collaboration in curriculum development [32,33] and the reactions of students to interdisciplinary instructional approaches.[26,34]

3.3. *Creating more quantitatively intensive courses at the upper level*

The initial step in strengthening the quantitative emphasis of the upper-level programme (the final two years of study for the BS degree) was to institute a requirement that each student in the General Biology specialization area complete one quantitatively intensive course. This requirement could be fulfilled by an advanced mathematics course, a statistics course, or a newly developed mathematical modelling in biology course.

Of the three options, the mathematical modelling course was the only one that made explicit linkages between the disciplines of mathematics and biology, and allowed students to apply mathematics to solving authentic biological problems. The course was developed by a biology faculty member with strong interdisciplinary background and research interests. In the course, students use a variety of mathematical approaches (non-linear difference equations, eigenvector analysis, multi-dimensional stability) to develop models of important biological phenomena in diverse biological disciplines, including population dynamics, molecular evolution, phylogenetics, and infectious disease.

Although there are a large number of students in the general biology major, relatively few of them ($<5\%$) opted to take this course in fulfilment of the quantitative requirement for their degree. Instead, a large majority of students completed a statistics course. This is probably because statistics is required or recommended for admission to many health profession programmes (e.g., medical and pharmacy schools). Because of low demand, the course was not offered every year. The course has recently been incorporated into the curriculum of our new honours programme in integrated life sciences as a capstone course. This programme enrols ∼75 students per year; consequently, we expect enrolment in the mathematical modelling course to increase in the coming years.

More recently, several other mathematically intensive courses have been created. These include Physics of Living Systems, Cell Biology from a Biophysical Perspective, Bioinformatics and Integrated Genomics, and Membrane Biophysics. Based on yearly enrolment, we expect that about 20% of the biological sciences graduates will have completed one or more of these quantitatively intensive courses. Even though current enrolment is relatively low, these courses provide interested students with options that were previously unavailable to them and serve as gateways to graduate training in these fields.

4. Discussion

By their very nature, effective interdisciplinary curricula require the engagement of either individuals with strongly interdisciplinary training or a team of individuals representing different disciplinary traditions or both. The development of quantitatively intensive upper-level courses was largely spearheaded by faculty members with strongly interdisciplinary research interests who worked fairly independently. In contrast, the revisions to all of our large enrolment, introductory courses were team efforts. Graduate teaching assistants and postdoctoral associates were integrally involved in the entire process and had primary responsibility for developing MathBench modules, creating problem sets for the new calculus sequence, providing instructions in the calculus problem-solving sessions, and conducting formative assessments of the NEXUS Physics course instructional materials. The engagement of graduate students and postdoctoral associates was made possible by external funding from the HHMI and the National Science Foundation, as well as substantial institutional support. There was additional institutional support for the effort in the form of faculty release time from teaching and other responsibilities.

A social-network analysis of the collaborative relationships between the faculty members participating in these curriculum-reform efforts shows the high levels of connectivity that have characterized the efforts (Figure 4). This analysis reveals a core set of individuals who participated in all or nearly all of the efforts. They are surrounded by clusters of individuals who primarily contributed to one or two of the efforts, but there is a high level of engagement of almost all individuals across the various efforts. As might be expected, the most central individuals were primarily from the biological sciences, but each individual effort relied on the contributions of individuals from multiple disciplines. Individuals with expertise in science education research have also been important contributors to our efforts, providing guidance in selecting appropriate pedagogies and measuring impacts of the new curricula.

This heavily collaborative approach is essential for creating a cohesive, interdisciplinary curriculum, in which each course in a programme allows students to build on what they have learned previously. To achieve this, it is important that the faculty within a discipline that teach courses in a linked series, as well as faculty from different disciplines who teach ancillary courses within a degree programme, have open conversations about the learning objectives and outcomes of each course. This requires a fundamental shift in perspective, from the somewhat traditional belief that course content is entirely the domain of the faculty member who teaches it,[35] to the view that the faculty *collectively* has responsibility for educating each cohort of students that passes through a programme. To make this work, faculty members must be receptive to using teaching approaches and materials developed by others.

