

Essay

Toward Integration: From Quantitative Biology to Mathbio-Biomath?

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In response to the call of *BIO2010* for integrating quantitative skills into undergraduate biology education, 30 Howard Hughes Medical Institute (HHMI) Program Directors at the 2006 HHMI Program Directors Meeting established a consortium to investigate, implement, develop, and disseminate best practices resulting from the integration of math and biology. With the assistance of an HHMI-funded mini-grant, led by Karl Joplin of East Tennessee State University, and support in institutional HHMI grants at Emory and University of Delaware, these institutions held a series of summer institutes and workshops to document progress toward and address the challenges of implementing a more quantitative approach to undergraduate biology education. This report summarizes the results of the four summer institutes (2007–2010). The group developed four draft white papers, a wiki site, and a listserv. One major outcome of these meetings is this issue of *CBE—Life Sciences Education*, which resulted from proposals at our 2008 meeting and a January 2009 planning session. Many of the papers in this issue emerged from or were influenced by these meetings.

INTRODUCTION

The national scientific and academic community has issued repeated clarion calls for revising college biology curricula and the mathematical and computational preparation for future life scientists to reflect the tools and practices of science (National Research Council, 2003; American Association for the Advancement of Science, 2009). Biomedical research is increasingly interdisciplinary in nature, involving communication and teamwork between individual researchers with expertise in diverse fields. In contrast, undergraduate coursework in the sciences is often fragmented and unconnected. *BIO2010* (Na-

tional Research Council, 2003) calls for future biomedical researchers to be better educated in the mathematical, physical, and molecular bases of biology and urges better integration between the disciplines. At the 2006 Howard Hughes Medical Institute (HHMI) Program Directors Meeting, participants from HHMI-funded institutions with interests in interdisciplinary curriculum reform established a consortium to investigate, implement, develop, and disseminate best practices resulting from the integration of math and biology. This led to an HHMI-funded mini-grant, led by Karl Joplin of East Tennessee State University (ETSU), in which 30 institutions joined in planning a series of summer institutes and workshops to document progress toward and address the challenges of implementing a more quantitative approach to undergraduate biology education. The goal of the mini-grant was to establish a network of interested biologists, quantitative scientists, and educators to explore progress on quantitative biology education. We convened faculty institutes in 2007 and 2008. Additional support from institutional grants (Emory and University of Delaware) enabled two more summer programs in 2009 and

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2010. Each meeting included invited speakers who addressed new research in the life sciences or mathematics, invited education presentations to illustrate biomath collaborations, workshops and discussions on key issues, and contributed posters and presentations.

Continued collaboration was facilitated by a listserv¹ and a wiki site.² Colleagues who share the goals of integrating math and biology in undergraduate education are encouraged to join the listserv. The wiki, Forum for Undergraduate STEM Education (FUSE), contains workshop agendas, presentations, and posters from the four meetings, draft white papers, and many teaching resources for quantitative biology.³ The site also contains:

- Initiatives on each participating campus <http://wikifuse.pbworks.com/2007QuantBioAbstracts>
- Teaching materials for a mathematics for neuroscience course <http://wikifuse.pbworks.com/browse/#view=ViewFolder¶m=Math%2520for%2520Neuroscience>
- Syllabi developed by participants in three consortium institutes <http://wikifuse.pbworks.com/browse/#view=ViewFolder¶m=BioMathMathBio%2520Syllabi>
- Papers that review integration of biology and mathematics, including papers on computational sciences, bioinformatics, calculus, and statistics

The first summer workshop was held July 18–20, 2007, at ETSU.⁴ In the 2007–8 year working committees developed draft white papers, which can be found on the wiki. The second workshop was held July 21–24, 2008, at HHMI headquarters and was attended by 66 biologists and mathematicians from 36 colleges and universities. In addition to presentation of the white papers, the 2008 meeting included invited talks, workshops, and a poster session. All materials are available at <http://wikifuse.pbworks.com/2008QuantitativeBiology>.⁵

A survey of the 66 participants suggested that the 2008 meeting guided the development of future meetings. Participants most highly valued:

- Specific examples of what works in integrating mathematics and biology;
- Networking and connections with like-minded individuals;
- Identification of existing resources (avoiding reinventing the wheel);
- Inclusion of multiple approaches;
- Inclusiveness of biology and mathematics faculty.

