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Essay

BioMaPS: A Roadmap for Success

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The manuscript outlines the impact that our National Science Foundation Interdisciplinary Training for Undergraduates in Biological and Mathematical Sciences program, BioMaPS, has had on the students and faculty at Murray State University. This interdisciplinary program teams mathematics and biology undergraduate students with mathematics and biology faculty and has produced research insights and curriculum developments at the intersection of these two disciplines. The goals, structure, achievements, and curriculum initiatives are described in relation to the effects they have had to enhance the study of biomathematics.

INTRODUCTION

The idea of creating a biomathematics program at Murray State University (MSU) began in 2003. A group of biology and mathematics faculty began meeting on a regular basis to explore common research and teaching interests. We were driven by a desire to work together to improve the quantitative skills of our biology majors and the modeling skills of our mathematics majors (National Research Council [NRC], 2003a,b). Interdisciplinary research experiences have been demonstrated to be of great benefit for undergraduates (Fortenberry, 1998; Lopatto, 2003, 2004, 2007, 2008; Erbes, 2008). In 2004, we received a Research Incubation Grant from the Kentucky National Science Foundation Experimental Program for the Stimulation of Competitive Research (NSF EPSCoR) that allowed us to fund a regular biomathematics seminar and a statewide workshop. In 2005, we were awarded an NSF Interdisciplinary Training for Undergraduates in Biological and Mathematical Sciences (UBM) grant to fund an interdisciplinary undergraduate research program in mathematics and biology—BioMaPS (http://campus.murraystate.edu/biomaps).

The BioMaPS program has enhanced the interdisciplinary environment between mathematics and biology colleagues and students. It also has created new relationships with disciplines such as chemistry, geosciences, animal health, computer science, and business that have served to further the impact that biomathematics have had at MSU and nationally. The students and faculty have provided many presentations and publications at local, regional, national, and international venues. The BioMaPS program has affected change in the collaborative research that has been investigated and the curriculum available for students interested in biomathematics opportunities. This manuscript outlines the BioMaPS program initiatives in regard to the seminars and workshops; UBM goals; UBM structure; and UBM achievements, curriculum opportunities, and discussion.

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SEMINARS AND WORKSHOPS

With funding from the Kentucky NSF EPSCoR, we initiated a biomathematics seminar in January 2004. Beginning in 2005, matching funds from the College of Science, Engineering and Technology allowed us to continue the seminar as part of our UBM award. The seminar has typically met eight times a year since its inception. Topics such as epidemiology, neuroscience, amphibian ecology, marine biology, genetics, immunocompetence, invasive species, and cancer models have been discussed. Mathematical techniques have ranged from continuous (differential equations, optimal control, and inverse problems) to discrete (combinatorics, graph theory, and game theory). Multivariate, spatial, and Bayesian statistics also have been applied to a variety of biological topics.

Although many of the speakers have been visitors, we also incorporated local speakers to emphasize that much of the research carried out by MSU mathematics and biology faculty is interdisciplinary. We also encouraged students to

give talks about their undergraduate research experiences at MSU and at Research Experiences for Undergraduates (REU) programs elsewhere. Of particular note was a seminar entitled "Mathematics and Biology Curriculum—What MSU Students Think!" given by our students. All BioMaPS seminars are open to the campus community.

The seed money from the Research Incubation grant also was used to fund the Biomathematics in the Commonwealth Workshop in 2005. Mathematicians and biologists from colleges and universities throughout the Commonwealth of Kentucky were invited to this meeting to discuss the intersections of biology and mathematics, with a view to positioning Kentucky as a leader in curriculum reform in response to *BIO2010* (NRC, 2003a). This was the first of a series of workshops that have been held as part of our program. Later workshops were designed with the needs of our UBM students in mind.

UBM GOALS

The BioMaPS program's main objective is to provide students with an intensive year-long interdisciplinary research experience involving teams of faculty and students with expertise in mathematical and biological sciences. We equip five to six students per year with the skills to understand patterns and to develop accurate models of biomedical and ecological phenomena. We developed a program that encompassed a calendar year cycle (January–December) that included bimonthly seminars, weekly meetings with faculty mentors, research proposal development, investigative research experience, and compilation of research into a final presentation and document. The program supports two or three teams annually, each consisting of two faculty mentors (one in each discipline) and at least two undergraduate students (one mathematics and one biology major). The program has had significant accomplishments, including presentations at conferences, participant awards for presentations at local and national events, invited plenary talks, minisymposium talks at national and international meetings, and peer-reviewed publications.

