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Commentary: *Bio2010*—New Challenges for Biology Educators

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Biology has changed. Research frontiers increasingly lie on the interfaces with other disciplines. Many of these are the more quantitative sciences. The biological researcher of the future will need to integrate multiple disciplines in order to make the important connections. How can undergraduate biology students acquire stronger backgrounds in chemistry, mathematics, engineering, physics, and computational science without compromising a liberal education? This was the challenge confronted by the National Academies' Committee on Undergraduate Education to Prepare Research Scientists for the 21st Century, chaired by Lubert Stryer.

The recently issued committee report, called *Bio2010: Transforming Undergraduate Education for Future Research Biologists* (National Research Council, 2003), makes eight recommendations designed to inspire changes in undergraduate biology education that are tuned to these new realities. The goal is to make biologists more comfortable with concepts from math and the physical sciences, which are increasingly part of doing innovative research in biology. Below I discuss the genesis of the report and how the committee proceeded. I comment on each of the recommendations. Most challenging for all of us involved in undergraduate biology education is how the recommendations of the report can be implemented to effect change. What follows is meant to be a guided tour to the report itself.

THE GENESIS OF *Bio2010*

The statement of task was issued in 2000 by the National Research Council, and the study was guided by their Board on Life Sciences (see Appendix A of the report). The committee was asked to examine current undergraduate curricula, training, and experience and relate them to needs for successful preparation of the next generation of life scientists. A specific goal was to identify fundamental skills in mathematics, chemistry, physics, computer science, and engineering that could be integrated into the biology major. Finally, case studies were to be generated that would provide concrete suggestions for implementing reforms at both universities and 4-year colleges.

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The specific focus was to be on preparing students for biomedical research in a postgenomic, interdisciplinary era. This emphasis derived from the interests of the sponsors of the report—the National Institutes of Health and the Howard Hughes Medical Institute. Yet it was realized that the report would necessarily evaluate undergraduate preparation for other life science disciplines, such as plant biology, population and evolutionary biology, and behavior and cognitive sciences, as well. The education of undergraduates headed for medical school is also inextricably linked to programs in biology.

THE COMMITTEE AND PROCESS

The committee assembled to prepare the report included scientists with diverse backgrounds and experience related to undergraduate biology education (see Appendix B of the report). The Chair, Lubert Stryer, Professor of Neurobiology at Stanford University, is the author of a textbook that has been the standard bearer of biochemistry to both undergraduates and medical students for nearly three decades. Ronald Breslow, Professor of Chemistry at Columbia University, has been honored multiple times for his teaching as well as research contributions. James Gentile, Dean for Natural Sciences at Hope College, is a cancer researcher whose devotion to improving undergraduate science education has included long-term involvement with Project Kaleidoscope (an informal national alliance devoted to strengthening undergraduate learning in science, mathematics, and engineering). David Hillis, Director of the School of Biological Sciences at the University of Texas, Austin, brought expertise in the innovative teaching of integrative and evolutionary biology. John Hopfield, now Professor of Molecular Biology at Princeton University, has taught the whole range of physics, chemistry, and, most recently, neural networks courses to undergraduates and graduate students, beginning at Caltech. Nancy Kopell, Professor of Mathematics and Science at Boston University, is Co-director of the Center for BioDynamics, a multidisciplinary center for biology, mathematics, and engineering. Sharon Long, Dean of the School of Humanities and Sciences at Stanford University, is a plant microbiologist who codesigned an interdisciplinary course for nonmajors on Light in the Physical and Biological World. Edward Penhoet, currently Director for Science and Higher Education at the Gordon and Betty Moore Foundation, integrated a career in biotech (as founder and CEO of Chiron) with teaching biochemistry to undergraduates at Berkeley. Charles Stevens, HHMI Investigator and Professor at the Salk Institute, focuses his research on synaptic transmission and has written widely for the broad scientific audience. Samuel Ward, Professor of Molecular and Cellular Biology at the University of Arizona, has directed undergraduate and precollege biology programs, is active with Project Kaleidoscope, and was chair of the National Research Council (1996) Committee that produced the report *The Role of Scientists in the Professional Development of Science Teachers*.

My invitation to join the committee was based, I believe, on my involvement in teaching molecular genetics to several generations of Yale undergraduates. Over much of this period, there have been two ways to major in biology at Yale—the program in my department requiring more quantitative courses, such as physical chemistry, and the other with a broader focus that includes evolution, ecology, and organismal biology. My interest in reforming undergraduate biology education was piqued by statistics that emerged from a National Science Foundation (1996) survey (1991–1995): whereas only 8% of U.S. undergraduates attended liberal arts colleges, 17% of science Ph.D.'s were granted to graduates of liberal arts colleges! What was happening at small colleges to generate and retain students' interest in science? What could we be doing better at my own institution?

