The Role of Institutes in Interdisciplinary Research and Education

An Example From Quantitative Biology

To form and orchestrate intelligent groups is a real challenge for 21st-century education and research. In this paper we show how a regional state university was able to facilitate interdisciplinary research and education through forming an interdisciplinary institute.

By Istvan Karsai and Jeff Knisley

The book of nature is written in the language of mathematics.

—Galileo

In 2003, the National Research Council issued the *Bio2010* report (2003), an assessment that suggests that the study of biology will become ever more quantitative and that as a result, the teaching of biology must become more quantitative as well. Specifically, the biologist of the near future will need to have a broader background in mathematics, computation and computer skills, physics, and chemistry than does the biological researcher today. Biological researchers and educators will also need to develop meaningful collaborations with mathematicians and scientists in other fields (May 2004).

However, biologists and medical scientists traditionally obtain results by relying heavily on experimental methods and observational schemes. When collaborations do occur, they often are induced by the need for sophisticated analysis, complex modeling, or some other quantitative tool that is beyond the expertise of the biologist who initiated the project (Couzin 2004). These collaborations are often multidisciplinary, which means that collaborators attempt to contribute to the solution of a problem from within the strict framework of their familiar disciplinary approaches (Hukkinen, Bruun, and Thompson-Klein 2006; van den Besselaar and Heimericks 2001). For example, in a multidisciplinary approach, a biologist might collect data without regard for the methods that will eventually be employed to analyze them. Although a statistician may be able to analyze such data, a failure to understand the biological context may lead to statistical results that have little relevance to the original question. The publications that may result from such multidisciplinary collaborations may contain flaws, and indeed, the mathematical or statistical analysis in biological research papers published to date is inadequate or omitted entirely (Bialek and Botstein 2004).

In contrast, the *Bio2010* report asserts that the biology of the future will necessarily be interdisciplinary and not just multidisciplinary. For instance, biologists will need to understand and appreciate the assumptions and restrictions inherent in mathematical models and computational approaches, while mathematicians and computer scientists will need to be careful to use only biologically justifiable assumptions in deriving models or algorithms. It is realistic to expect that the study of biology will eventually require an extensive background in mathematics, computation, chemistry, and physics. However, with significant exceptions (such as population genetics and some areas of neuroscience and structural biology), most biologists today rarely achieve mathematical competence beyond elementary statistics and calculus. Even if tomorrow's biologists do have a more extensive mathematical and computational background, a single person could not, in general, pursue all fields of science in depth, thus making the formation of interdisciplinary collaborations essential to the pursuit of biology itself (Tadmor and Tidor 2005).

In this paper, we suggest how such collaborations can be initiated and fruitfully maintained to the benefit of all the fields involved. In particular, we describe how such collaborations were formed and are being maintained at the Institute for Quantitative Biology (IQB) at East Tennessee State University (ETSU). These collaborations are based on a *team* approach that is built upon a common understanding of the biological problem that allows individual members of the team to contribute to the investigation of the problem according to their skill sets (Kaufman and Felder 2000). That is, we have found that the initial effort required for a collaborative description of the problem allows individual creative efforts both to be individually recognized and to become part of the larger investigation. Similarly, this team-centered approach to collaborative research extends naturally to a team-oriented approach to undergraduate research and curriculum transformation.

A brief history

East Tennessee State University is a regional state university with approximately 10,000 undergraduate and 2,000 graduate students. ETSU has relatively recently become a research-intensive university and currently enjoys about $30 million per year in external funding. Both the math and the biology departments are medium in size with faculty size fluctuating around 15. Both of these departments have master's programs, and both are intensively committed to undergraduate education and research.

The formation of our team-oriented approach and the corresponding IQB are due in large part to factors common to many departments of biology and math. In 2002, there had been and were already a few collaborations between the departments. A small group of biologists had been working for a few years with a statistician on various research projects (Seier, Moore, and Joplin 2002). Also, a mathematician (Larry Neal) and a biologist (Dan Johnson) had developed and team taught an innovative systems-ecology course.

Also, by 2002, both the biology and math departments at ETSU found themselves separately engaged in several innovative curriculum efforts. The math department had recently obtained an NSF grant (NSF-DUE 0126682) to improve statistical education, while the biology department's HHMI grant "Enhancing Undergraduate Education" (HHMI # 71100562101) supported the hiring of a quantitative biologist (Istvan Karsai) to foster inquiry-based education in biology labs (Johnson et al. 2006).

Due in part to the release of the National Research Council's *Bio2010* report, some of us desired to create an interdisciplinary framework that could respond to the urgent call to incorporate more mathematics and physical sciences into the biology curriculum. In particular, we were motivated to start such interdisciplinary work early in a student's career, in part because *Bio2010* states that "undergraduate biology students who become comfortable with the ideas of mathematics and physical sciences from the start of their education will be better positioned to contribute to future discoveries in biomedical research" (NRC 2003, ix).

