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Interfacing Mathematics and Biology: A Discussion on Training, Research, Collaboration, and Funding

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Synopsis This article summarizes the discussion at a workshop on "Working at the Interface of Mathematics and Biology" at the 2012 Annual Meeting of the Society for Integrative and Comparative Biology. The goal of this workshop was to foster an ongoing discussion by the community on how to effectively train students from the biological, physical, engineering, and mathematical sciences to work at the intersection of these fields. One major point of discussion centered on how to be a successful interdisciplinary researcher in terms of where to publish, how to successfully write grants, and how to navigate evaluations for tenure and promotion. An emphasis was placed on the importance of developing strong multidisciplinary collaborations and clearly defining one's career trajectory to the home discipline. Another focus of the discussion was on the training of students and postdoctoral fellows in interdisciplinary work and helping these junior researchers to launch their careers. The group emphasized the need for the development of publicly available resources for biologists to learn basic tools for mathematical modeling and for mathematicians and engineers to see how their fields may be applied to current topics in the life sciences.

Overview/Introduction

An evening workshop on "Working at the Interface of Mathematics and Biology" was held at the 2012 Annual Meeting of the Society for Integrative and Comparative Biology (SICB). The workshop consisted of a broad discussion of issues related to conducting research and training students at the intersection of these fields. The discussion was held in the format of questions posed to a panel, with additional questions, discussion, and viewpoints provided by the audience. The attendees included researchers from various departments including mathematics, biology, physics, and engineering. The workshop was affiliated with the SICB symposium entitled "Combining Experiments with Modeling and Computational Methods to Study Animal Locomotion." Although the discussion was not explicitly limited to this particular area of mathematical biology, a large number of the attendees had a background in research on animal locomotion. Therefore the discussion included perspectives from a somewhat limited set of subfields of mathematical biology.

This workshop was motivated by several papers, workshops, and symposia during the past several years that have focused on mathematical modeling in biology and working at the interface of these fields (Levin 1992; Palmer et al. 2003; Childress et al. 2012). The broad goal of much of this recent activity has been to promote new collaborations between biologists, physical scientists, and mathematicians (Hastings and Palmer 2003; Hastings et al. 2003), to inspire the next generation of biology students to use quantitative approaches (Jungck 1997), and to use applications in the life sciences to fuel the development of new mathematical and numerical techniques (Cohen 2004; Reed 2004). The common challenges that have emerged from these discussions center on best practices for training students and the need to develop mechanisms that foster

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multidisciplinary collaborations. To address these challenges, a variety of educational initiatives, funding programs, and institutes focused on mathematics and biology have been established over the past decade. In particular, two major mathematical biology institutes were founded by the National Science Foundation, the US Department of Homeland Security, and the US Department of Agriculture: the Mathematical Biology Institute at the Ohio State University and the National Institute for Mathematical and Biological Synthesis (NIMBioS) at the University of Tennessee. Despite these initiatives many challenges remain, particularly for junior researchers.

Training and mentoring

An important theme in the discussion was the training and mentoring of researchers at the interface of mathematics, engineering, and biology. The panel discussed the ideal timing of a switch from a more traditional disciplinary education to a more interdisciplinary education—at the undergraduate level, the graduate level, or beyond? There was a general concern expressed about interdisciplinary students gaining breadth at the expense of depth. Less depth in a traditional field can be a significant disadvantage when applying to, and completing the requirements for, a graduate degree in a particular field. However, faculty pursuing interdisciplinary research are more likely to admit students who have shown an interest in previous interdisciplinary work. Ultimately, success in coursework and research is strongly enhanced by following one's intellectual interests. Pursuing research that overlaps with the priority research areas of faculty and funding opportunities is one of the practical realities of training students.

Undergraduate students

At the undergraduate level, colleges and universities are offering increasing numbers of courses and degree programs that cross the interface of mathematics and biology. The panelists and workshop attendees generally agreed that these courses were excellent mechanisms to pique student interest in interdisciplinary work and that undergraduate education often allows the flexibility for students to develop a solid background in more than one field. One of the most common courses being developed is BioCalculus (i.e., Calculus for Life Scientists). This course typically focuses on covering standard calculus material using applications to biology. More and more colleges and universities are also offering upper level courses such as Quantitative Biology (from the biology side) or Mathematical Biology (from the mathematics side). The National Academy of Sciences reports that "BIO 2010: Transforming Undergraduate Education for Future Research Biologists" presents an overview of recommendations for these programs (National Research Council 2003).

