Creating Quantitative Biologists:
The Immediate Future of SYMBIOSIS†

Darrell Moore[1], Dept. of Biological Sciences, East Tennessee State University
Michel Helfgott, Dept. of Mathematics & Statistics, East Tennessee State University
Anant Godbole, Dept. of Mathematics & Statistics, East Tennessee State University
Karl H. Joplin, Dept. of Biological Sciences, East Tennessee State University
Istvan Karsai, Dept. of Biological Sciences, East Tennessee State University
Hugh A. Miller III, Dept. of Biological Sciences, East Tennessee State University
Edith Seier, Dept. of Mathematics & Statistics, East Tennessee State University

Name of Institution: East Tennessee State University	
Size	about 15,000 students
Institution Type	regional state institution with graduate programs
Student Demographic	freshman curriculum for all biology majors
Department Structure	Mathematics and Biology are individual departments in College of Arts and Sciences

Abstract

The SYMBIOSIS project is an innovative sequence of three courses designed for the first three semesters of the undergraduate curriculum. They involve a thorough integration of biology, mathematics, and statistics. In order to maintain our interdisciplinary approach beyond the SYMBIOSIS courses, a number of pedagogical and cultural barriers must be bridged.

COURSE STRUCTURE

- Weeks per term: 15 weeks
- Classes per week/type/length: M (Lec-2 hrs), T (Lab-2 hrs), W (Lec-2 hrs), Th (Lec-2 hrs), F (Lec-2 hrs)
- Labs per week/length: one 2-hr lab/wk
- Average class size: 16 students in one section
- Enrollment requirements: Students supported by our NSF STEP grant
- Faculty/dept per class, TAs: One biology and one math instructor, two TAs
- Next course: IBMS 1200, Integrated Biology and Calculus
- Website: http://www.etsu.edu/cas/symbiosis/default.aspx

---

† supported by HHMI grant #52005872
[1] moored@etsu.edu

Introduction

Biological research is undergoing a major transformation, but biological education is not keeping up. Biology is becoming much more quantitative and computational, incorporating concepts and methods that integrate the biological sciences with mathematics, the physical sciences, and computer science. Because most undergraduate biology programs are not designed to prepare students for the changes, the National Research Council issued a call, published in their *Bio2010* report (National Research Council 2003) to incorporate more mathematics and physical sciences into the undergraduate biology curriculum, suggesting that it be done early in the student's academic career. We at East Tennessee State University have created the SYMBIOSIS project (Joplin et al 2012), funded by the Howard Hughes Medical Institute, as an answer to the *Bio2010* call.

Our approach is atypical, even among those programs that integrate mathematics and biology. We present the biology and the mathematics in a mutually reinforcing, storytelling methodology, starting in the first semester of college. There is no separation between the disciplines, in contrast to more traditional curricula.

The SYMBIOSIS program comprises the first stage of an effort to incorporate more mathematics into the biology major. By introducing students to an interdisciplinary program from the start of their academic careers, we hope to make lasting connections between the two disciplines. However, to make an enduring impression on the students, the program must be expanded so that the lessons learned early are reinforced in upper division courses. A way to plan the future direction of the SYMBIOSIS program is to ask what we expect of graduating students who have successfully navigated our quantitative biology curriculum. Of course, we expect them to think like practicing scientists! But what will it take, beyond the three semesters of integrated SYMBIOSIS courses, to get them there?

Overcoming textbook inadequacies

A reading of introductory biology textbooks provides insight into the state of pedagogy in the biological sciences. All the popular introductory texts contain over 1200 densely packed pages and are authoritatively written, up-to-date, and profusely illustrated. There is little difference among them in subject matter. Each has a glossary defining nearly 2000 terms. Although the authors make an effort to reinforce major concepts in each chapter, they are difficult to discern (especially for the novice student) through the dense jungle of facts and new terms. Most of the material is presented as factual, and therefore students cannot get a sense of the thought processes behind the discoveries. Some introductory textbooks include shaded boxes separate from the text proper that show examples of important experiments and the testing of hypotheses. Rather than being treated as side issues, they should be developed in more detail and form the core of the textbook. None of the introductory biology textbooks includes references: if students want to pursue the subject in greater detail, they must go elsewhere to find the original literature. In many ways, the introductory texts resemble encyclopedias. The compendium approach to biology, evident in the introductory textbooks, serves to reinforce rote memorization rather than problem-solving.

Introductory biology textbooks de-emphasize quantitative thinking. For example, numerical results are reported as means, but without error bars. Graphs may show the results of treatments relative to each other and to controls, but without mention of statistical significance. Perhaps the authors of introductory biology textbooks assume that beginning students do not have the background to understand the importance of probability and statistics or that they are not necessary. We believe that to comprehend how biology is done, students must come to grips with the issues of variability, sample size, and significance. The earlier in the student's education this is accomplished, the better the student will be prepared to go beyond a superficial level of understanding. The non-statistical trend is not confined to the introductory texts: it is present in upper level textbooks as well. Such simplification of the data may, at first glance, appear to allow the student to focus on larger issues. However, by omitting statistical details, the authors are asking students to accept conclusions on faith, without essential supporting evidence. We don't operate this way within the scientific community. As role models for our students, we should deliver and accept nothing less in the classroom.