Our project is motivated by the increasing need for professionals who can understand the mathematics behind biology and the biological implications of mathematical models (Steen 2005a,b). As stated by Steen, "Mathematics is a science of patterns, and biology overflows with patterns" (Steen 2005b). Within the research programs, our objectives are to equip students with the skills to understand such patterns and to develop accurate models of biomedical and ecological phenomena by using methods from statistics, optimization, and differential equations. The projects have included modeling of ecological and evolutionary processes relating to fecundity, parameter identification, developmental stability, biodiversity, anthropogenic disturbances, invasive species, and population fluctuations in salamander populations.

UBM STRUCTURE: HOW DOES BioMaPS WORK?

Our project design has been sculpted by assessments conducted during our current BioMaPS project. Annual cohorts of student members creating two research teams consisting of at least one mathematics and one biology student engage in interdisciplinary research with BioMaPS faculty (at least one from each discipline). Students in the program are required to take our Principles of Biomathematics course (MAT/BIO 460) and courses suggested by their mentors that are relevant to their research projects. They work on their research project throughout the calendar year, with more extensive time devoted during the summer. Although our program advances discovery in the intersection of mathematics and biology, it also promotes the integration of research and teaching in mathematics and biology.

Student participants are selected by the end of October. To continue our success in undergraduate research in biomathematics, we advertise, recruit in our classes, and evaluate potential undergraduate researchers from both the Departments of Biological Sciences and Mathematics and Statistics for research positions. To increase the size of the applicant pool, we ask other faculty members in both departments to nominate students who are both interested and qualified to be undergraduate researchers. We also have both faculty and current undergraduates who are involved in biomathematics research visit classes, from freshmen orientation to upper-level courses, to help recruit other promising young scholars. We target students during the beginning of their sophomore year for a 1- to 3-yr research experience. We pursue a variety of avenues to actively recruit from groups underrepresented in the sciences, including women, minorities, low-income, and first-generation college students through our McNair Scholars Program and Student Support Services. After we have built a pool of strong candidates, we personally contact and recruit these students. Students are chosen based on both their academic accomplishments (minimum grade point average of 3.0), assessed through a comprehensive application, letters of recommendation, statement of goals, and a personal interview.

An initial meeting between mentors and students to discuss their research plans takes place in November to determine whether a particular course(s) is needed to better prepare the students for the research. Course work is scheduled for the spring term.

Beginning in January (Table 1), students meet with their faculty mentors at least weekly to learn the fundamentals of scientific research at the interface of mathematics and biology. The first meetings focus on developing and writing a research proposal, to be orally presented during a BioMaPS seminar. Research projects begin after faculty mentors have approved the proposals. Also during this time, students develop an action plan for their research goals and activities. As the spring semester comes to a close, students will orally present their preliminary research plans and any findings.

All students and mentors attend scheduled BioMaPS meetings throughout the academic year. Within these meetings, the goal is collaboration among the groups. If a team has a biological or mathematical question, these meetings create opportunities for other teams to provide input and possible solutions. Issues related to careers in biomathematics, such as government, industrial and academic opportunities, internships, Graduate Record Examination preparation, gender and racial issues in science and mathematics, and choice of and preparation for graduate and professional schools are addressed.

Table 1. Timeline for student activities

Fall 1	Spring	Summer	Fall 2
Application (Oct.) Schedule classes (Nov.)	Weekly mentor meeting (start Jan.) Biomathematics course Monthly BioMaPS seminars Research proposal (April)	Workshop (April/May) Full-time research (May/June)	Weekly mentor meeting Monthly BioMaPS seminars Revised research plan (Aug.) Symposium (Sept.) Outreach presentations (Oct.) Reapplication (Oct.) Interim/final report (Dec.)