A deliberate pace of change is also desirable. While it is tempting to try to overhaul many aspects of the curriculum at the same time, there is a benefit to allowing reforms to evolve organically and gradually. In our case, this has allowed some of the same individuals

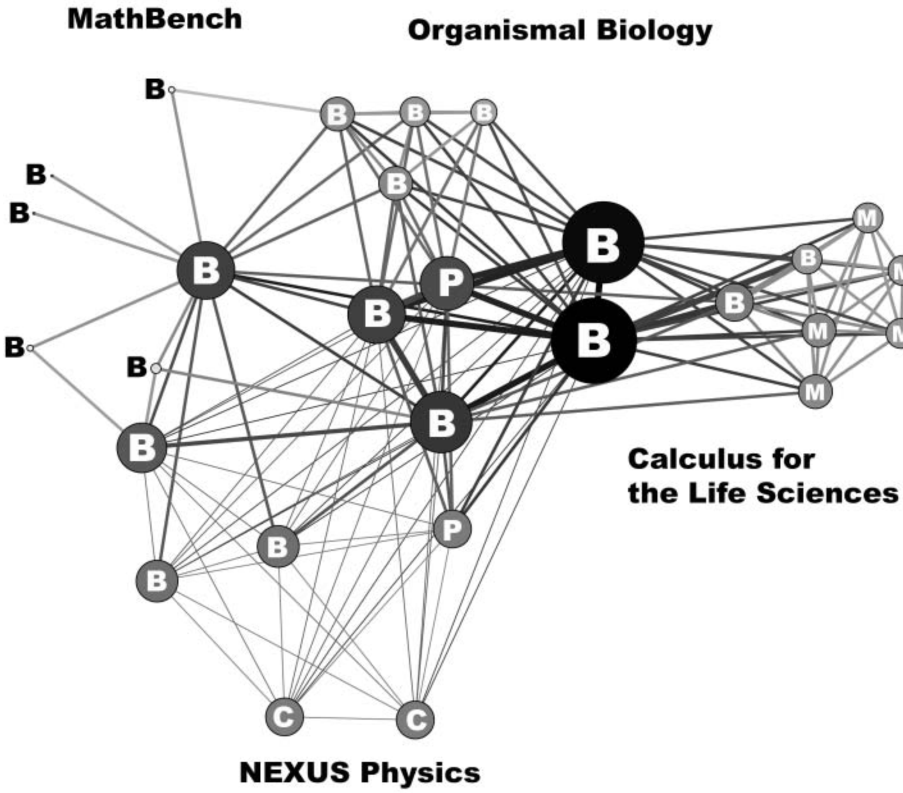

Figure 4. Social network diagram for faculty participation in several projects designed to strengthen the quantitative emphasis of students in the biological sciences. Nodes represent individual faculty members and are labelled according to the faculty member's departmental affiliation (B = biology, C = chemistry, M = mathematics, and P = physics). Edges (connections between nodes) represent co-participation in curriculum development initiatives. The thickness of the edge indicates the extent to which the connected individuals participated in the same curriculum initiatives, with thick edges denoting pairs of individuals that participated together in multiple curriculum initiatives. Node size indicates degree (number of connections with other individuals), such that large nodes denote individuals that played a role in many of the initiatives while small nodes denote individuals that participated in only one initiative.

to play central roles in related initiatives (Figure 4) and has increased the coherence of the final outcome.

These efforts have departed from traditional coursework in their fundamentally interdisciplinary approach and emphasis on competency building. The interdisciplinary emphasis will be a challenge for the sustainability of our efforts, as teaching an interdisciplinary course requires a broader range of expertise than teaching entirely within a traditional discipline. The need for instructor fluency across disciplines is more easily met at a large, research-intensive university where some faculty members are likely to have expertise in more than one discipline than at a small institution with more limited faculty numbers and expertise. Nevertheless, there will be a need for faculty training and support materials to help faculty become well versed in teaching across disciplines. We see this as a particularly pressing need in the case of NEXUS Physics, because the coursework in biology is not a part of the traditional training for doctorates in physics. We are currently partnering with institutions in the United States and Australia to implement some of these initiatives and measure their feasibility and impact at a range of institutions.

