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On the Edge of Mathematics and Biology Integration: Improving Quantitative Skills in Undergraduate Biology Education

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INTRODUCTION

The challenges future biologists face dictate a change in the way we prepare undergraduates who wish to pursue a career in the life sciences. In *A New Biology for the 21st Century* (National Research Council [NRC], 2009), four main challenges are articulated: enabling sustainable food plant growth in changing environments, sustaining ecosystems and biodiversity in rapidly changing environs, expanding sustainable alternatives to fossil fuels, and understanding human health. Solutions for 21st-century challenges involve complex systems that no single discipline can fully address. As many of the key problems involve biology, future biologists must be ready to work in diverse settings in interdisciplinary collaborations. Equipping biologists with current disciplinary knowledge is essential, but biologists also need to develop strengths outside their specialty to fully contribute to and engage with these problems. There is a rich history of interdisciplinary work in mathematics and biology producing exciting and sometimes unexpected new knowledge and discoveries (Jungck, 1997). To insure the continued success of such interdisciplinary work and the public's ability to absorb and understand the implications of this work, it is important that mathematical approaches become an integral component of undergraduate biology education. Even within biology, the increasing use of large data sets requires biologists to acquire skills in mathematics, particularly statistics, and computer science. This goal can best be accomplished by incorporating mathematical tools and approaches in all biology courses. For example, a molecular forensics program at California Polytechnic State University integrates this theme across the curriculum by integrating biology into applied areas that include database design and a strong emphasis on data analysis (Kitts, 2012).

Deficiencies of quantitative knowledge and approaches in biology curricula have been noted over the past decade (Gross, 2000; Bialek and Botstein 2004). Frequently, mathematics and biology courses are taught in near independence of each other (Gross, 2000). This approach often leaves students with parallel tracks of knowledge but unable to understand how each discipline informs and influences the other. Students have difficulty when applying their knowledge from one course to another and are often unable to synthesize their knowledge into a cohesive framework. A decade-long survey of plant physiology students revealed persistent weaknesses in students' abilities to answer quantitative questions (Llamas *et al.*, 2012). Limitations in basic quantitative abilities can have real implications for biology and health students. A study of Australian nursing students demonstrated conceptual and computational errors in calculating drug concentrations, skills that are commonly used in the workplace (Eastwood *et al.*, 2011).

Fostering quantitative competencies is important for professional biologists in virtually all subdisciplines as well. A recent analysis (Fawcett and Higginson, 2012) shows that a greater concentration of mathematical equations presented in the main text of papers published in ecology and evolution journals lowers the number of citations of that paper by other biologists (as judged by information in the Science Citation Index). The Fawcett and Higginson paper raised a lively conversation on possible causes for the effect. One possibility drawn from some of the commentary is that the biology audience lacks comfort with mathematically dense papers, which limits the impact of ideas and findings within them. Providing

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more quantitative approaches during the early education of biologists would improve their ability to handle mathematical models and therefore their ability to contribute to and benefit from key approaches within their fields of interest. Quantitative competencies are critical for analyzing data. An analysis of behavioral, systems, and cognitive neuroscience studies found multiple articles that incorrectly used statistical analyses, leading to potentially wrong conclusions that went undetected by the researchers, reviewers, and editors (Nieuwenhuis *et al.*, 2011). Quantitative competencies are essential skills for professional biologists, enabling them to effectively interpret and communicate complex data.