Each year, a cohort of BioMaPS students attend a workshop. A major goal of the workshop is to provide instruction in research methods above and beyond what students learned during introductory mathematics and biology courses. The workshops provide students with appropriate tools for all stages of their research and focus on data collection and analysis, presentation of results, and writing. Some topics included in the workshops are as follows: sampling, experimental design, use of software for statistical analysis (such as R), use of graphics for reporting scientific results, modeling rates of change with calculus and differential equations, basic laboratory techniques, and ecological theory. These workshops have included outside speakers. In 2008, we provided a nationally publicized biomathematics workshop free to all and encouraged undergraduates to present their research in a poster session. It also provided opportunities for our students to have interactive discussions with our plenary speakers: John Jungck (Beloit College), Andy Long (Northern Kentucky University), and Chris Mecklin (MSU). In 2007 and 2009, students attended conferences as their workshop to learn from international experts (Mathematical Association of America/Society for Mathematical Biology (SMB) NUMBeRS Workshop and SMB international meeting).

During summer, extensive time is spent on research projects. Each pair of students is expected to work full-time on their project and students are paid appropriately so that other employment will not be necessary. In September, a symposium is held for BioMaPS participants, where students along with their mentors present their findings. Potential future participants are invited to the symposium as well, at which time the framework of the program and the application procedure are explained. The symposium serves as a recruitment opportunity for the next cohort of students. During the fall semester, participants give presentations about their BioMaPS research within freshman orientation groups, residential colleges, and local high schools. The goal of these presentations is to give current and future undergraduates a better understanding of what biology and mathematics can accomplish when viewed as a cohesive unit rather than disjoint disciplines, as well as to train our current BioMaPS students in teaching and outreach.

UBM ACHIEVEMENTS

Undergraduate BioMaPS fellows have given 30 presentations at local, national, and international conferences. In conjunction with students, the faculty has given an additional 29 presentations at professional conferences. The students serve as coauthors on seven peer-reviewed publications and BioMaPS faculty have generated a total of 33 peer-reviewed articles. The students and faculty have been successful in obtaining 12 research grants from local and national organizations during the past 4 yr.

A defining aspect of the project is the collaboration of four female and three male investigators across two disciplines. These mentors have the ability to attract a diverse group of students based on their different but complementary backgrounds. The mentors have experience working with >140 undergraduates who have given >100 research presentations during the past 10 yr. Each student group has given oral and poster presentations at MSU Scholar's Week annually. The teams also submit poster presentations for the local Sigma Xi Poster Competition, with two teams being selected as the Best Undergraduate Presentations in different years. Four teams have provided presentations at the Kentucky Academy of Sciences annual meeting, with one team receiving the Outstanding Undergraduate Research Award in their discipline. Three student groups have given presentations at the Southeastern Ecology and Evolution conference, the American Society of Mammologists meeting, and Southeastern Atlantic Differential Equations meeting. The teams have presented posters about our UBM program and have given invited research talks at the SMB meetings and at the Undergraduate Research Conference at NIMBioS. UBM students have visited local high schools and engaged students in conversations related to their research presentations. Several of our students were selected to present at Kentucky's Posters-at-the-Capitol. At this event, students had the unique opportunity to discuss their research with politicians and to highlight the benefits of undergraduate research.

We have had several students extend their program because they were eager to continue their research. To date, we have worked with a total of 12 students (three males and nine females). Of the six students who graduated, three students are in Ph.D. programs in biology with mathematical modeling emphases, one student is in a computer science master's program, one student is an industrial database manager, and one student is entering law school. Of the six remaining students, four students are graduating in 2010. Of these four students, three students will enter graduate school in science fields and the other student will teach mathematics at the secondary level. The remaining two students will graduate in 2011.

Our project has impacted non-BioMaPS students in courses taught by the UBM faculty because faculty inte-

grated biomathematics applications in their courses from the freshmen through graduate level. In the past 4 yr, approximately 1000 students have had access to biomathematics concepts in this manner. Approximately 200 students (and numerous non-BioMaPS faculty) a year attended the BioMaPS seminars at which UBM students and external speakers gave research presentations. The seminars incited further interest in the BioMaPS program and provided opportunities to involve students not supported by UBM funds in biomathematics research. In two cases, graduate students worked in the laboratory with the UBM teams providing further integration outside of the program.

CURRICULUM DEVELOPMENT

Students in the BioMaPS program are required to take our Principles of Biomathematics course (MAT/BIO 460) and courses suggested by their mentors that are relevant to their research projects. With prerequisites in Calculus and Introductory Biology, the course is designed to prepare students for interdisciplinary work and provide them with a thorough understanding of scientific principles.

The course uses materials from *An Invitation to Biomathematics* (Robeva *et al*., 2008). Where possible, topics are chosen to best serve the students enrolled in the course. Approximately half of the course is taught in a traditional lecture format. The remainder consists of guest speakers, inquiry-based computer labs, wet labs, reading discussions, and student presentations.