Convincing authors and editors to make extensive changes to their textbooks is not realistic. However, we can begin the process in the direction of textbook reform by adhering to a new set of standards in the classroom. We need to jettison the encyclopedic approach to biology (as exemplified by biology textbooks) and infuse our classes with the process and excitement of biological discovery (National Research Council 2005). We need to incorporate discussions of how biological concepts were discovered, including the quantitative methods used to analyze data, so that we give students a more accurate picture of how science is conducted. Students should see principles that can be applied to new situations. If the goal is for our students to think like practicing scientists, then the process of doing science is much more important than a description of the end results of that process.

A more quantitative, process-driven approach takes time. Therefore, rather than trying to cover every subject in the textbook, we need to cover fewer items but do them well. But what subjects do we sacrifice? These are tough decisions, but we should not lose sight of our ultimate goal–we are training our students to become problem-solvers, not fact- recalling automatons.

Standard first-year biology textbooks (and texts for more advanced courses) could be enhanced by using some basic mathematical techniques, drawn mainly from high school algebra and geometry. For instance, when discussing the phenomenon of diffusion across cell membranes, we can take advantage of Fick's law to make a quantitative analysis of the surface to volume ratio for cells of fixed volume but different shapes (spheres, cylinders, etc.). When discussing enzymes, the opportunity should not be lost to analyze the Michaelis-Menten equation qualitatively and quantitatively. This leads to important conclusions through the use of transformations of variables and linear and nonlinear regression (Ledder 2012).

Biology textbooks are full of opportunities to use mathematics to help illuminate the biological processes. Although mathematical formulae are few and far between in introductory biology textbooks, several texts present the Nernst equation used to calculate the equilibrium potential for a single ion species in terms of the ion's concentrations outside and inside of the cell. Typically, the equilibrium potential is given for potassium ions (E_K) and the point is made that potassium is at equilibrium when the inside of a cell membrane is more negative than the outside ($E_K \approx$-75 millivolts for squid giant axon at 20^o Celsius). Since the resting membrane potential (V_m) is somewhat more positive than E_K ($V_m \approx$-70 millivolts), other ions besides potassium must contribute to V_m. Rather than stopping here, why not employ the Goldman-Hodgkin-Katz equation (Nicholls et al 2012), which incorporates the concentration gradients from several permeant ions simultaneously and the membrane's relative permeabilities to them? The GHK equation can be shortened to include just sodium and potassium ions:

$$V_m = 58 \log \frac{p_K[K]_{out} + p_{Na}[Na]_{out}}{p_K[K]_{in} + p_{Na}[Na]_{in}}.$$

We can make the analogy between permeability and membrane conductance to different ion species (the more open ion channels there are in the membrane, the higher will be the conductance). Also, by increasing the permeability (and, by analogy, conductance) of the membrane to sodium, V_m moves toward the equilibrium potential for sodium, which is exactly what happens during the initial phase of the action potential or during excitatory postsynaptic potentials. Thus, mathematical manipulation of the relative permeabilities sets the stage for understanding the biological changes in membrane conductances that underlie action, synaptic, and receptor potentials.

Many standard first-year textbooks of mathematics used by biology majors present few if any examples related to the biological sciences. And when an example is presented, say the flow of blood across an artery, no explanation is provided for the startling fact that the volume of blood that flows through a cross section of an artery in unit time is proportional to the fourth power of the radius. An application of Poiseuille's law, in the developing the main ideas of integration, could shed light on the problem of blood flow.

Changing Teaching Strategies

We need to incorporate more of the learning approaches that have been shown to promote transfer learning – the ability to use information in a new situation. Currently at our institution, we are dismayed by our students' lack of retention from the introductory to the upper division classes. Our students perform much like novices (Larkin et al 1980) when confronted with problems and intellectual challenges: they do not seem to be able to form connections. We are continually doing remedial teaching of basic concepts in our upper division courses. Instead of a coherent set of unifying principles, biology (for many students) is an amorphous collection of facts. So, it should not be surprising that retention is low. The literature provides some suggestions for improving transfer learning.

- Insightful problem solving can be trained by showing students how to improve their metacognitive ("thinking about thinking") skills (Davidson and Sternberg 1998)
- The application of hypothetico-deductive reasoning is like the way that people naturally process thoughts and, therefore, instruction should provide students with increasingly complex opportunities to propose and test hypotheses (Lawson 2005).
- Rather than continually boosting students' self-confidence, a better approach may be to give them a challenging task early in the semester, thus giving them a healthy "shock" to stimulate their effort and reasoning skills (Lawson et al 2007).

Our SYMBIOSIS curriculum encompasses only the first three semesters of college. To reinforce the integrative approach to biology, upper division biology courses must include more quantitative examples and incorporate more quantitative approaches to solving problems. It is imperative that the interdisciplinary approach not disappear in the remaining two and a half years in their course of study. How can this be accomplished? The following suggestions certainly are not novel, but we consider them to be vital to the continuation of our SYMBIOSIS initiatives.