¹ <https://listserv.umd.edu/archives/bio-math-consortium.html>. Those interested in joining can find directions for subscribing on the listserv website, or can send an email to listserv@listserv.umd.edu with the following text in the body of the email: subscribe bio-math-consortium Your Name. Messages to be distributed to the entire list can be sent via the web interface or by sending an email to bio-math-consortium@listserv.umd.edu.

² To register for the wiki, Forum for Undergraduate STEM Education (FUSE), go to <http://wikifuse.pbwiki.com/FrontPage>.

³ <http://wikifuse.pbworks.com/Symposia>.

⁴ Presentations, posters, and other materials available at <http://wikifuse.pbworks.com/2007QuantitativeBiology>.

⁵ Twelve institutions presented posters on a variety of science education initiatives. All abstracts and most of the posters can be downloaded from <http://wikifuse.pbworks.com/2008QuantitativeBiology>.

Sixty-four percent of participants suggested more and longer workshops with a focus on problem-based learning (PBL) and cases, curriculum development and sharing materials, sources of funding, and perhaps a focus on specific courses. Thirty-nine percent also suggested that perhaps small colleges and larger universities have different challenges and might resolve them better in more focused meetings. Other suggestions included focusing more on assessment and conducting a more comprehensive review of available materials. Another result of these discussions is this special issue of *CBE—Life Sciences Education (CBE-LSE)* on quantitative biology. Other suggestions called for extending the repository of materials in one of two ways, either through some existing website or wiki or by establishing a new online journal. Potential challenges to the implementation of these ideas included finding reviewers, ensuring classroom testing of materials, and cost.

The third meeting in 2009 was a focused workshop on PBL and investigative cases held at Emory University and sponsored by the Emory HHMI grant. Thirty people attended from 19 universities and colleges. The 2009 meeting sought to bring together teams of biologists and mathematicians to develop case-based and PBL-like exercises for education in biology, mathematics, computer sciences, and quantitative biology. J. P. (University of Delaware) and P. M. (Emory) introduced the idea of adopting and adapting existing materials using invasive species cases and models as examples. They led the workshops on creating new materials to help students see the connections between mathematics and biology.⁶ Six teams developed cases that were being piloted during 2009–2010. Once the cases are field-tested they will be placed in the Emory Cases Online site (www.cse.emory.edu/cases).⁷

The fourth meeting, Education at the Edge, was held June 9–11, 2010, at the University of Delaware. Sixty attendees participated in plenary talks, workshops, and planning sessions. The primary focus was to highlight progress and to plan the future of the network. Sixty attendees from 26 universities, colleges, and regional pharmaceutical companies participated in plenary talks, workshops, and planning sessions. The primary focus was to highlight progress and to plan the future of the network. Attendees reiterated calls for discussions of the differing challenges that confront smaller and larger institutions and the development of one comprehensive site for syllabi, materials, and resources for integrating mathematics and biology. Participants highlighted concerns

⁶ For full details and the beginnings of our products, visit <http://wikifuse.pbworks.com/2009MBBM>. Workshop resources are available at the wiki site (<http://wikifuse.pbworks.com/browse/#view=ViewFolder¶m=MBBM%2520PBL%2520Resources>).

⁷ Draft cases can be viewed at <http://wikifuse.pbworks.com/browse/#view=ViewFolder¶m=MathBioCases>. Examples include a PBL case of human differences developed by Marty Thomas (Georgia Gwinnett College) for an introductory statistics course; swine flu case and virus cases developed by Aditi Pai (Spelman College), Muhammed Rahman (Clayton State), and Weihu Hong (Clayton State); a microbial diversity case developed by Bill Hoben and Ming Chen (University of Montana); and a case involving student athletes and knee injuries developed by Jeff Knisley (ETSU) and Wendy Newstetter (Georgia Institute of Technology). Gilberto Schleiniger (University of Delaware) presented the case he developed at the February 2009 Pan American PBL meeting in Sao Paulo, Brazil. Several new interuniversity collaborations emerged from this institute and resulted in papers submitted to this issue of *CBE-LSE*.

about the often subordinate roles of mathematicians and computer scientists in mathematical biology and quantitative literacy programs.