The *Vision and Change in Undergraduate Biology Education* report calls for a focus on the core competencies of quantitative reasoning, modeling, and simulating complex systems. Undergraduate students should learn how to apply quantitative skills to biological topics and use quantitative reasoning to interpret data. Students should also be proficient in the use of modeling and in exploring systems with computational approaches (American Association for the Advancement of Science [AAAS], 2011). *BIO2010: Transforming Undergraduate Biology Education for Future Researchers* by the NRC, the American Association for Medical Colleges–Howard Hughes Medical Institute's *Scientific Foundations for Future Physicians*, and the College Board Advanced Placement Biology Test each acknowledge the importance of quantitative reasoning and skills for modern biology (NRC, 2003, 2009; Association of American Medical Colleges–Howard Hughes Medical Institute, 2009; College Board, 2012). *CBE—Life Sciences Education* has dedicated an entire issue to mathematics and biology (see Marsteller, 2010). Despite attention given to the need to improve quantitative competencies, many biology courses remain unchanged. However, prime opportunities do exist for biologists to introduce innovative courses and curricula that best use the resources at their institutions to provide biology undergraduates with the quantitative competencies they need to meet the demands of current and future challenges.

In this paper, we describe how two institutions are helping their undergraduate biology students build quantitative competencies. Incorporation of quantitative skills and reasoning in biology are framed through a discussion of two cases that both concern introductory biology courses, but differ in the complexity of the mathematics and the type of changes involved. First, at the University of Maryland–College Park, MathBench Biology Modules (via an interactive Web-based instructional service) are providing supplemental materials to illustrate and develop quantitative competencies basic to biology. The second example, at Davidson College, uses a unique text to introduce a wide range of students, including those with no calculus experience, to challenging mathematical concepts in biology. The textbook emphasizes learning through modeling and data analysis, activities that are integral to developing understanding in biology.

MATHBENCH BIOLOGY MODULES

Project Description

Beginning biology students start their introductory classes with a very diverse set of mathematical experiences. Students may need assistance to integrate their mathematical knowledge into their biology courses or even to develop the basic quantitative skills essential for success in updated introductory biology courses. The MathBench Biology Modules, designed by Kären Nelson and colleagues at the University of Maryland College Park, are interactive Web modules detailing critical beginning concepts for biology students (Thompson *et al.*, 2010).

These modules foster numerical literacy, reinforce biological themes, and lay the foundational competencies required for more advanced biology courses. The modules cover a range of topics from measurements and statistics to growth rates and diffusion, all of which are core concepts in biological processes (Table 1). More than 40 modules have been developed to date. Each contains interactive examples and problems that can illustrate real-world applications, such as the doubling time for bacteria or diffusion in different environments, each of which incorporates important quantitative concepts. Modules are written in an accessible style, making them appealing and easily understood. The modules are succinct, are hosted online (http://mathbench.umd.edu), and can be completed within students' schedules. Biology educators can use the modules in a number of ways, such as during a class presentation to reinforce selected concepts, as a pre-lab activity, or as an intervention for students needing assistance to become proficient in essential quantitative skills.

Assessment and Outcomes

The modules positively impact a number of factors for biology students (Thompson *et al.*, 2010). Importantly, students navigating the modules show improved outcomes relative to their starting quantitative skills as measured by pre- and posttests. Other effects noted include improved understanding regarding how mathematics is used in biology and increased student engagement with the biology class.

MathBench Biology Modules represent one example of how biology educators can incorporate materials to improve quantitative skills and reasoning into introductory courses. As the materials are stand-alone in nature and freely available, educators can utilize the materials as needed and experiment with implementation of the modules. Beyond their use to reinforce concepts in the classroom, the modules can be particularly beneficial for students taking laboratories that typically accompany biology courses.

INTEGRATION OF MATHEMATICS AND BIOLOGY BY USE OF A NEW TEXTBOOK

Textbooks are central components to introductory courses. Textbook design can influence how students incorporate information or relate new knowledge to their cognitive framework. Textbooks can shape how students perceive biology. However, an examination of current popular biology textbooks reveals a presentation of biology focused on facts and images presented as conclusions and take-home messages. The process of science, which involves interpreting data to inform understanding and develop concepts, is largely absent (Duncan *et al.*, 2011). Understanding the process of science is clearly stated in *Vision and Change* as a core competency (AAAS, 2011) and is advanced by the other reports cited above. Altering introductory biology textbooks to focus on