- Make modifications to current biology courses, such as including quantitative modules – if a few modules are added, the entire course does not need to be overhauled. One or two new modules can be added each time the course is taught.
- Make modifications to current mathematics courses, using biological examples rather than the more traditional engineering problems.
- Have a greater emphasis on handling and analyzing data sets in biology courses, in the lecture and the laboratory. Incorporate statistical tests of hypotheses as often as possible.
- Create new interdisciplinary courses, with biologists and mathematicians as co-instructors. This takes a great deal of effort and cooperation between departments and perhaps a reorganization of teaching responsibilities.

Culture Shock

"It is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is the most adaptable to change."

-- Charles Darwin

Change is difficult. Sweeping changes, such as those envisioned by *Bio2010*, require a concerted effort by entire departments and institutions. What are some of the barriers to implementing the *Bio2010* suggestions? First, while most biology professors recognize the need for a more quantitative pedagogy, inertia must be overcome before there can be any progress. For many, the quantitative approach evokes an almost reflexive defensiveness. Others may be willing to change, but feel that they are already overburdened or unprepared. Still others may believe that they already are doing enough in their own classes and see no need to participate in any large-scale initiatives. A second set of barriers comes from the students. Many choose to major in biology because they see it as less mathematical than physics and chemistry, the age-old math phobia problem. We hope that an integrated curriculum (such as SYMBIOSIS), where students are shown from the beginning that mathematics and biology are complementary to each other, may help treat this malady. How can we minimize the loss of biology majors (many of whom will be pre-medicine) and encourage more faculty members to make modifications to our undergraduate curriculum? We think it will require nothing less than a change in the culture of biology instruction.

How can a tradition of teaching, firmly entrenched over many decades, be transformed? How can we convince students that a more quantitative biology will better prepare them? Somehow, the subject matter has to be relevant and accessible to the students and the professors. The old perception that mathematics and biology are in different domains must be dispelled. We must establish a community of scholarship in which interdisciplinary interactions are recognized, encouraged, and rewarded. Here are some recommendations:

- Encourage research publications in which both mathematicians and biologists are co-authors. Publications are rewards that can benefit all participants. With some success, others may see benefits. At our institution, we have established several collaborative research groups that are beginning to yield publications.
- Encourage publishing articles in education journals describing ways of incorporating quantitative approaches to traditionally qualitative lectures and laboratories. The publications should be rewarded in the tenure and promotion process.
- Have courses taught by colleagues from both departments.
- Design interdisciplinary graduate and undergraduate student projects with quantitative and biological components. Assign at least one committee member from each of the mathematics and biology departments.
- Teaching assistants in the biology department must be trained and prepared to help the permanent faculty in making the transition.
- Invite seminar speakers with quantitative biological research and who have the ability to make the mathematics accessible to a general biological audience.
- We desperately need a program for faculty development. Many biologists would like to have more quantification, but don't have the mathematical skills. Such development typically requires time, motivation, and funding. We need to identify some mechanisms by which the biology faculty can improve their competence in mathematics.
- Hire new faculty members who have quantitative skills and who can establish both research and teaching interdisciplinary collaborations.
- A cultural change within the Mathematics Department is needed as well; more mathematicians need to appreciate that linking mathematics to biological applications enriches learning mathematics as well as biology.

References

Davidson, J. E., and R. J. Sternberg, 1998: Smart problem solving: how metacognition helps. *Metacognition in Educational Theory and Practice*, D.J. Hacker, J. Dunlosky, and A.C. Graesser, Eds., Lawrence Erlbaum Associates, 47-68.

Joplin, K. H., E. Seier, A. Godbole, M. Helfgott, I. Karsai, J. Knisley, D. Moore, and H. A. Miller III, 2012: SYMBIOSIS: An integration of biology, math and statistics at the freshman level: walking together instead of on opposite sides of the street. This volume, xx-yy.

Larkin, J., J. McDermott, D. P. Simon, and H. A. Simon, 1980: Expert and novice performance in solving physics problems. *Science*, **208**, 1335-1342.

Lawson, A. E., 2005: What is the role of induction and deduction in reasoning and scientific inquiry? *J. Res. Sci. Teach.*, **42,** 716-740.

Lawson, A. E., D. L. Banks, and M. Logvin, 2007: Self-efficacy, reasoning ability, and achievement in college biology. *J. Res. Sci. Teach.*, **44**: 706-724.

Ledder, G., 2012: A terminal post-calculus-I mathematics course for biology students, this volume.

National Research Council, 2003: *Bio2010: Transforming Undergraduate Education for Future Research Biologists*, National Academies Press.

National Research Council, 2005: *How Students Learn: Science in the Classroom*, M. S. Donovan and J.D. Bransford, Eds., National Academies Press.

Nicholls, J. G., A. R. Martin, P. A. Fuchs, D. A. Brown, M. E. Diamond, and D. A. Weisblat, 2012: *From Neuron to Brain*, 5th ed., Sinauer.