CHALLENGES AND OPPORTUNITIES

As this issue of *CBE-LSE* attests, many good ideas are emerging for integrating quantitative and computational competencies in life sciences education, yet much remains to be accomplished and many challenges remain. As the Quantitative Biology summer institutes and this issue illustrate, a wide range of approaches exists to integrate mathematics and biology. These include adding quantitative material to upper-level courses, creating problem-based modules and integrative seminars, restructuring calculus courses to incorporate biology, integrating quantitative approaches throughout the curriculum, and completely integrating freshman-level math and biology courses. Focusing on undergraduate research is another key strategy. However, participants in our summer institutes identified challenges in these areas:

- Development, evaluation, and refinement of bio/math curricular modules;
- Creation of a repository or digital library for integrative materials;
- Strategies to create equitable win-win partnerships between biologists and mathematicians and other quantitative scientists;
- Recognition that institutions of different types may present very different challenges;
- Strategies for faculty and future faculty development to enhance faculty expertise to teach these cross-disciplinary modules;
- Administrative strategies necessary to implement these practices and transform the science curriculum (such as enhancing cross-departmental interactions).

While the field of mathematical or quantitative biology has deep historical roots, it is only relatively recently that interest in quantitative biology undergraduate education has blossomed. This interest may be directly traced to the 2003 report, *BIO2010: Transforming Undergraduate Education for Future Research Biologists*, issued by the National Research Council and sponsored jointly by the National Academies, the National Institute of Medicine, and the Howard Hughes Medical Institute. The *BIO2010* Report recommended several radical changes to the undergraduate biology curriculum. In particular, the importance of training future research biologists to think quantitatively and to be conversant with the tools of the mathematical sciences was emphasized. Typical is "Recommendation #1" which states:

Given the profound changes in the nature of biology and how biological research is performed and communicated, each institution of higher education should reexamine its current courses and teaching approaches to see if they meet the needs of today's undergraduate biology students. Those selecting the new approaches should consider the importance of building a strong foundation in mathematics, physical, and information sciences to prepare students for research that is increasingly interdisciplinary in character. The implementation of new approaches should be accompanied by a parallel process

of assessment, to verify that progress is being made toward the institutional goal of student learning.

Recognizing that "...building a strong foundation in mathematics..." would require an interdisciplinary approach to undergraduate instruction, the *BIO2010* Report also makes specific recommendations as to how the development of new interdisciplinary materials should be approached. Recommendation #3 of *BIO2010* spells this out:

Successful interdisciplinary teaching will require new materials and approaches. College and university administrators, as well as funding agencies, should support mathematics and science faculty in the development or adaptation of techniques that improve interdisciplinary education for biologists. These techniques would include courses, modules (on biological problems suitable for study in mathematics and physical science courses and vice versa), and other teaching materials. These endeavors are time consuming and difficult and will require serious financial support. In addition, for truly interdisciplinary education to be achieved, administrative and financial barriers to cross-departmental collaboration between faculty must be eliminated.

Since the release of *BIO2010*, a wide variety of universities and four-year colleges have undertaken the development of new courses in quantitative biology, the modification of traditional biology and mathematical courses to include quantitative approaches, and the development of new integrated degree programs in quantitative biology. The Mathematical Biology major at Harvey Mudd College (HMC), established in 2002, is an example of just such an integrated program, jointly housed by the Departments of Biology and of Mathematics. The creation of the HMC program was supported by funds from the W.M. Keck Foundation. In other cases, much of this development has been spurred on by targeted funding from the HHMI. For example, developments of the degree program in Quantitative Biology at the University of Delaware and the degree program in Systems Biology at Case Western Reserve University are a direct result of HHMI support. Other institutions have undertaken the development of "modules," i.e., self-contained classroom materials that may be used to infuse mathematics into biology courses or vice versa (Table 1). Typical of these efforts is that undertaken by the group at the University of Maryland. In nearly all cases, there was funding in place specifically dedicated to supporting innovations and developments in mathematical biology education programming.

