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Essay

A Transformative Model for Undergraduate Quantitative Biology Education

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The *BIO2010* report recommended that students in the life sciences receive a more rigorous education in mathematics and physical sciences. The University of Delaware approached this problem by (1) developing a bio-calculus section of a standard calculus course, (2) embedding quantitative activities into existing biology courses, and (3) creating a new interdisciplinary major, quantitative biology, designed for students interested in solving complex biological problems using advanced mathematical approaches. To develop the bio-calculus sections, the Department of Mathematical Sciences revised its three-semester calculus sequence to include differential equations in the first semester and, rather than using examples traditionally drawn from application domains that are most relevant to engineers, drew models and examples heavily from the life sciences. The curriculum of the B.S. degree in Quantitative Biology was designed to provide students with a solid foundation in biology, chemistry, and mathematics, with an emphasis on preparation for research careers in life sciences. Students in the program take core courses from biology, chemistry, and physics, though mathematics, as the cornerstone of all quantitative sciences, is given particular prominence. Seminars and a capstone course stress how the interplay of mathematics and biology can be used to explain complex biological systems. To initiate these academic changes required the identification of barriers and the implementation of solutions.

CONTEXT FOR CHANGE

The National Research Council's *BIO2010* report (National Research Council [NRC], 2003) and a Howard Hughes Medical Institute (HHMI)–sponsored report with the Association of American Medical Colleges on the *Scientific Foundations for Future Physicians* (AAMC-HHMI, 2009) concluded that a strong undergraduate foundation in the mathematical and physical sciences is necessary for future success in the life sciences. However, many life science majors enter universities having seen only a traditional descriptive model of biology and are unaware of the importance of mathematics and the physical sciences to modern biology. Students with more quantitative interests—those with four years of high school mathematics including calculus—more often choose university majors like engineering, physics, or mathematics. Once in college, life science majors for the most part receive minimal additional mathematical training, and the math skills that are developed are seldom well integrated into the rest of the life science curriculum (Bialek and Botstein, 2004). In short, life science curricula do little to attract mathematically talented students to the field. Most secondary and collegiate mathematics instruction is similarly negligent, preferring traditional examples from physics to motivate and apply the mathematics.

In 2004, the problems outlined in the two reports were discussed by a group of seven University of Delaware faculty—four in mathematics, one in biology, one in chemistry and biochemistry, and one in chemical engineering. This group developed into a Biology-Mathematics Steering Committee (henceforth referred to as the Steering Committee),

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whose goal it was to create a more enriched mathematical environment, particularly in the life sciences. Initially, the discussions pointed toward improving the calculus skills of all biology majors at Delaware, but as the mathematicians became more aware of the details of the two reports, and as they listened to the other members of the group talk passionately about the need for quantitative approaches for the future of biological research, they began to suggest other avenues to reach the ambitious goal in the *BIO2010* report (NRC, 2003) of developing research scientists skilled in mathematical modeling.

The establishment of the Steering Committee was essential for the success of all the curricular changes. The driving force for this collaboration was an HHMI grant for Undergraduate Education, which focused on the recommendations made in the *BIO2010* report. Initial discussions occurred between the codirectors of the grant and mathematics faculty, who were interested in applied mathematics. As the initial group became aware of other quantitatively oriented faculty interested in quantitative approaches to biology (e.g., engineering and physics faculty), the group evolved into a Quantitative Biology Steering Committee. The committee met monthly to discuss curricular and more recently scholarship issues, and it sponsored university-wide lunches to inform the campus of the Steering Committee's goals. These lunch meetings turned out to be important for developing ideas and garnering faculty support. After about a year of initial meetings, the Steering Committee settled on two overarching goals to enhance the mathematical environment for the life sciences:

(1) Develop in biology majors an appreciation of the importance of mathematics in analyzing experimentally collected data; and
(2) Attract talented students into the field by offering them an enriched curriculum focusing on advanced mathematical skills needed to solve complex biological problems.

CURRICULAR CHANGES TO CURRENT OFFERINGS

The change that had the greatest direct impact on all biology students was in calculus. Faculty in the Department of Biological Sciences approved a change in the degree requirements from a business-oriented, first-semester calculus course to one more appropriate for science majors (e.g., mathematics and engineering majors). However, faculty were initially unconvinced the change was necessary. Faculty had to be persuaded that the higher level of calculus was important to student learning. Many faculty members were not in favor of the change, either because the change was perceived as being too difficult for the students or, for the research intensive-faculty, that a background in calculus was unimportant to their own research. The biology faculty also entertained the idea of substituting the calculus requirement with statistics.