One remaining challenge is establishing strong evidence for benefits of the quantitatively enhanced curriculum. The positive effects of some initiatives (e.g., MathBench) have been easy to demonstrate, while the impact of other initiatives has been less clear. Some of the difficulty stems from trying to translate a rather global objective (e.g., improving the ability of biology students to apply quantitative approaches to solving biological problems) to specific, measurable learning outcomes. Another difficulty is in identifying appropriate evaluation measures. For the MathBench initiative, we designed an instrument to help measure specific aspects of quantitative skills deemed important by our faculty.[25] This instrument was adequate to show a positive effect from the use of MathBench, but took several years to fine-tune and validate. The improvements in the quantitative skills seen in second-year courses were relatively small in magnitude and it could not be determined whether this was the result of a small effect size or a lack of sensitivity in the assessment instrument. For the calculus for the life sciences initiative, we attempted to use a variety of existing measures to evaluate how the revised course influenced student preparation for subsequent, quantitatively rigorous coursework. No differences were apparent for any of these measures between students who had completed the original course and students who had completed the revised course. While it is logical to expect that students who complete a revised course will have better achievement in the latter coursework, in practice, this is difficult to demonstrate using easily available measures such as grades. These measures fall short because they integrate many potentially confounding factors that are known to have a strong influence on student achievement, such as student aptitude, motivation, and academic preparation.[36–38] It is possible to account for some of these confounding factors by incorporating them as covariates in statistical analyses, but for others, identifying appropriate covariate measures is difficult. Another approach is to use existing, validated assessment instruments. This is an attractive option, but if the instrument is not well aligned with the goals of the project it may provide misleading or irrelevant information. The best solution may be to develop assessment instruments that are narrowly tailored to address specific, measurable components of the phenomenon of interest. However, this approach also has drawbacks. It takes expertise and time to craft a reliable, valid instrument. In addition, there must be careful coordination with those involved in the curriculum-development aspects of the projects to ensure that the assessment items are well aligned with the effort's learning goals. This process is complicated by the fact that often the learning goals of a project change during the collaborative process of negotiating course content and pedagogy, especially when developing courses with interdisciplinary foci.[32] While it may be desirable to have controlled studies that result in quantitative evidence of success for all major curriculum changes, in practice, this may not be possible. Comparison groups may not exist or may exist only for fleeting periods of time. Also, the development of valid assessment instruments may not keep pace with changes in the curriculum; it is not realistic to 'undo' a change that faculty believe is valuable and needed just to gather comparative data for assessment.

Ultimately, the most realistic measure of success for curriculum-enhancement efforts may be a combination of qualitative, quantitative, and anecdotal evidence. Survey feedback from graduating students who have experienced the traditional and enhanced curricula provide some insight as well. These data suggest that these interlinked efforts to enhance the quantitative rigour of our biological sciences curriculum have resulted in an increase in student appreciation for the role of mathematics in modern biology (Figure 5(A)).

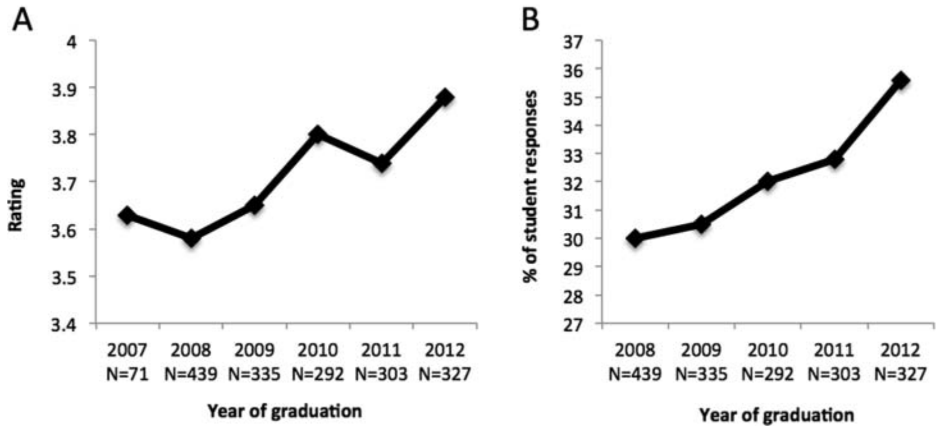

Figure 5. (A) Mean change over time in student attitudes regarding the importance of mathematics in the biological sciences. Graduating seniors were asked to rate the importance of mathematics on a 5-point scale, where 1 = not relevant, 2 = can be useful but is not really necessary, 3 = helpful, 4 = essential for cutting edge biology, and 5 = essential for doing any biology. (B) Change over time in percentage of graduating students indicating they liked math and enjoyed having classwork that included math.

This has been accompanied by a similar, modest but steady increase in the percentage of graduating students, who indicate that they not only like math but also enjoyed encountering mathematical content in their coursework (Figure 5(B)). This evidence for changes in attitudes supports the impressions of the faculty that the changes we have made in the undergraduate curriculum are benefiting students. Perhaps the most important, pervasive outcome of this 10-year effort is the institutionalization of an evidence-based approach to curriculum development that explicitly relies on the ongoing efforts of an interdisciplinary team to achieve coherent and relevant curriculum transformation.

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