The four white papers,⁸ developed by our meeting participants, formed the basis of sessions on future curriculum directions.

Lester Caudill and Kathy Hoke, University of Richmond, presented *Incorporating Biological Problems Into Mathematics Courses* (White Paper 1). They described a small number of institutions that have attempted to incorporate biological problems into required math courses. These efforts generally fall into one of three categories: (1) incorporating biological problems and examples into existing mathematics courses, (2) incorporating mathematical techniques into existing biology courses, or (3) creating new "hybrid" mathematical biology (or biomathematics) courses from scratch. The authors summarized different approaches from seven colleges and universities

⁸ White papers are located at [http://wikifuse.pbworks.com/browse/#view=ViewFolder¶m=Biomath White papers](http://wikifuse.pbworks.com/browse/#view=ViewFolder¶m=Biomath%20White%20papers).

Table 1. Universities and colleges using biological examples to teach mathematical concepts

Institution	Course	Contact and website
Univ. Richmond	Scientific Calculus I and II	Lester Caudill, lcaudill@richmond.edu http://as.richmond.edu/student-research/other_sources/hhmi/course.html
ETSU	Symbiosis I	Karl Joplin, Joplin@etsu.edu www.etsu.edu/cas/symbiosis
Emory	Life Science Calculus I and II	Dwight Duffus, Dwight@mathcs.emory.edu www.cse.emory.edu/projects/projectsttopics.cfm#math
Haverford	Intro Scientific Computing	Rob Manning, rmanning@haverford.edu www.haverford.edu/math/rmanning/math222.html
Davidson	Calculus and Modeling I and II	Laurie Heyer, lahey@davidson.edu www.davidson.edu/math/heyer
Univ. Florida	Math Methods for Life Science	Sergei Pilyugin, pilyugin@math.ufl.edu Patrick De Leenheer, deleenhe@math.ufl.edu www.math.ufl.edu/~pilyugin/HHMI_07/main.html www.math.ufl.edu/course_guides/map/4484.html
Univ. Arizona	Calculus and Differential Equations Statistics	Jim Cushing, cushing@math.arizona.edu for calculus and differential equations Joe Watkins, jwatkins@math.arizona.edu for statistics http://math.arizona.edu/~hhmi

to incorporate biological examples into introductory mathematics and computational courses (Table 1).

In White Paper 2, David Usher and John Pelesko described existing Biology/Mathematics Interdisciplinary Majors and Minors.⁹ They surveyed existing majors in quantitative biology, identified integrative structures in these courses and majors, and compared course structures at various institutions. This group identified two different types of programs. One type of program developed skills in statistics and computer sciences. These were programs in bioinformatics and computational biology. The other program, variously called mathematical biology, systems biology, or quantitative biology, focused on developing skills to be used in producing predictive mathematical models of biological systems. The group identified many programs devoted to bioinformatics, but only 11 interdisciplinary biology and mathematics programs. The group concluded that all the interdisciplinary programs had a common group of core courses that was independent of the department in which the major resided. However, each program did offer a menu of courses that depended on the strengths of the department housing the major. Majors housed in mathematics departments required more mathematics, and majors housed in biology departments required more biology courses. Few programs required more than a single year of physics or two years of chemistry. What made these programs unique were activities that integrated biology and mathematics. These activities were quite varied but generally included a capstone course, seminar, or research experience. A few programs developed new courses for their curricula.