Discussions in faculty meetings concerning the *BIO2010* report (NRC, 2003) were important in changing faculty attitudes, but what had the biggest impact was a discussion about research productivity. Faculty members who had attended the luncheons sponsored by the Steering Committee were an important source of support for the proposed changes. Also important were statements from National Institutes of Health (NIH) study session chairs about the importance of mathematical modeling in gaining research grant support. These and discussions about grant opportunities involving teams of life sciences researchers and statisticians or mathematicians helped convince faculty of the need for a more rigorous undergraduate mathematics requirement.

The Department of Biological Sciences' agreement to change the calculus requirement allowed the Steering Committee to propose a "life-science" interest section of the first semester of the three-semester foundation calculus course sequence (MATH 241, MATH 242, and MATH 243). Because of scheduling concerns and a desire to maintain compatibility within the existing three-semester calculus sequence, the math faculty on the Steering Committee led an effort in mathematics to reorder some of the topics in the first two semesters of calculus so as to better fit biology's one-semester requirement. The Department of Mathematical Sciences switched to an "early transcendentals" style for natural logarithms and exponentials, and introductory differential equations were moved from the second semester to the first (in exchange for solids of rotation in the second semester). These changes led to a more relevant syllabus for biology students, most of whom will not take the second semester of calculus. The new bio-calculus section is neither required of nor restricted to biology majors, and it is conceptually identical to the other nonbio-calculus sections.

A bio-calculus section of MATH 241 is distinguished from its siblings in two key ways. First, whereas prototypical models and examples are traditionally drawn from application domains that are most relevant to engineers, the bio-calculus section draws models and examples heavily, though not exclusively, from the life sciences. Second, calculus topics can be motivated differently in the bio-calc sections. For example, traditionally, the derivative is motivated by relating the concept of velocity to a change in position. However, change dominates all physical and chemical processes. While motion is relevant in life sciences, we experimented with motivating the concept of change with different chemical and thermodynamic processes. For instance, in one semester we motivated the concept of change by relating diffusive flux of chemical compounds to their gradient using Fickian diffusion through membranes. In another semester, we motivated change by relating heat flux to temperature differences using Newton cooling. Ultimately, all these approaches lead to the same mathematical concept, the derivative, and its geometric interpretation as the slope of the limiting case of a secant line. The key difference is that the motivating processes are revisited outside of students' calculus courses.

One of the challenges we discovered is that the natural tendency for life sciences students to understand how categories of life forms differ from one another is turned upside down in mathematics, where we wish to illustrate how seemingly disparate phenomena observed in unrelated applications are driven by identical mathematical descriptions. One of the more successful activities for addressing this challenge combined student-created problems and collaborative writing with the wiki tool in our Sakai learning management system. At the beginning of the semester, students chose one image from a collection provided by the instructor. Each image captured one or several dynamic processes, usually obviously involving the life sciences. Examples of images include bracts drifting away from a dandelion, a mosquito sucking blood, and a squid tentacle grasping at prey. Students, working in groups of up to three, complete three staged activities throughout the semester working with their image. For the first stage, students must assign variables to as many elements in the image as they can, identifying variables such as the velocity of a bract, the amount of blood in the mosquito, or the length of a tentacle. Working together, they start to see quantitative information in diverse and often unexpected places. For the second stage, students find ways to relate the identified variables in equations and formulas, by asking natural questions: How far will a bract travel? How fast can a giant squid swim? In the third and final stage, students pull together the best ideas from the first and second stages to write original calculus application problems (and a solution guide). Peer assessment is used in all three stages so that students learn from one another and receive feedback from sources within and outside their group. By guiding students through this activity, we hope to develop a habit of mind that transfers to other life sciences courses.