The guest speakers allow integration of the course with the existing biomathematics seminar. The guest speakers provide students with an understanding of how mathematics and biology can be integrated to solve problems that are interesting, timely, and important to both disciplines. Students are required to submit papers that summarize the presentation, discuss the significant biological and mathematical issues raised by the speaker, and make connections to what they have learned in other classes in mathematics, biology, or both.

The computer labs allow students to explore simulations of predator–prey models, SIR models, Mendelian genetics, and Hardy–Weinberg equilibria and to perform data analysis such as *t* tests and analysis of variance. Wet labs have studied intraspecific competition for plants and polymerase chain reaction analysis. Students are expected to submit assignments based on the computer and wet labs. Papers for the reading discussions have included Jungck (1997), Munz *et al*. (2009), Wainer (2007) and Ives *et al*. (2008). Future plans for this course include testing bioalgebraic modules being developed by Terrell Hodge (Western Michigan University) and Raina Robeva (Sweet Briar College).

A major portion of the Principles of Biomathematics course revolves around the term project. Students must choose a topic in mathematical biology for their project. During the first 2 yr that the course was offered, students were required to choose their topic from the ten equations paper by Jungck (1997). Some of the topics that students chose included the Michaelis–Menten equation, the Hodgkin–Huxley model, the Haldane function for genetic mapping, Luria–Delbruck models of fluctuation and mutation, and phylogenetic trees. In 2010, students were encouraged to choose their own topics, although suggestions were available. Topics chosen included chemotaxis (Murray, 1988) and the use of PageRank in ecosystems (Allesina and Pascual, 2009). A preliminary article including a brief mathematical description of the model and some discussion of the biological situation being modeled is submitted. Students also must present their term project at a special session of MSU's Scholars Week (Undergraduate Research and Scholarly Activities, 2010). For this presentation, students must write a scientific abstract for the Scholars Week program. Finally, students write a 10- to 12-page final paper providing the biological background and mathematical justification for the topic they studied. At a minimum, they must explain the notation and the equations in the model. Some students have derived the relevant equations. Others have provided numerical and graphical examples. Students must explain why and how the model is used. They are expected to identify the biological questions that the models have allowed scientists to answer. They also are asked to discuss what new mathematics, biology, or both (if any) have arisen from these equations.

To better serve our BioMaPS students and to affect change across the university, we have developed a mathematical biology emphasis within the context of the existing applied mathematics area. The mathematical biology emphasis is based on relevant biology and mathematics courses. We are in the process of incorporating a mathematical biology emphasis into the biology area. Our goal is to develop a Mathematical Biology minor consisting of current courses such as Calculus, Differential Equations, Biological Inquiry and Analysis, Botany, Zoology, Ecology, Biostatistics, and Principles of Biomathematics.

During its last offering, our Mathematical Modeling course was restructured to incorporate biological topics. This course will continue to be offered every other year. As our next step, we will develop and offer special topics courses for juniors and seniors in Biostatistics and Mathematical Biology with a view to incorporating them as cross-listed courses into the regular curriculum.

COMPARISON

Our program is unusual in that it provides an integrated research experience to our undergraduates. Unlike a summer research program, such as an REU, our students have time to delve into the literature during the spring semester and also to write papers based on their research in the fall. In several cases, students have continued to work on their research after they have completed their time as BioMaPS fellows but before they have graduated. REU participants benefit from the new perspective offered by working with students and faculty who are not at their home institution. The expertise of the faculty involved may be substantially different from that of the faculty at their home institution.

The long-term nature of the mentoring was of great benefit to both the students and the faculty. The integration of the Principles of Biomathematics class and seminar into the BioMaPS program in the spring semester provided training for the students as they developed their research proposal. The seminar speakers gave BioMaPS students exposure to different areas of expertise and a sense of the importance of

their interdisciplinary studies. The continuation of the seminar in the fall provided students an opportunity to present their work. Students were invited to suggest speakers that were relevant to their projects and they did!