In White Paper 3, Karen Nelson described her subcommittee's work gathering information for the potential construction

⁹ Their subcommittee included John A. Pelesko (University of Delaware), David C. Usher (University of Delaware), Istvan Karsai (ETSU), Nancy Horton (University of Arizona), Bill Holben (Montana State University), Paul Tian (William and Mary), Robin Snyder (Case Western Reserve University), and Joydeep Bhattacharjee (University of Louisiana).

of a database of teaching materials to incorporate mathematics into biology.¹⁰ The subcommittee developed a preliminary database to catalog the resources identified thus far (eight major online series of math/biology modules, miscellaneous modules, and online databases). The white paper summarizes progress on creation of a list of available resources and a preliminary database structure, using categories such as mathematical level, format, pedagogy, level of instructor preparation needed, and assessment. They described the type of information that may be useful to instructors evaluating online resources (such as level, length, and usability), and preliminary attempts to include these categories in a searchable database.¹¹ The subcommittee discovered a wide variety of modes of integration and concluded that the variety provided instructors with a diversity of modules they could adapt to their classrooms. For example, modules on epidemiology (SIR [susceptible, infected, recovery]) included modules that used Web pages to launch static graphics¹² (and included units that could be revisited in precalculus through differential equations¹³).

Some of the modules examined are included in Table 2. Other searchable databases that may have relevant content include:

- BEN: www.biosciencednet.org/portal
- NCTM Illuminations (National Council of Math Teachers): <http://illuminations.nctm.org>
- Open Educational Resources (OER): www.oercommons.org

¹⁰ The group included Stephan Aley (University of Texas at El Paso), Jeff Knisley (ETSU), Bob Kosinski (Clemson University), Jennifer Nelson (Canisius College), and Ethel Stanley (BioQUEST, Beloit College).

¹¹ A preliminary version of this list is available at http://mathbench.umd.edu/mod_instructors/sabertoothResources.html.

¹² Ellemeyer and Burke, Kennesaw State University.

¹³ ES+EEM modules on the same topic offer interactive manipulation of model parameters. MathBench modules allow interaction and exploration on narrower topics.

Table 2. Mathematical biology education modules

Series name	# in series	URL	Institution	Notes
ES+EEM	39	www.bioquest.org/esteem/index.php	BioQUEST	Basic biology; spreadsheets
Microbes Count!	40+	www.bioquest.org/microbescount	BioQUEST	Microbiology
Bedrock	170	http://www.bioquest.org/bedrock/participant_projects.php	BioQUEST	Bioinformatics; contributions from conference participants—quality may vary
Case It!	12	http://caseit.uwrf.edu/caseit.html	BioQUEST	Molecular biology; case studies
ICBL	40+	http://www.bioquest.org/icbl/cases.php	BioQUEST	Various
BIRDD	1	http://www.bioquest.org/birdd/index.php	BioQUEST	Evolution
MathBench Biology Modules	28	www.mathbench.umd.edu	Univ. of Maryland	Basic biology; 10–20 page html + interactive modules
Symbiosis Project	10	www.etsu.edu/biology/symbiosis/index.htm	ETSU	Basic biology; each module is 10 lectures + wet lab + dry lab
Robert Kosinski			Clemson	Biobytes for sale with textbook
HHMI Virtual Labs	5	www.hhmi.org/biointeractive/vlabs	Univ. of Tulsa	Simulated labs
ILAPS		www.ilaps.utulsa.edu	Univ. of Tulsa	
PLTL(Peer-led Team Learning)	12	www.pltl.org	Univ. of Miami	Various; intended as student workshop material
Lou Gross	40+	www.tiem.utk.edu/~gross/bioed/modulelist.html	Univ. of Tennessee	Basic biology; short text + a few problems
Connected Calculus	10	www.math.duke.edu/education/ccp/materials/biology.html	Duke	Population dynamics
PostCALC	7	www.math.duke.edu/education/postcalc	Duke	Various
CCP (Connected Curriculum Project)	10	www.math.duke.edu/education/ccp/materials/biology.html	Duke	Various (calculus)
Patterns in Nature	80+	http://polymer.bu.edu/ogaf	Boston Univ.	Fractals; hands-on or interactive
Java for Probability	10	www.math.csusb.edu/faculty/stanton/m262/index.html		Probability; interactive online demonstrations
Probability by Surprise!	10	www-stat.stanford.edu/~susan/surprise	Stanford	Probability; interactive online demonstrations
Kimball's Biology Pages		http://users.rcn.com/jkimball.ma.ultranet/BiologyPages	Retired from Harvard	Basic biology; open-source textbook, some nice mathematical examples
Epidemiology Modules	5	http://science.kennesaw.edu/~mburke/modules	Kennesaw State Univ.	Epidemiology; same material at 5 levels of mathematical sophistication
Water on the Web	15	http://waterontheweb.org/curricula/bs/bs_index.html	Univ. of Minnesota	Water resources; virtual data-gathering and interpretation

- MERLOT: www.merlot.org/merlot/index.htm
- MathWorld (Wolfram Mathematica Site): <http://mathworld.wolfram.com>

REPOSITORY OR A NEW JOURNAL?