Mathematically, expectations remain the same for all MATH 241 sections. All students in all sections were instructed in the same mathematical concepts and skills, even though the concepts in the bio-calculus section were illustrated differently. In the first three semesters of this project, instructors administered the same common final exam to all sections of calculus to ensure that instructors for both the bio- and generic sections had uniform expectations of student learning and mastery of mathematical concepts and skills. Performance on the final exam in the bio-calculus section has served as one way to check that biology majors were performing as well as other majors. [Note: A majority of Physics, Engineering, and Mathematics majors and a minority of Biological Science majors enter the university with advanced placement credit for MATH 241 and enroll in MATH 242.] In the bio-calculus sections of MATH 241 given over three successive semesters, the biology students performed at least as well as nonbiology science majors. In a pilot course, biology majors scored an average of 77% on the final and received an average 2.54 grade point average (GPA) in the course. This was significantly better than the nonbiology majors who on average scored 59% on the final exam and had a GPA of only 1.58. The differences observed in the pilot year were similar but of lesser magnitude during the first two semesters the course was fully offered. In 2007 and 2008, respectively, biology majors scored 80% and 82% on the final and earned GPAs of 2.7 and 3.2. In the same two classes, nonbiology majors scored 77% and 64%, respectively, on the final and received an average of 2.5 and 2.1 GPA for the course.

To make sure that biology students are taking courses for which they are properly prepared, the Mathematical Sciences Department also revamped the usage of the Mathematics Placement Exam (MPE) exam, which is given to all incoming freshmen. Delaware's MPE consists of questions on basic algebra and trigonometry and places students into one of six levels, with a "level six" indicating a student is ready for first-semester calculus. A "level five" student is marginal and suggests that the student would likely benefit from taking pre-calculus before taking calculus. A lower score indicates that it is unlikely that the student will succeed in calculus and should take either pre-calculus or a noncredit remedial course.

The MPE was carefully evaluated, initially to determine whether biology majors were being properly placed. Before the evaluation, the MPE was advisory only and students could register for any course they chose. The evaluation of biology majors demonstrated that the MPE score was strongly correlated with grades in the first-semester calculus course (MATH 241). Acting on these data, the Biological Sciences Department strongly enforced the MPE placement recommendations during freshman fall registration. This study led the Mathematical Sciences Department to change its placement recommendations from being merely advisory to being mandatory for students in all majors.

The interactions arising from the collaboration between mathematics and biology faculty led to other developments relevant to biology undergraduates. In one collaboration, a stand-alone MATLAB (MathWorks, Inc., Natick, MA) module was developed for an advanced genetics lab course to build scoring matrices from data collected by the students themselves. The module helped bridge the gap between tiny examples worked by hand and widely used scoring matrices available in public databases. The Biological Sciences Department also added mathematical rigor to the introductory biology laboratories by embedding activities that required quantitative approaches into laboratory exercises. One goal set for the introductory biology laboratory was to develop an understanding of basic statistics.

To assist faculty in the design of appropriate exercises in introductory biology laboratories, the Department of Biological Sciences used undergraduates and graduate students from the Department of Mathematical Sciences as teaching assistants (Math Fellows). This team approach to learning also benefited the Math Fellows because they had to learn some basic biology to communicate effectively with the biology faculty members teaching the course. The Math Fellows reported to the instructor of the biology course and were advised by a mathematics faculty member, who was a member of the Steering Committee. The Math Fellows initially were undergraduate math majors, who were paid from the HHMI grant. Subsequently, mathematics graduate students were used. A major barrier to using graduate students was and is still a lack of available funding outside the HHMI grant.

In the future these Math Fellows will be assigned to the more advanced Biology Investigative Laboratories. These three-credit courses are Discovery Learning courses required of all biology majors and taken by them in the junior or senior year. Because all students will have had calculus, the function of the Math Fellow will be to assist faculty develop Systems Biology approaches for the labs.

CREATION OF A NEW MAJOR IN QUANTITATIVE BIOLOGY

The Steering Committee determined that success in research as envisioned in the *BIO2010* report (NRC, 2003) required more rigorous training in mathematics than was possible in current life sciences degree programs at the university. The

Steering Committee decided that a successful new degree program had to account for local strengths and realities. Delaware has a long history of developing innovative undergraduate programs. The university has become a national leader in problem-based approaches to learning (Duch *et al*., 2001) and was one of the first universities to recognize undergraduate research in the development of critical thinking skills in its students (Bauer and Bennett, 2003). None of the above suggests that Delaware was uniquely situated to create a new B.S. degree program in Quantitative Biology. However, the existence of a mathematics department populated with applied mathematicians and biology and chemistry faculty with national reputations in science education led the Steering Committee to submit a grant application to the Howard Hughes Medical Institute for Undergraduate Education. The grant was funded in 2006, and the program was instituted.