Outside the classroom, there are numerous initiatives to engage mathematics and biology students in research. The Interdisciplinary Training for Undergraduates in Biological and Mathematical Sciences (UBM) program of the NSF provides an excellent funding mechanism for immersing students in research at the intersection of the biological and mathematical sciences. Miller and Walston (2010) described the phenomenal success of this program in integrating mathematical and life sciences at Truman State University. As stated in the program solicitation, "The core of the activity is jointly-conducted long-term research experiences for interdisciplinary balanced teams of at least two undergraduates from departments in the biological and mathematical sciences." Similar research experiences for undergraduates (REUs) have been developed at many universities as components of larger training programs or individual grants. The group generally agreed that pairing undergraduate students from different backgrounds on research projects provides an excellent means to expose the students to different academic cultures and views. If successful, group projects may address some of the key challenges in interdisciplinary training such as getting engineering and mathematics students comfortable with the uncertainty of biological data and helping biology students to formulate mathematical and computational questions.

Graduate students

One of the biggest challenges in interdisciplinary graduate training is navigating the cultural differences that make overlapping training programs in mathematics, biology, and engineering difficult. Graduate students in mathematics tend to enter Ph.D. programs without an advisor or specific research area in mind. They usually spend 2 or more years taking general coursework before identifying a thesis advisor. The purpose of this coursework is to develop a unified set of skills, and demonstration of mastery is established through the passing of comprehensive exams. Biology students typically enter into a Ph.D. program having already identified their advisor or a small group of potential advisors among whom the student will rotate in the first year before selecting an advisor. The student's training is often focused upon developing the specific tools needed to perform scientific research with that advisor. More variation is seen within engineering programs, and the course of study typically falls somewhere between these extremes.

In recent years, new Ph.D. programs in mathematical, quantitative, and computational biology have emerged in an effort to foster interdisciplinary training. In mathematics departments, training in mathematical biology can be pursued within an Applied Math degree program or a separate Mathematical Biology program. Also, many researchers in Mathematical Biology have come from pure math backgrounds. There is increasing input from Algebra and Combinatorics to biological problems such as bioinformatics (Barnett 2005). In biology and medicine, Ph.D. programs have emerged in Bioinformatics and Computational Biology. These programs often attract a mixture of students from computer science, engineering, and biology. Since there are many flavors of interdisciplinary work, some programs with the same name can have rather different requirements. To a large extent the implementation depends upon the research interests of the faculty at each institution.

Postdoctoral fellows

As noted in a previous workshop report on "Mathematics and Biology, the Interface: Challenges and Opportunities" (Levin 1992), postdoctoral fellows are uniquely positioned to actively pursue research at the interface of mathematics and biology since they have already demonstrated an ability to perform disciplinary research independently. One question posed to the panel was how to best ensure that a postdoctoral fellow's interdisciplinary research experience is productive. The importance of providing the postdoctoral fellow with a familiar disciplinary community was emphasized. For mathematicians working in biology, it is important that the postdoctoral fellow be part of a larger mathematical community while working in the new field. The same idea also holds true for biologists and engineers. This approach provides the fellows with the support of a familiar community while also ensuring that their work stays grounded in the discipline to which they will be applying for jobs and grants. It was also stressed that postdoctoral fellows should continually think about what direction their research will take over the next 10 years and how their research might fit into a particular field. When looking for jobs, the panel agreed that mentors should be explicit in recommendation letters about the postdoctoral fellow's role in the research project and how they fit into a disciplinary community. Postdoctoral fellows should be encouraged to explicitly address during interviews the possible trajectories of their career, the challenges of their research, and why their work is significant to disciplinary communities.

Junior faculty

The panel and workshop group emphasized the importance of mentoring interdisciplinary junior faculty and several explicit recommendations were made during the discussion. Some of the challenges faced by junior faculty include the need for nontraditional resources, teaching students and courses from different disciplines, and educating faculty in a disciplinary department on interdisciplinary journals, grants, and awards. If a junior faculty member is hired in a field that is different from that of his or her Ph.D. department, teaching some courses may be challenging. Team teaching with a senior faculty member is an excellent way to help train junior faculty to cover material outside of their discipline. Courtesy joint appointments can provide a useful mechanism to help junior faculty attract a wider variety of students and obtain a broader base of grants. The panel generally felt that fully joint appointments could be risky for tenure track faculty since two departments would be involved in the tenure decision. On the other hand, it may be useful for a departmental tenure committee to include members from both disciplines spanned by the faculty member. This could be particularly useful when evaluating the impact of research and the prestige of journals in which the junior scientist has published.