Unfortunately, these efforts have occurred largely in isolation. Widespread dissemination of best practices, course materials, degree structures, and modules does not exist. As a consequence, the Quantitative Biology community is fail-

ing to leverage hard-won local experience in order to effect a national change in the biology curriculum as outlined in *BIO2010*. The “potential barrier” to implementing new courses or degree programs remains high at institutions across the board; this barrier could be significantly reduced if dissemination were increased. The benefits of leveraging current efforts and drastically increasing the impact of both funded and nonfunded initiatives are clear. Mechanisms for doing so include the organization of national meetings, talks by experts in university colloquia, the organization of short-courses, and the creation of a national clearinghouse.

What Format Should a Clearinghouse Take?

There are several potential formats for a clearinghouse. Chief among these are a Web-based repository, existing scientific journals, and the creation of a new, targeted journal. Before examining these alternatives, it is necessary to state and explain the criteria by which these options will be judged. Five criteria will be applied.

(1) The clearinghouse should be easily accessible to both mathematicians and biologists. Quantitative Biology is inherently interdisciplinary. Teaching materials, courses, and degree programs are being created by individuals from biology, individuals from mathematics, and interdisciplinary teams of faculty. Effective dissemination requires that these materials be accessible to all interested faculty.

(2) The clearinghouse should be flexible and allow for varied content such as computer code, Java applets, and other simulations. The development of Quantitative Biology educational materials, especially “modules,” often includes the development of computer simulations or computer toolboxes. Creating such simulations is time consuming and involved. A clearinghouse should be flexible enough to allow for dissemination of these valuable products.

(3) The system should include peer review. Peer review is the standard by which the quality of academic products is judged. When applied to educational materials, peer review serves as a “vetting” process and lowers the barrier to adoption of new materials by instructors, departments, and institutions. While search engines such as Google allow one to quickly find a large quantity of material on a given subject, the quality of what one finds is not readily apparent. Determining quality is a time-consuming process; the peer-review system eliminates the need for this step on the path to adoption.

(4) Items in the clearinghouse should be self-contained. As mentioned in criteria number three, finding large quantities of information on a given topic is not difficult, but putting this material in a usable form often requires one to follow a long torturous path through non-peer-reviewed literature. This is a barrier to adoption. A clearinghouse of self-contained materials eliminates this barrier.

(5) The format should include a built-in incentive to encourage faculty in both biology and mathematics to participate. As stated in Recommendation #3 of *BIO2010*, the development of educational materials for Quantitative Biology is both time-consuming and difficult. Significant barriers, both administrative and financial, tend to impede progress in this area. Participation in a clearinghouse should not create an additional barrier, but instead should help lower existing barriers to faculty participation.

White Paper 4, developed by John Pelesko and Lisette de Pillis, called for the creation of a new online journal to serve as the primary repository for math-bio teaching materials. The rationale for a new journal is that faculty must publish in peer-reviewed journals for their work to be recognized and rewarded. The white paper is available on the wiki (<http://wikifuse.pbworks.com/2008QuantitativeBiology>). They argued that the most widely discussed format, the Web-based repository, has several drawbacks. Peer review is generally

absent from such repositories. Further, the academic community has little or no history of peer review for these types of clearinghouses. Individual faculty members typically receive no “credit” for serving as a peer reviewer for Web-based repositories. This problem goes deeper in that individual faculty members also typically receive no credit for producing materials for such a repository or spending the time necessary to bring their already developed materials into a form usable by someone accessing the repository. Because faculty time is limited, this creates a large disincentive to participate in a Web-based Quantitative Biology clearinghouse. Additionally, while a Web-based repository is a natural home for “modules,” it is not a natural home for a discussion of course structures, best practices in the classroom, or the steps in creating a successful degree program. A local repository may be useful on an institution-by-institution basis where these difficulties may be overcome; as a national solution the Web-based repository falls short of the mark. Advantages include that materials placed in the repository are instantly available to anyone worldwide, and computer code, simulations, and applets are easily incorporated into the system.