Because other universities were also establishing programs to meet the aims of *BIO2010*, a review of degree programs specializing in Biomathematics was undertaken in 2008 (Quantitative Biology II meeting at HHMI Headquarters, July 21–24, 2008; http://wikifuse.pbworks.com/2008QuantitativeBiology). Undergraduate majors variously named mathematical biology, quantitative biology, computational biology, or systems biology were quite varied in their approaches but they did have some things in common.

- Programs residing in mathematics departments, as expected, were more mathematically intense, and programs residing in biology departments were more intense in one or more different areas of biology.
- Foundation courses in introductory physics, chemistry, biology, and mathematics were similar for all programs.
- Biology courses beyond a two-semester introductory course were generally selected from a menu of courses that depended on the department in which the major resided.
- Few programs required more than four semesters of chemistry, two semesters of physics, or an introductory-level computer sciences course.
- Almost all programs required a capstone course and/or an undergraduate research experience.

The curriculum for the University of Delaware Quantitative Biology program (QBIO; http://wikifuse.pbworks.com/2008QuantitativeBiology) requires the same foundation courses in physics (two semesters), chemistry (four semesters), biology (two semesters), and mathematics (three semesters) found in other similar degree programs (University of Delaware Quantitative Biology homepage; www.udel.edu/qbio/curriculum). However, the curriculum also requires additional courses in biochemistry and biology. Like many similar programs, the biology courses are chosen from a menu of courses in several subdisciplines of biology. Unique to our program are investigative laboratory courses, one of which must be taken by the QBIO majors. These laboratories are meant to be taken by students after they have completed all foundation courses and core biology electives. The laboratories in part analyze problems from faculty research laboratories and are "discovery learning" in nature.

However, the main emphasis of the Quantitative Biology degree program is mathematics. The curriculum draws from existing courses in calculus, discrete mathematics, ordinary and partial differential equations, linear algebra, probability and statistics, and numerical computation. To integrate math and biology, two new courses were created: MATH 260 and MATH 460.

MATH 260 is a one-credit integrative seminar taken by students in the spring of each of their sophomore and junior years. It was designed to allow our quantitative biology majors to experience the links between mathematics and biology by working on cutting-edge research problems in biology where mathematics plays a central role. During the course, students read scientific literature, work in small groups, and construct and analyze simple mathematical models. In-class activity largely consists of discussion, while student activity outside of the classroom is coordinated via the use of a wiki; half of a student's grade is based on contributions to the course wiki.

A typical instance of this course was in the spring semester of 2008, when the selected topic was domain formation in lipid bilayers, inspired by an article by Collins and Keller (2008). This article was chosen because of the relative simplicity of the experiments, its lack of mathematical modeling, and the clarity of the observed phenomena. Coauthor Keller served as a course consultant via e-mail. In the first class meeting, students were given the primary source paper as well as two papers on the Ising model, and the class period was spent discussing how to read a scientific paper. Students were also introduced to the course wiki, on which each week a set of at least 10 questions would be posted. Students were instructed to record their answers on the wiki, and credit was given only for the first correct posted answer (or partial answer). The next three weeks of course meetings were spent discussing the posted answers. Students were repeatedly challenged to defend and refine their answers, as the emphasis shifted from simply understanding the papers to formulating quantitative questions about domain formation. By week five, students had arrived at a long list of possible aspects of the problem that might be probed mathematically. This class session was then spent narrowing the task and partitioning the work. During the remainder of the semester, wiki questions and class sessions were directed toward guiding students in the development of an evolving mathematical model. The final class period was reserved for a presentation to which faculty in mathematics and biology were invited.

Topics in other semesters have included data mining in ecology and pattern formation in biological systems. While the course is offered through the Mathematics Department and taught by mathematics faculty, a biologist is often brought in as a consultant during class discussions. One unexpected outcome of this course was that the students started their own campus registered organization, the Society of Mathematical Biology, where they could meet socially with other students not necessarily in the course.

MATH 460 (Introduction to Systems Biology) is a capstone course for the major. Its goal is to help the students integrate their "course-based" knowledge in biology and mathematics by modeling biological problems of varying degrees of complexity.