The Institute for Quantitative Biology (*www.etsu.edu/iqb*) was formed as a vehicle for initiating and supporting this interdisciplinary framework, first by attracting as many mathematicians and biologists as possible into the formation of quantitative biology collaborations. And while it would seem logical to start our interdisciplinary work in education, our first goal was to foster and support collaborative research projects.

A team-oriented approach

Our experience suggests that a team-oriented approach can ameliorate the demands of forming interdisciplinary collaborations and can allow greater results collectively than would have been obtained individually. Indeed, the business (Katzenbach and Smith 1992) and engineering (Oakley et al. 2004) worlds have long recognized the importance of teams, and already in many scientific fields, the tendency of a scientist to work in isolation is giving way to a team-based research paradigm (Humphrey et al. 2005; BECON 2003).

In fact, in the 2003 Bioengineering Consortium (BECON) symposium entitled "Catalyzing Team Science," it was concluded that an effective team must have a compelling reason to exist, and the following general principles were deemed to be important to that end (BECON 2003):

1. Each team should be based on a central problem, a motivation that brings the team together and encourages collaboration.
2. Individual creativity should be preserved while taking advantage of the synergy of team approaches
3. Team members should be based on team needs and not necessarily on location of those members.

However, the value of team research and the principles espoused above do not answer the question of how to effectively form interdisciplinary teams. Indeed, many researchers desire to form scientific collaborations, only to become discouraged by the time required to attain a background in another field and the limited rewards that come from working outside of one's particular research areas (Tadmor and Tidor 2005).

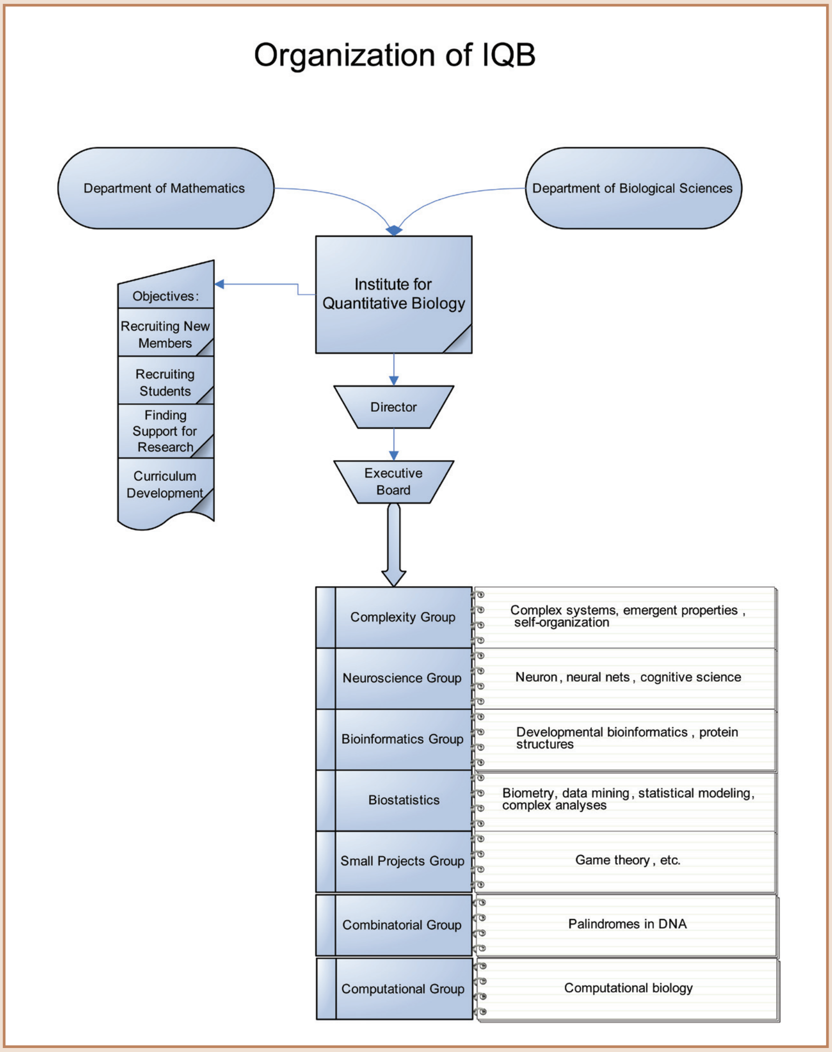
Teams at the IQB are formed as part of the process of collaboratively defining and interpreting a specific research problem. The teams themselves comprise students and faculty from both disciplines, and everyone on a team shares the effort in pursuing the research goal. In this way, team members need only attain the background in another field sufficient for understanding the statement of the problem (as long as there is a team member whose expertise is in that field). Typically, however, a team's statement of a problem does not fit cleanly into any particular field. Also, the statement of the problem must be specific enough to allow each team member to contribute to the solution, so that all team members benefit not only from their own contributions but also from the contributions of other members.