The committee's deliberations included two critical activities. First, it impaneled three subcommittees to undertake more detailed analyses and develop recommendations in three specific areas: chemistry, physics and engineering, and mathematics and computer science. Each panel was chaired by a member of the *Bio2010* committee and included additional experts with interdisciplinary experience and dedication to undergraduate science education (see Appendix C of the report for panel rosters). The reports of the three panels, which are included in Appendix C of the report, contain carefully developed lists of concepts from these disciplines considered important for biology students to master. Equally valuable in the panel reports were innovative proposals for revamping courses and laboratories. A most important aspect of the panel deliberations was consideration of subjects that have been traditionally included in undergraduate courses in these disciplines but may not be essential for biologists. For example, the Physics and Engineering Panel recommended that topics such as angular momentum, specialized relativity, and magnetism are not as salient as mechanics (including gravity), thermodynamics, optics, and spectra for understanding biological systems. Such recommendations provided the parent committee with insights critical for suggesting how the integration of physical concepts into biology courses, and vice versa, might be accomplished without compromising time for nonscience courses in the undergraduate curriculum.

The second critical activity of the parent committee was a summer Workshop on Innovative Undergraduate Biology Education. Workshop invitees (listed in Appendix G of the report) included faculty from both large universities and small liberal arts colleges who had developed novel teaching methods or interdisciplinary courses. They provided inspiring descriptions of what can be done and how successful revamped courses and programs have been in generating and maintaining student interest in science.

THE RECOMMENDATIONS

A fundamental premise of the committee's deliberations was that their recommendations concerning the structure and content of undergraduate biology programs should not compromise time for liberal education. The eight recommendations are as follows.

> 1. 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, and the 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. Lists of relevant concepts are provided within the body of this report.

As stated in the report, the new biology curriculum should be designed to give undergraduates "a sense of the power and beauty of science that takes full advantage of the richness of ideas and tools provided by a broad range of disciplines." The five separate concept lists for biology, chemistry, physics, engineering, and mathematics and computer science presented were compiled based on the panel reports. These lists are not meant to be obligatory items in a curriculum roster. Rather, they provide a guide to the types of ideas and skills that will arm future research biologists with the tools necessary to make innovative leaps in exploring the biological world. Each institution will need to adapt them as appropriate to the needs of its particular student body and program.

> 2. Concepts, examples, and techniques from mathematics, and the physical and information sciences should be included in biology courses, and biological concepts and examples should be included in other science courses. Faculty in biology, mathematics, and physical sciences must work collaboratively to find ways of integrating mathematics and physical sciences into life science courses as well as providing avenues for incorporating life science examples that reflect the emerging nature of the discipline into courses taught in mathematics and physical sciences.

How can all the relevant concepts be communicated without the entire undergraduate experience being devoted to science? The report details a number of innovative examples of how physical concepts can be introduced into the discussion of biological problems and, conversely, how biological examples could make physical courses more appealing, even for students who are not biologically oriented. The argument here is that in pure physics, for example, a proton has no function. In contrast, biology is intrinsically about understanding function and is more appealing to us as human beings. The idea of adding interdisciplinary modules to enrich standard course offerings can be found scattered throughout the report.

Four potential 4-year curricula for the biology major are presented. They include three important suggested revisions of the current standard undergraduate program: (1) a reorganization of chemistry offerings to incorporate organic chemistry earlier, (2) an expansion of physics to include engineering principles, and (3) a new mathematics sequence that integrates and compresses standard topics to allow for the inclusion of more computer science. The four potential curricula differ in their emphasis on evolution, ecology, and systematics versus chemistry, physics, and math and computer science in the level of precollege preparation that students bring to their science courses and whether biology courses are delayed until a strong background in the physical sciences is acquired (maintaining interest in biology with a first-year seminar in current research).

> 3. 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.

New textbooks can create or profoundly impact a field. Examples are James Watson's *Molecular Biology of the Gene* and Lubert Stryer's *Biochemistry.* This section of the report provides concrete examples for the content of interdisciplinary modules, courses, and seminars. Sources are provided for details and more information. In addition, if we are to achieve interdisciplinary education, we must all work to break down departmental territoriality inherent in hiring decisions and in competing for university funding based on a tradition of strict boundaries separating scientific disciplines.

> 4. Laboratory courses should be as interdisciplinary as possible, since laboratory experiments confront students with real-world observations that do not separate well into conventional disciplines.

Laboratories are a natural for introducing concepts and approaches from divergent disciplines. Interdisciplinary labs will both reduce the time committed to formal laboratory courses and engage student interest. Labs should be project-based, modeled on how scientists actually proceed to solve real problems. Four new laboratories are proposed as examples: in physics, chemistry, genomics, and engineering-for-life-scientists. Students are prompted to ask questions, make observations, analyze data, and integrate the new information they acquire, just as in a research lab (Figure 1). Again, sources for additional information are provided.

> 5. All students should be encouraged to pursue independent research as early as is practical in their education. They should be able to receive academic credit for independent research done in collaboration with faculty or with off-campus researchers.