The initial offering was in the fall semester of 2008. The course started with an introductory lecture on systems biology, including review papers and a lively discussion of the different points of view regarding the "definition" of the subject. Most students ultimately agreed that dynamics, network connectivity, hierarchical feedback systems, and large data sets are common to problems in systems biology. A guest lecture by a researcher from Entelos on modeling of diabetes served well to impress on the students what the subject entails. The Entelos top-down approach to modeling starts off at a high level and then bores down into molecular levels of details as necessary. Other lectures on modeling were presented by invited researchers from industry (AstraZeneca and Rosa Pharma) and academia (University of Delaware).

Students worked on several projects involving modeling of biological systems with different levels of depth. To introduce the iterative process of modeling and the roles of goals, assumptions, variables, parameters, functional relationships, and model validation, students began with problems from two areas: the population of bacteria in a bioreactor, in which six increasingly complex versions of the model were investigated, and improving a pharmacokinetics compartment model found in the literature for cancer drug distribution dynamics in the body, with the goal of designing a dosage and delivery regime to minimize side effects in the course of effective treatment. The second project involved exploration of other models that examined interactions between populations of bacteria in a mixed culture, as students worked in groups on problems suggested by the instructors. Finally, in the longest semester project, groups of students proposed their own problems from one of several targeted areas: the dynamics of calcium in egg fertilization, pharmacodynamics of drugs delivered by nano particles and of quantum dots, and the use of imaging and cognitive assessment to inform modeling and treatment of Alzheimer disease.

Based on student feedback from the initial offering, the next iteration of the course (in fall 2010) will temper the problem-based approach with more lectures about specific modeling approaches in systems biology, including differential equations, discrete math, networks, and stochastic and Bayesian modeling. This course has also recently become a core requirement in a newly established graduate program in bioinformatics. The graduate students in bioinformatics can work among themselves or collaborate with QBIO undergraduates.

Although not a requirement of the degree, QBIO majors are encouraged to become involved in undergraduate research. The University of Delaware has a long and successful track record in undergraduate research (University of Delaware Undergraduate Research Program; http://urp.udel.edu) and has an established Office of Undergraduate Research. Students routinely present their research at regional and national meetings and author or coauthor publications with their faulty mentors. To support this research, summer undergraduate fellowships in the sciences are available from the Experimental Program to Stimulate Competitive Research (EPSCOR), IDeA Networks of Biomedical Research Excellence (INBRE), HHMI, Beckman Foundation, National Science Foundation (NSF), NIH, and Department of Defense grants. The HHMI grant specifically reserves funds for students who work in departments other than their academic major. Pairs of students from different departments collaborate on projects supervised by a pair of faculty members from the respective departments. This model has worked well for students and faculty in our Quantitative Biology program, which in one instance paired students and faculty in wildlife ecology with faculty and students from mathematics to work on a project of spore dispersal, and in another instance paired a QBIO major with faculty in mathematics and biology to study colon cancer.

Barriers to approving this major had to be overcome. First, although the degree program was designed as an interdisciplinary program between the Biological Sciences and Mathematics Departments, University of Delaware regulations stated that a major had to be housed in a single department. The quantitative biology curriculum lacked sufficient biology credits to be considered a Biology degree. Fortunately, the Department of Mathematical Sciences has a long tradition of strength in applied mathematics, and the majority of its faculty works in applied areas. In addition, the department had previous experience in starting another interdisciplinary major, the B.S. in Math and Economics, in collaboration with the Economics Department, which is also housed in Mathematical Sciences. These factors facilitated approval by the math faculty to house the new major in Mathematical Sciences and the process of submitting the proper proposal to college and university committees for the establishment of the new major. There were arguments at the college and university levels to the effect that this major was too rigorous and would not attract enough interest to make it a viable major. These arguments were overcome by citing national studies, in particular the *BIO2010* report (NRC, 2003). These discussions also pointed out to the Steering Committee that they had to be proactive in contacting feeder high schools to inform science mathematics teachers about national science priorities and how the new degree program addresses those concerns. These efforts have been planned with the assistance of the Admissions Office and will be implemented in the future.

To evaluate the appropriateness and effectiveness of the quantitative biology curriculum, to offer technical expertise and assistance in the design and use of classroom materials, and to help students become aware of opportunities for off-campus research and future employment, the Steering Committee formed an external Advisory Board with goals to:

- Provide ongoing evaluation of the appropriateness and effectiveness of the QBIO curriculum;
- Offer technical expertise and assistance in the design and use of classroom materials; and
- Help the faculty inform QBIO students of opportunities for off-campus research and future employment.