The traditional structure of an academic journal addresses many of the deficiencies of the Web-based repository. Peer review is an integral part of the journal structure, publication in a peer-reviewed journal is an accepted use of faculty time and results in proper “credit,” and the journal structure allows for both the dissemination of classroom modules and for discussions of best practices. The rise of the online journal even allows for easy incorporation of computer code, simulation, and applets into the traditional journal article structure. What remains is to identify an appropriate online journal targeted at Quantitative Biology that is equally accessible to both biologists and mathematicians.

BEYOND PREACHING TO THE CHOIR

To address issues raised at our four workshops we have concluded that it is time to bring many other voices to the table. We hope to develop a National Science Foundation (NSF) Research Coordination Network grant to continue this work. We invite all readers of this issue to join our listserv and wiki to continue advancing the mission of this nascent consortium. In particular, we call on mathematicians, computer scientists, and life scientists to join us in completing the inventory of resources that can be used in integrating biology, mathematics, and computation. We also seek your collaboration in developing a single database or digital library that will allow instructors to find resources that they can adopt and adapt to their own institution and students, evaluate resources, and share their own resources with the community. New voices can help us address the differing needs of faculty and students at different types of institutions. For example, small colleges with a limited number of faculty in biology and mathematics departments may need to find ways to gain credit for collaborative teaching. At larger, research-intensive institutions, faculty hyper-specialization and a reward system that focuses on research publications and grants may be the limiting step. We need to ask, who teaches the first courses in biology and mathematics at various institutional types and what are the barriers to integrating quantitative skills? Are the textbooks a part of the problem?

Another real barrier to moving forward is faculty time. Revising and transforming courses will require new grants and summer institutes for faculty to adopt and adapt existing materials and to create new ones. Future faculty, graduate students, and postdocs must become part of the choir too, so that disciplinary barriers will not be re-erected with each new generation. We must address faculty and future faculty concerns that this work must count toward tenure and promotion.

Although only a small percentage of students who initially enroll in our life science and mathematics courses will become researchers or physicians, it is essential that these students develop fluency in the quantitative tools used in science (Gross, 2000; Association of American Medical Colleges and Howard Hughes Medical Institute, 2009; National Research Council, 2009; Labov *et al.*, 2010). For prospective researchers or physicians we urge the community to review the *Scientific Foundations for Future Physicians: Report of the AAMC-HHMI Committee* (Association of American Medical Colleges and Howard Hughes Medical Institute, 2009) and begin to develop lists of quantitative competencies for entry into graduate programs in the life sciences and in mathematics that parallel the recommendations for future physicians. All institutions may need valid assessments of mathematical skills to address these kinds of learning outcomes. Different institutions may have students with differing levels of mathematics preparation that must be addressed. The other students who enroll in our undergraduate courses deserve our attention, too. They need quantitative literacy skills that will allow them to become scientifically literate citizens who are able to weigh competing claims and make responsible decisions. Perhaps this group deserves even more of our attention, because they will become voters, lawyers, policy-makers, and leaders who decide on what science should be funded.

Preparing students for integrated biomath at the college level calls for us to begin working more closely with K–12 educators. Mathematics teachers are particularly interested in engaging materials that incorporate biological examples. For example, Problems and Research Integrating Science and Mathematics (PRISM) is an NSF Graduate Fellows in K–12 Education (GK-12) program¹⁴ at Emory that is transforming K–16 science education. Since 2003, the program

has offered graduate and undergraduate students fellowship opportunities to partner with local teachers to engage middle and high school students in science and math through PBL. Approximately 10 teams per year develop and implement engaging lessons that connect and integrate science disciplines and highlight science in the real world. GK–12 programs also develop collaborations between future scientists and mathematicians and can be a strategy for long-term change in integrating biology and mathematics.

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