Table 1. Examples of MathBench topics and demonstrated concepts

Section	Examples
Measurement	Basic techniques, logs and pH, metric conversions
Visualization	Graphing, three-dimensional becomes two- dimensional
Probability and Statistics	Normal distributions and science process, SE, Punnett squares
Statistical Tests	*t* test, chi-square, goodness-of-fit simulations
Miscellaneous	3/4 Scaling law
Cellular Processes	Diffusion, osmosis, Nernst equation
Microbiology	Meningitis case study, growth rates
Population Dynamics	*Escherichia coli* population dynamics, mutation and equilibrium
Environmental Science	Sampling, evolved immunity, watershed, coal and mountaintop removal
Climate Change	Graphs for climate change, CO_2

process presents an opportunity to emphasize integration of quantitative competencies for early biology students.

Project Description

Biologists Malcolm Campbell and Chris Paradise have teamed up with mathematician Laurie Heyer to redesign an introductory course at Davidson College by writing a textbook de novo. The book, being tested in classes at diverse institutions, takes an approach that rejects the encyclopedia-like biology textbooks and opts to focus on core themes and ideas central to biology. Rather than feeding overwhelming amounts of information to the students, this new biology textbook provides real data and challenges students to construct their own knowledge of the key concepts of biology. Many current textbooks are noted for their "mile-wide, inch deep" approach, which provides broad coverage but minimizes the process of science, leading to a shallow perspective of biology (Duncan *et al.*, 2011). Interpreting data is essential for any biological researcher, so it makes sense to teach students to think critically and examine both visual and quantitative information as a means of constructing or clarifying concepts. The book utilizes published research and data sets from key papers, allowing students to work with the data, organize their interpretations, and develop the scientific meaning. The use of figures as data (rather than decoration or a collection of take-home messages) helps biology students see their discipline as a science rather than a foreign language with long lists of terms to memorize. The text's emphasis on data analysis, interpretation, and developing concepts can greatly facilitate active-learning practices in the classroom and has already demonstrated gains for students (Barsoum *et al.*, 2013).

Mathematics is incorporated throughout the text as accompanying pieces termed BioMath Explorations (BMEs). The BMEs are designed to enhance biological concepts through interactive mathematical examples. To maximize accessibility, the text assumes no more than high school mathematics (including some algebra, but no calculus) as the basic mathematics preparation for students entering the course. Basic quantitative skills are developed through explorations that highlight the close relationship of mathematics and biology. Throughout the explorations, students manipulate data sets and develop concepts from the data. In one exploration, students curve-fitted data to understand how abiotic vesicles can steal lipids from competitors and discover possible mechanisms for the origins of life. Another exploration helps students calculate genetic distances and correlate these with geographic distance, using plant populations to better understand gene flow. A third exploration uses simple geometry (area of a triangle) to approximate the amount of DNA present in each band from Meselson-Stahl's classic experiment on semiconservative DNA replication.

Assessment and Outcomes

Skeptics often raise the concern that students using the process of science to learn the content will suffer from a lack of fundamental knowledge due to decreased content. Throughout one semester of introductory biology, the authors measured the effects of their new textbook on the students by comparing students in the revised course with students in two sections using a traditional text (Barsoum *et al.*, 2013). Teaching approaches consisted of Socratic discussion mixed with teacher presentations. Across the three sections, teaching methods were consistent to measure the impact of the textbook. Content examinations revealed similar levels of knowledge for students using the new text and students using a traditional text, indicating that reducing factual content and focusing on central themes is not detrimental to student outcomes related to content. Furthermore, students using the new text exhibited better retention of the content when surveyed several months later. Perhaps more importantly, students using the new text demonstrated better abilities to interpret novel data sets. Students using the new textbook also were more likely to disagree with viewing the science of biology as a set of definitions and processes to memorize.

RESOURCES

The preceding descriptions illustrate two examples of how we can incorporate quantitative competencies into biology instruction. Additional examples of textbooks and online resources that integrate mathematics and biology are found in Table 2.