Members of the Board were recruited from local industry, medical research centers, and academia. The recruitment of the Board members was aided by personal contact of faculty from the university with their collaborators at these institutions. The criteria for being a member of the Board were a history of working at the interface of mathematics and biology and an interest in undergraduate education. The response we received was overwhelmingly positive.

Two of the Board members are researchers from medical research centers (Helen F. Graham Cancer Center and A.I. DuPont Nemours Hospital for Children). Both of these members are actively involved in mentoring graduate and undergraduate students in research. Three Board members are researchers from industry (AstraZeneca, Rosa & Co., and Entelos). They represent a broad range of experiences. One comes from a life sciences company that produces predictive biosimulation software. The sixth member of the Board is the director of the Delaware Biotechnology Institute, who has a long career of research in the life sciences and is well aware of the issues in educating future life science researchers.

The QBIO Advisory Board meets yearly with faculty from the Steering Committee. At this meeting academic and administrative progress is reviewed and discussed. The Board has offered very constructive criticisms. However, they have helped in other ways throughout the year. In particular, they have been invited lecturers in the capstone course for the major, they have helped mentor students in undergraduate research, and they have provided guidance in ways to improve the curriculum for the program. A more systematic approach to identifying internship opportunities for QBIO majors is being worked on with the help of the Board.

Two years after the program was approved, there are 20 quantitative biology majors. Most students in the early cohort transferred from other baccalaureate programs at the University of Delaware. These included majors from biology, mathematics, and various engineering departments. Interestingly, in its second year, five students chose to apply to University of Delaware specifically because of the existence of the QBIO major. A survey of students in the program indicated that they plan to continue their education in either graduate or medical school.

The impact of losing students from the other majors, particularly from biological sciences, was minimal. For example, biological sciences has more than a thousand majors. Also, as the QBIO degree program is considered an interdisciplinary degree program, students in the program are still considered biology-related, even though its home is in mathematics, and thus the program is considered resource neutral by the department. The QBIO major is listed on the Biological Sciences website as an optional degree program, and academic advisors are identified from both mathematics and biological sciences. Finally, the Chair of Biological Sciences considers faculty time coteaching QBIO courses to be a normal part of a faculty member's teaching workload. The issue of resources was an important issue, which was thoroughly vetted before the program was approved by both departments.

BROADER IMPACTS

Although discussions among Steering Committee members were important in designing the curricular changes cited above, it was just as important that the whole university science community became involved. To do this we developed an interdisciplinary biology/mathematics lecture se-

Table 1. Logic model for the assessment of the quantitative biology degree program: student-focused assessment

Inputs	Strategies	Outputs	Outcomes	Impacts
QBIO, life science, and other majors Mentors: University of Delaware faculty in multiple disciplines, graduate students, and industrial collaborators University support Grant funding Research projects Lab facilities	Summer research: Mentoring by faculty representing two areas in quantitative biology Summer research fellowships dedicated to QBIO majors (co-advised by QBIO affiliated faculty in two areas) Mentoring by faculty and industrial researchers Core Bio Labs: Add a strong quantitative analysis component to the investigative labs Bio-Math Seminar: Regular seminar on quantitative biology accessible to undergraduates; expert outside speakers invited periodically Orientation on graduate studies and science careers for quantitative biology and other undergraduate students	Number of students demonstrating stronger quantitative background Number of students pursuing graduate studies in science or professional schools Number of students participating in undergraduate research at the interface of life sciences and math and statistics Number of students whose attitudes about science and scientific discovery change	Students develop appreciation for the value of, and excitement about, research in QBIO Students become interested in careers in science and advanced studies Students develop good communication skills (reports, posters, oral presentations) Mentors' skills in interdisciplinary research mentoring are enhanced More faculty involvement in student research mentoring Students complete advanced studies in science or professional schools and pursue careers in scientific fields Graduate student and postdoc mentors apply their skills to mentor students once they start on their careers (academic or industrial) Faculty continue their involvement in undergraduate research mentoring University invests more resources to support undergraduate research to expand the opportunities for a larger number of students	A shift of university culture toward integration of interdisciplinary research in teaching, especially the inclusion of a quantitative component Wide range and largely inclusive opportunities for undergraduate research for undergraduate students at the university A significant increase in the number of talented students pursuing careers in science and research