Curriculum development: Looking forward

The panel and workshop group generally agreed that more curriculum development is needed at the interface of mathematics and biology. Parallels can be drawn to some degree between physics and mathematics. These fields have a long history of intersecting research and education. Physics majors take a significant number of mathematics courses, and substantial mathematics is included in many physics courses. Applied mathematics courses often are motivated by examples from physics. A limitation in mathematical biology training is due to the fact that while students may take a course in mathematical or quantitative biology, these ideas are not reinforced in other courses. If a freshman takes a course in biocalculus, for example, but does not see many applications of mathematics in the courses that follow, this training likely will not be retained.

A consensus was reached during the discussion that publicly available lesson plans that easily could be incorporated into standard classes by nonexperts have the potential to greatly enhance training at the interface. Repositories of biological examples in mathematics should be available for mathematicians with little to no biology training. There is a similar need for straightforward applications of mathematics and computation to standard material in the biological sciences. The use of publicly available software could enable biologists to incorporate more examples from mathematics into their courses and laboratories. It was noted that some materials are already publicly available through various societies and institutes. For example, the SICB Digital Library has a number of lessons and exercises that are related to the application of engineering and mathematics to biology (SICB 2012). The NIMBioS has developed a comprehensive website that links to many educational resources in mathematical biology for all levels of students (NIMBioS 2012). There are also opportunities for researchers to publish papers on laboratory activities that effectively teach applications of mathematics to biology, such as the use of the movements of brine shrimp to teach students about diffusion (Kohler et al. 2010).

One challenge in developing mathematical biology curricula is that, despite wide interest in the field, there is often no single group at a given university or college with the critical mass necessary to implement a course focused on any particular subtopic or tailored to a particular major. One approach to this problem is to design courses that generally address how to develop mathematical models in biology. The construction of original mathematical models for new biological problems can be both tractable and challenging to many students at all levels. Furthermore, mathematical modeling lends itself well to the implementation of in-class group activities as a mechanism to improve students' performance. A variety of studies over the past 15 years have shown the benefits of such inquiry-based, small-group teaching strategies at the college level in science and mathematics. A study sponsored by the National Institute for Science Education (NISE) concluded that small-group cooperative learning had a significant positive effect on students' comprehension (Cooper and Robinson 1998). The Boyer Commission led a study that considered the effects of various teaching strategies on all academic disciplines (Boyer 1998). They recommended that faculty provide more research-focused, interdisciplinary opportunities in the classroom. Furthermore, several studies have shown that small group, inquiry-based instruction is particularly effective for teaching women and minority students (Belenky et al. 1986; Boyer 1998). Finally, Zastavker (2006) found that work and hands-on activities by small groups have a particularly strong impact on women's interest in and attitudes about engineering.

Grants and funding

Virginia Pasour, one of the panelists, was available to describe funding opportunities through the Army Research Office (ARO). The ARO funds basic, high-risk research in major fields in science, mathematcs, and engineering, including a new program in Biomathematics. The standard kind of funding is the single investigator (SI) grant, which provides funds up to $120 K/year for expenses including principal investigator (PI) support and funding for a graduate student or postdoctoral fellow. ARO Program Managers can also fund Short Term Investigative Research (STIR) grants, which provide $50 K over 9 months to investigate very high-risk ideas for feasibility, as well as support for conferences and workshops. In addition, through the URI program, instrumentation and Presidential Early Career Award for Scientists and Engineers (PECASE) are made and MURIs (Multidisciplinary University Research Initiatives) topics are approved and funded at $6.25 M over 5 years. The ARO HBCU/MI program provides extra support for research efforts by and with minority institutions, and the ARO Youth Outreach Program, among other things, provides support for high school and undergraduate students to become involved in existing grants. Current focus areas funded through the ARO Biomathematics Program are as follows:

(1) Fundamental Laws of Biology: The field of physics has long been "mathematized" so that fundamental principles such as Newton's Laws are not considered the application of mathematics to physics but actually physics itself. The field of biology is far behind physics in this respect.

(2) Computational Cellular and Molecular Biology: The currently increasing ability to generate large volumes of biological data provides a significant opportunity for biomathematical modelers to develop advanced analytic procedures to handle these data.