Indeed, we began with a series of weekly seminars specifically for the purpose of creating teams. The usual seminar setup, in which a single author speaks to an interdisciplinary audience, did not seem to us to be an effective method for forming interdisciplinary teams. Instead, these weekly seminars were joint presentations by at least one biologist and one mathematician of a problem that would require results from both fields. Typically, each presentation would begin with a biologist leading up to a biological impasse that required a mathematical intervention, and then the mathematician would describe the mathematical tools and concepts necessary for that intervention, after which the biologist would describe how the mathematical results would be used biologically. Thus, the biologists focused their efforts on moving the biology into a quantitative arena, after which the mathematicians and statisticians constrained themselves to working within this biological context.

These seminars generated a great deal of discussion and feedback, allowing teams to begin jointly developing a formal statement of their problem. Students enjoyed being treated somewhat as peers in a research team. They felt their comments were valued, and they may have learned more from being in such a hands-on environment. The IQB fostered and collected these formal problem statements, and the teams were identified with working groups within the institute (Figure 1). These formal problem statements then catalyzed the activities of the team, in that

FIGURE 1

Organization of IQB.



they allowed the individual expertise of each member to contribute to the pursuit of the problem.

For example, a team in the complexity working group began by considering if the dynamics of a published top-down model of the division of labor in a wasp society (Karsai and Balázsi 2002) could be reproduced by an agent-based model. The common statement of the problem argued that to be of value biologically, the agent-based model would need to be based on the same observations and assumptions that produced the top-down model. So, the question was whether or not the division of labor described in the top-down model would also emerge automatically from individual interactions. As another example, it was suggested that neural networks had been used for data mining of microarrays, thus leading a team in the biostatistics group to define the problem of using neural network analysis of microarray data to reduce the dimensionality of the data and thus reduce the amount of laboratory analysis of gene expression.

In addition, computers are now powerful enough to allow life scientists to explore mathematical models using simulations and to draw biological conclusions from these theoretical experiments. This represents a revolutionary change in research in that such simulations allow scientists with different backgrounds to make individual contributions within a common context (May 2004).

Team-oriented undergraduate research

Undergraduate research involves not only students but also their faculty mentors. Consequently, it is only natural that undergraduate researchers should be added as team members to existing faculty research teams. To do so in our NSF-supported summer program (NSF DUE-0337406), we created a multistage process that would prepare students to become a part of a research team, and we also created a proposal process that required each student to develop an understanding of a team's problem and to define his or her role as an individual member of a research team. That is, the proposal process was the equivalent of a team's collaborative development of a formal research problem, and thus, in the proposal process the entire team had to communicate intensively and explicitly so that the student could prepare a competitive proposal. An independent panel of reviewers ranked and selected the summer participants. Even though we always received more quality proposals than we could support, students who were selected were invariably those who were most engaged in a specific team.

With these summer programs, we were able to provide a truly interdisciplinary research experience for 17 students, and not a few of these students have remained in quantitative biology. Moreover, this team-oriented approach to research is instrumental in the ETSU math department's undergraduate research course that is required of all math majors. The student teams in this course tend to form naturally around a multifaceted, well-defined mathematical problem, and on their own students tend to form individual avenues of investigation that contribute uniquely to the problem's solution. Indeed, in fall 2006, one student in particular became involved in several different teams because of his expertise in programming and with the computer algebra system Maple.

We are also fostering the formation of teams in our NSF-STEP program "Talent Expansion in Quantitative Biology" (NSF 0525447). We are doing so by (a) including several opportunities for students to prepare for and engage in research and (b) exposing students to well-defined, multifaceted problems in quantitative biology. That is, as in the formation of our faculty research teams, the fostering of undergraduate research in quantitative biology is based on the concept that teams "rally around a problem," and thus it is the development of these problems that is the primary reason for and motivation of our institute.

Innovative curriculum development

The institute was formed not only to foster research collaborations in quantitative biology but also to introduce new curriculum and educational experiences that address the intellectual development and professional goals of students interested in quantitative biology. Because our curricular efforts have been preceded by our research initiatives, it is perhaps not surprising that we have a team-oriented approach to curriculum development as well, in particular in our Symbiosis project (HHMI 52005872).

Our efforts are in response to general calls for collaborations between mathematics and biology, which can be found in a number of reports and grant programs, such as *Bio2010* (NRC 2003) and *Mathematics and 21st Century Biology* (NRC 2005). Collaboration between mathematics and the other sciences has been lacking and has been recognized as being difficult to implement. The statistics, calculus, and multivariable mathematics necessary for a quantitative exploration of biology are not covered in traditional mathematics courses in a way that biologists will perceive and use, and adding math content into a biology course can overburden students in that course (Comar 2004).