ENABLING CHANGE

As faculty consider ways to merge quantitative reasoning and mathematical skills with core content in biology, the process of bringing new materials and concepts into the classroom can be difficult due to limited time and resources. Assistance from funding agencies exists to advance new educational opportunities and can support faculty in changing teaching practices to help biology students meet the 21st-century challenges.

Table 2. Resources for integrating mathematics and biology

Name	Description	Website
Modeling the Dynamics of Life: Calculus and Probability for the Life Sciences (textbook)	Examines mathematics in diverse biology fields. Connects principles of central biological concepts with an emphasis on modeling and mathematics.	
Calculus for Life Sciences: A Modeling Approach (online textbooks)	Free online texts to cover concepts without and with calculus.	http://cornette.public.iastate.edu/CLS.html
Undergraduate Mathematics for Life Sciences: Models, Process, and Directions (book)	A collection of courses from diverse institutions portraying varied attempts to integrate mathematics and biology	www.math.unl.edu/~gledder1/MathBioEd/MAANotes_Preface_TOC_Intro.pdf
ESTEEM	Modules in Excel that allow students to explore and learn concepts that have transformed contemporary biological practice	http://bioquest.org/esteem
Numbers Count	Emphasizes biological problem solving with contemporary biological problems using real data	http://bioquest.org/numberscount
Bedrock	Inquiry-based approach to use bioinformatics for solving biological questions	http://bioquest.org/bedrock/problem_spaces
University of California–Davis Quantitative Computer Labs	Computer labs covering a variety of biological topics	http://biosci3.ucdavis.edu/qcourses
Society for Mathematical Biology	Upcoming 2013 annual meeting at Arizona State University	http://math.asu.edu/SMB2013

External support can foster relationships among faculty and support faculty to invest in curricula development. National Science Foundation (NSF) programs such as the Transforming Undergraduate Education in STEM (TUES) program, the Research Coordination Networks–Undergraduate Biology Education (RCN-UBE), the Science Talent Expansion Program, and the Research Experiences for Undergraduates are all aimed at supporting such changes (NSF, 2006, 2011, 2012a, 2012b).

Faculty talent and interests are often segregated into discrete and diverse disciplines; the challenge for faculty is to bring quantitative skills and attitudes into biology courses at all levels. Finding like-minded colleagues in sister disciplines and the time to develop strong working relationships with them is critical. Therefore, opportunities to bring faculty together prove to be invaluable for facilitating the spread of knowledge, enabling partnerships to form, and bridging the gap between biology and mathematics. Interdisciplinary workshops have helped shape the field (NRC, 2009; Marsteller *et al.*, 2010; Making Biomath Happen, 2012). Future gatherings of educators are critical for sharing practices and exploring the rich variety of ways mathematics and biology intersect. One such effort is an HHMI Quantitative Biology Conference (http://bioquest.org/qb2013), organized by Pat Marsteller and scheduled for June 11–14, 2013, at Emory University, to cover high-profile efforts by BioQuest, the National Institute for Mathematical and Biological Synthesis, and the HHMI Quantitative Biology Consortium. The TUES and RCN-UBE programs both support efforts to bring educators together to explore these issues and development of courses and materials that support these goals (NSF, 2006, 2012a). The community is strongly encouraged to seek out these opportunities as their work warrants the support.

CONCLUSION

The goal to change biology teaching to match the "biology that we do" is an opportunity for educators to creatively explore and forge interdisciplinary relationships between mathematics and biology. As biology research is further integrated with quantitative methods and knowledge creation, it becomes paramount that future generations of biologists be appropriately educated. In this paper, we highlight two cases to help frame the scope of mathematical and quantitative competency issues. Both improve student quantitative competencies and reasoning and can contribute to the future success of these students. Other examples may provide more details and ways for all institutions to incorporate quantitative skills in biology (see Marsteller, 2010). The next article in this series will provide many more examples and will provide an overview of the challenges and advantages of these varied approaches to merge mathematics and biology. The charge is clear, and NSF is ready to help the biology community meet the challenge.

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