(3) Multiscale Modeling/Inverse Problems: Biological systems function through diversity with large-scale function emerging from the collective behavior of smaller-scale heterogeneous elements.

The inverse problem is just as important as the forward problem: from an understanding of the overall behavior of a system, is it possible to determine some of the nature of the individual elements? An important subproblem is how to represent the heterogeneity of individual elements and how much heterogeneity to include in the model.

(4) Modeling at Intermediate Timescales: Understanding the dynamics of a system at intermediate timescales, as opposed to its long term, asymptotic behavior, is critically important in biology, more so than in many other fields.

In addition to the ARO, the National Science Foundation, the National Institutes of Health, the Burroughs Wellcome Fund, other public and private foundations have established funding mechanisms for researchers working at the interface of mathematical biology. The NSF Division of Mathematical Sciences (DMSs) has established a program in Mathematical Biology that supports research in areas of applied and computational mathematics with relevance to the biological sciences. The recent emphasis at the NSF on interdisciplinarity is illustrated by the recent Dear Colleague Letter for "*Unsolicited Proposals at the Interface of the Biological, Mathematical and Physical Sciences, and Engineering*" and the new Postdoctoral Research Fellowship in Biology for "*Intersections of Biology and Mathematical and Physical Sciences.*" Similarly, the National Institutes of Health (NIH) and the Burroughs Wellcome Fund (BWF) both currently offer generous career awards for mathematical, physical, and engineering postdoctoral fellows who are pursuing research projects in the life sciences.

Mathematical funding in the biological sciences is often focused on development of new mathematical tools and theory. As stated in the NSF Mathematical Biology program solicitation, "Successful proposals are mathematically innovative and address challenging problems of interest to members of the biological community." Successful grants in the life sciences, on the other hand, are often hypothesis driven and focused on answering fundamental biological questions. There was a strong consensus in the audience that strong collaborations can greatly strengthen proposals at the interface. It was generally agreed that proposals based upon superficial collaborations are usually not funded and that potential collaborators should establish a solid working relationship before seeking funding. It was also noted that interdisciplinary grants could be more vulnerable to criticisms since it is difficult to find reviewers who can evaluate all elements of the proposal. Requesting that multiple panels from different divisions and programs review the proposal can sometimes mitigate this issue.

Research and collaboration

Given the importance of collaboration in interdisciplinary research, there was significant discussion at the workshop focused on mechanisms to enhance multidisciplinary interactions. In general, the panel and participants agreed with previous workshops and reviews that the most effective way to encourage collaborations between biologists, mathematicians, and engineers is through direct co-involvement with a particular problem (Levin 1992; Hastings et al. 2003). The panel also agreed that group projects could enhance interactions across fields at all levels from undergraduate through senior faculty. It is also critical that the groups work on a "value-added" idea. Unless each team member is able to do better research because of the interaction, the collaboration will not last.

Initiating interdisciplinary collaborations can be particularly challenging for junior scientists. A variety of suggestions were offered from the workshop's participants. For example, it was suggested that junior faculty organize departmental seminars and workshops and take the opportunity to invite speakers from other disciplines who could be potential collaborators. Junior scientists should also be encouraged to explore as many potential collaborations as possible and to not be discouraged if some of the interactions are not productive. Some participants also suggested that universities and colleges should do more to develop structures that enhance interdisciplinary collaborations. Lee et al. (2010) provided a convincing study that shows that the impact of collaborations is positively correlated with physical proximity. To strengthen interdisciplinary interactions, universities should provide physical spaces and events to encourage communication among departments.

Conclusions

It seems appropriate to finish the article with some insights offered by one of the workshop's junior participants. "Perhaps much of the difficulty of working at the interface of math and biology stems from its lack of acceptance as a traditional interdisciplinary field. Many mainstream fields of study today are no longer regarded as interdisciplinary, but as disciplines in their own right. After all, what is chemical engineering but work at the interface of chemistry and engineering? What is engineering but work at the interface of applied math and physics? This prompts the question: what really constitutes an academic discipline? What is an interdisciplinary field? More and more of these academic chimeras emerge with each passing year, and many have passed into the domain of accepted fields: neuroscience, women's studies, information technology, and more. These fields have their own classes and funding agencies and departments and jobs because over time, they have gained academic and popular acceptance as distinct disciplines. Biophysics, biostatistics, and biochemistry are beginning to be recognized as fields in their own right. Perhaps biomathematics will be next."

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