In contrast, a more progressive solution may be found in *Math & Bio 2010: Linking Undergraduate Disciplines*, which "envisages a new educational paradigm in which the disciplines of mathematics and biology, currently quite separate, will be productively linked in the undergraduate science programs of the twenty-first century" (Steen 2005). The Symbiosis project seeks to create such a new education paradigm by replacing the traditional Biology I, II, III, Probability and Statistics, and Calculus I courses into an integrated curriculum that uses active learning strategies and a context-driven approach to truly integrate mathematics and biology.

The new curriculum is based on a modular design, and each module will be designed according to the following general template:

- Investigations of biological phenomena to motivate mathematical concepts
- Development of mathematical concepts into analytical tools
- Application of mathematical tools in analyzing the original biological phenomena
- The use of topic-specific modules has several advantages, not the least of which is that it allows us to use a team-oriented approach to developing the curriculum, activities, and lab experiences associated with each lab.
- The team that develops a module will also be the team that teaches that module.
- Measuring and assessing success

The effort to establish the Institute for Quantitative Biology has already been paid off several times. The success cannot be assessed easily via surveys, but it can be measured by comparing the state of several issues before and after the IQB was formed (Table 1).

Both student and faculty activity in interdisciplinary areas increased, and the outcomes clearly indicate the success. The number of faculty (around 30) and students (a few dozen per year) who potentially participate in interdisciplinary research and education is small compared to larger universities. The existence of an institute was essential to recruiting faculty and students from such a small pool of availability and focusing their efforts while fostering enthusiasm for the overall effort. We consider this an important step toward our future goals (Moore et al. 2008). We also carry out targeted assessments for each of our programs (Govett et al. 2008).

These efforts led to an NSF-UBM award entitled "A Multi-Stage Approach to Undergraduate Research in Mathematical Biology" (NSF DUE-0337406). In this grant, we asked for support for 16 undergraduate students to participate in an interdisciplinary summer research project similar to the National Science Foundation's "Research Experiences for Undergraduates (REU)." It also helped IQB faculty in their pursuit of research grants in biostatistics (Don Hong, NSF DMS-0408086) and discrete models (D. Knisley, NSF DMS-0527311).

However, undergraduate education and curriculum development are also key goals of the IQB, and in this vein, the IQB was able to obtain an NSF-STEP grant, "Talent Expansion in Quantitative Biology" (NSF 0525447), as well as a Howard Hughes Medical Institute award, "Symbiosis: An Introductory Integrated Mathematics and Biology Curriculum for the 21st Century" (HHMI 52005872). These awards have the purpose and potential for revolutionizing both biology and mathematics at ETSU. More importantly to this paper, these awards reflect in some small way the success the IQB has enjoyed in bringing faculty together to create meaningful collaborations in quantitative biology research and education.

Conclusion

Robert May (2004) makes an interesting assertion: "A paradigmatic account of the uses of mathematics in the natural sciences comes, in deliberately oversimplified fashion, from the classic sequence of Brahe, Kepler, Newton: observed facts, patterns that give coherence to the observations, fundamental laws that explain the patterns. These days mathematics enters at every stage: designing the experiment, in seeking the pattern, in reaching to understand underlying mechanisms." The Human Genome Project is an excellent example in support of May's assertion, and correspondingly, interdisciplinary approaches will likely be the norm rather than the exception in the biological research of the future.

Fifty years ago, the difficulties of scientific revolution emerged from the duality of scientific and humanistic culture (Snow 1959). Today it seems we have two cultures within biology itself, one mathematical and the other not (Bialek and Botstein 2004). If biology is to assimilate into the world of quantitative science, interdisciplinary teams need to be formed and maintained. It is important to recognize that making biology a more quantitative science cannot be achieved by specifying a minimum level of mathematical expertise for future biologists, but communication abilities and possibilities need to be developed between math and biology

TABLE 1

Item	Before	After
Interdisciplinary research group	1	9
Students in interdisciplinary team	0	17
Interdisciplinary courses	1 occasionally	5 regularly
External funds for interdisciplinary work	0	$2,700,000

(Bialek and Botstein 2004). Computer simulations can be used as effective tools for collaborative research and education (Peck 2004), but such simulations will only exacerbate the need for collaborative teams with effective communication among all the teams' members. An institute like the Institute for Quantitative Biology is able to foster the formation of such teams and to develop the necessary communication among researchers in different fields.

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Istvan Karsai (karsai@mail.etsu.edu) *is an associate professor in Department of Biological Sciences and* ***Jeff Knisley*** *is an associate professor in Department of Mathematics and Statistics at East Tennessee State University in Johnson City, Tennessee.*