However, the long-term structure was not without its challenges. Problems did not go away when the summer was over. Our pool of student applicants was sometimes very limited. In any institution, there are a finite number of talented biology and mathematics majors with sufficient interest in both disciplines to be willing to apply. Of those students, some may choose to pursue a more traditional summer experience elsewhere because of a desire to strengthen a graduate school application. Furthermore, in the current economy our students are under considerable financial pressure. Committing to research for the summer rather than to a job that would pay their next semester's tuition was simply not an option for some. In one unfortunate situation, a participant's economic interest outweighed their scientific interest, which led to problems with his/her team members that were difficult to resolve.

We believe that the integration of the traditional summer research experience into the undergraduate curriculum in this program is very portable. The basic structure of long-term research combined with course work and a seminar is manageable at many different types of institutions, particularly those with a strong emphasis on undergraduate research.

CHALLENGES

Changes in the BioMaPS program have evolved from experiences with curricular and communication issues. With curricular components, two challenges arose. Because the Principles of Biomathematics course was initially team taught by a mathematics and a biology professor, the professors desired to have this course count in their load. Yet, this did not occur. It was taught as an overload for one and was not counted for another. Basically, it was taught for the benefit of the students without compensation. Even though team teaching at a regional university is plausible, it can be difficult to put into practice. The succeeding iterations of this course involved one lead instructor (with the course counting in her load) with guest modules. The modules incorporated active-learning experiences with experimentation and statistical algorithms. These scenarios introduced the flavor of a team-taught course with expertise from three or four faculty members in biology or mathematics and provided the students with interactive learning experiences. A second curricular challenge surfaced from the development of a biomathematics area as well as the instigation of the Principles of Biomathematics course. The area is comparable to a major and minor combined into one concentration. The background work among the biology and mathematics faculty was relatively painless. One issue for the faculty was the appropriate course number for the Principles course and obtaining a cross-reference feature for it to count toward a mathematics or biology degree, but this was readily resolved. The time-consuming constraint was obtaining the necessary approval for the course and the biomathematics area through the proper administrative channels. Having contacts within those administrative channels is invaluable.

Contacts and communication go hand and hand. Whether a grant is received for a similar project or this framework is developed without external funds, the person in charge must have good interpersonal skills to be able to navigate the politics across two disciplines as well as within administrative positions. Learning how to communicate in understanding the expectations of the parties involved in the different disciplines is crucial to the success of each project. First, a retreat or workshop with faculty and students that encourages open communication is highly recommended. The BioMaPS program was involved in a Communications across the Disciplines workshop organized by faculty from Old Dominion University in theater and mathematical biology that centered on an interactive atmosphere with an underlying component of trust. It gave each participant an understanding of personality types and different communication styles. Such retreats could be developed with consultations with organizational communications departments, theater, and discipline-specific departments. Second, an important aspect of communication and trust involves successful liaisons built with administrative offices. For the BioMaPS program, these connections have been built through much patience with areas as accounting. On different occasions, the BioMaPS investigators felt that there was little control of such items as dispersal of necessary payments. Solid oral and written communication skills are critical to resolving these issues. Third, in a modest-sized, regional university such as MSU, the support staff has many responsibilities. Therefore, it is imperative to find a competent staff member to address the many paperwork issues that arise. The overarching theme of the changes within the BioMaPS program incorporates a greater understanding of the necessity of excellent communication skills.

The focus of the BioMaPS program has made inroads into increasing the number of educated undergraduates who can communicate effectively and professionally in their interdisciplinary studies of biology and mathematics. The goals of the BioMaPS program encourage these students to continue in these efforts. As mentioned in the UBM achievements section, the BioMaPS students have demonstrated their success through selection in graduate programs with mathematical biology emphases, with one receiving an NSF graduate research fellowship. Other students are using their skills in computer technological careers and as educators in the K–12 classroom.

DISCUSSION

"Modern biology is integrative; the goal should be to erase the boundaries between disciplines" (Haushalter and Asai, 2006). This principle has guided our biomathematics program from its inception. Over the past 5 yr, with the help of the NSF UBM–funded BioMaPS project, we have increased the amount of interdisciplinary research between faculty and undergraduate students in biology, mathematics, and statistics. Our ongoing biomathematics seminar has increased both the awareness and interest of mathematical biology among our students. Labov *et al*. (2010) describe the lack of communication between biology and mathematics departments as one of the impediments to The New Biology. Our group considers communication to be one of its highest

priorities. Through our course and program development and through our undergraduate research program, we have improved MSU's ability to integrate the education of its mathematics and biology students with the goal of providing a model for other cross-disciplinary integration across our campus.

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