ries and scheduled a series of working lunches. Two distinguished lecturers presented interdisciplinary seminars. The seminars by James Murray, a distinguished mathematical biologist from the University of Oxford and the University of Washington, and Glenn Tesler of the University of California, San Diego, were based on scholarly work and attracted a wide audience. One purpose of the lunches was to gain faculty support for establishing undergraduate research projects for quantitative biology majors. But the simple act of getting faculty in different disciplines together started a larger discussion of joint biological and biomedical research involving mathematics, engineering, and mathematics faculty, their graduate students, and undergraduates. A direct outcome of these meetings was proposed projects in rehabilitation sciences as it impacts bone function and cardiovascular research involving the identification of patients, who are at strong risk for a cardiac event. One of the lunch meetings led to biology students and faculty participating in the Mathematical Problems in Industry workshop where a team of mathematical modelers helped refine postprocessing techniques.

We feel our effort to link faculty scholarship to undergraduate learning was an important factor in garnering faculty support for curricular changes in biology and the establishment of the new interdisciplinary degree program. One outcome of this was when the Math Department searched for a new faculty member specializing in mathematical biology. These contacts proved essential in identifying candidates with strong impact both in mathematics and in the life sciences. Another consequence of engaging the science community was the acceptance by many faculty to become QBIO-affiliated faculty, who were willing to co-mentor QBIO students in undergraduate research.

All new degree programs at the university are approved for a five-year period. After that time they must be assessed before being given permanent status. We developed a logic model for our program's assessment. The assessment model in Table 1 focuses on the impact of our program on students. The assessment model in Table 2 focuses on the impact of the program on faculty. The table also includes activities which initial assessments by the Steering Committee and Advisory Board suggested would improve the current curriculum.

Table 2. Logic model for the assessment of the quantitative biology degree program: faculty-focused assessment

Inputs	Strategies	Outputs	Outcomes	Impacts
University faculty in multiple departments University graduate students Faculty at collaborating institutions Grant funding and strategic support University support for collaborative teaching Workshops, in some cases with financial support, for faculty development	Two- to three-day workshops: To help faculty, graduate students, and postdocs enhance their teaching skills (POGIL, PBL) To help faculty develop collaborations across disciplines To help faculty get started in integrating quantitative components in life science teaching Four- to six-day workshops: To collaborate with other institutions in faculty development and disseminate materials for quantitative biology teaching Create one-day consultations with math and computer science faculty for lab instructors to research new quantitative approach and collaborate Offer mathematical development experiences for interested BISC faculty Extend Math Fellows/CISC Fellows program to offer assistance to the faculty supervising the labs Create biologically relevant materials for use in CISC108 (Introduction to Computer Science) Regular brainstorming meetings of faculty in multiple disciplines to discuss teaching, mentoring, and other interdisciplinary educational and research activities	Number of faculty in multiple disciplines who: Are prepared to mentor and teach quantitative biology Value and seek collaborative teaching across disciplines Number of Bio domain areas available for QBIO projects and research Amount of material developed by faculty (at University of Delaware and at other institutions) accessible to faculty teaching courses in quantitative biology Number of books, journal articles, teaching modules, etc., published by university faculty on the teaching of quantitative biology Number of Bio faculty engaged in teaching with quantitative approaches	Greater number of research faculty who: Are mentors and teach quantitative biology Value and seek collaborative teaching across disciplines More diverse bio domain areas available for QBIO projects and research Accessible materials developed by faculty (at University of Delaware and at other institutions) Journal articles and teaching modules published on QBIO Graduate students and postdocs disseminate the culture of quantitative biology teaching and mentoring throughout their careers Books focused on courses in quantitative biology authored by university faculty University hires new faculty focusing on quantitative biology An increasing number of faculty and academic units implement more quantitative skills into the curriculum An increasing number of research faculty mentor undergraduate research in areas of quantitative biology New inter- (multi-)disciplinary courses in math and science developed and offered	University administration implements greater flexibility in workload assignment to facilitate crossdisciplinary teaching and co-teaching National leadership in interdisciplinary and discovery-based teaching Campus-wide expansion of the offering of interdisciplinary courses University culture of incorporating research in teaching and of emphasis in quantitative skills

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