Virtually every active scientist can point to an early research experience that introduced (and addicted) him or her

Figure 1. Linda A. Hicke (Assistant Professor, Department of Biochemistry, Molecular Biology & Cell Biology, Northwestern University) mentors an undergraduate student. (Photograph courtesy of Linda A. Hicke; http://www.searlescholars.net/people/hicke.html.)

to the thrill of scientific discovery. Although independent research for every biology student may be difficult to orchestrate at very small colleges and very large universities, credit could be given for off-campus research in a variety of environments (including laboratories abroad). The student participant will experience not only designing and executing real research, but will become a member of a lab community. Writing and talking about research accomplishments to peers will provide exposure to yet another important aspect of doing science. Whatever the mechanism, encouraging students to engage as early as possible in independent research should be an integral part of every undergraduate biology program.

> 6. Seminar-type courses that highlight cutting-edge developments in biology should be provided on a continual and regular basis throughout the four-year undergraduate education of students. Communicating the excitement of biological research is crucial to attracting, retaining, and sustaining a greater diversity of students to the field. These courses would combine presentations by faculty with student projects on research topics.

It is imperative to communicate to future biologists that all problems are not yet solved. Participation in seminars that focus on the excitement of current research in biology will not only maintain interest throughout the undergraduate years, but assure students that they personally have an important role to play in the future of scientific discovery.

> 7. Medical school admissions requirements and the Medical College Admissions Test (MCAT) are hindering change in the undergraduate biology curriculum and should be reexamined in light of the recommendations in this report.

"Harmonizing" is the term used in the report for what needs to be done to reconcile the above recommendations with hurdles currently faced by medical school applicants. We argue that medicine itself is becoming more interdisciplinary and that the reforms suggested would therefore benefit future physicians as well as future biology researchers. Particularly with respect to the curricular changes advocated in Recommendation 2, we urge that medical school admissions requirements be accordingly de-rigidified through independent review and consideration.

> 8. Faculty development is a crucial component to improving undergraduate biology education. Efforts must be made on individual campuses and nationally to provide faculty the time necessary to refine their own understanding of how the integrative relationships of biology, mathematics, and the physical sciences can be best melded into either existing courses or new courses in the particular areas of science in which they teach.

Faculty time off is needed to prepare new texts and teaching materials (such as those listed in the report) that can be disseminated to others or to introduce revisions into current courses. Time off requires additional funding that we hope will be provided in part by foundations and federal agencies, displacing the burden borne by undergraduate institutions themselves. Already in planning is a pilot summer institute funded by the National Research Council to be held in the summer of 2003 at the University of Wisconsin—Madison on strategies for integrating research into the undergraduate curriculum.

THE CHALLENGE OF IMPLEMENTATION

The transformation of undergraduate biology education on the scale advocated in the *Bio2010* report will be effected only with input from many. Those teaching undergraduates must be supported both financially and ideologically by university administrators, as well as by federal agencies and private foundations. Whatever each of us can do in changing how we teach or communicating the results to others will help.

I can relate the outcome of my own efforts at Yale. Just a month after attending the summer Workshop on Innovative Undergraduate Biology Education, I was scheduled to assume leadership of a course sponsored by my department for advanced undergraduates entitled "The Medical Impact of Basic Science." Traditionally, the course leader recruited a number of faculty from Yale Medical School to present lectures concerning the impact of basic research on understanding and designing therapies for specific diseases. Assigned readings related to the lectures were covered on an exam, and at the end of the term, students were asked to choose a disease and write a paper reviewing the relevant literature and proposing their own experiments or ideas for therapy. Guided by materials developed by the Biology Core Curriculum, a four-semester honors program at the University of Wisconsin—Madison, I decided to change the course to an interactive format. I hoped to engage the undergraduates, who already had a solid two-semester biochemistry course, in critical reading of the literature. Thus, I instructed each lecturer not to provide comprehensive coverage of a field but, rather, to focus on preparing the students simply to read one or, at most, two papers from the recent primary literature. The students were also given concept lists and study questions with each lecture. Then, in weekly mandatory discussion sections, the students collaborated in groups of three to write answers to questions about the papers assigned for one of the two lectures that week. The nature of the questions was such that it was essential to read the papers in advance of the section meeting; changing the composition of the student subgroups weekly provided additional impetus for active participation. This cooperative learning venture accounted for 30% of the grade in the course. Exams on lectures that were not the topic of written answers and the term paper described above accounted for the remainder of the grade. Personally, I found that my own lectures were substantially different when the goal was to prepare students to read only a limited number of papers very thoroughly. Not only has the course been great fun to teach (I just finished the second year), but the student critiques revealed that our objective was largely accomplished! One student, who after graduation switched his research lab from molecular genetics to neurobiology, informed me that since he now knew how to read a paper, he would not have to worry about making the transition successfully.

I end by quoting Donna Shalala (1995) Secretary of the Department of Health and Human Services in the Clinton administration. The number 1 and 2 items on her "top 10 list of things we must do to ensure that today's children are scientifically literate" are as follows:

> **2. Cultivate science activism.** We will never change university curricula and teaching quality unless scientists, mathematicians, and engineers truly engage themselves in curricular reform and university policy.
> **1. Take the lead now.** We will not have change unless the mavens of science—you and I—drive our society into action.

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