BIO 2010: Transforming Undergraduate Education for Future Research Biologists

Research in biology has undergone a major transformation in the last 10 to 15 years. Three powerful innovations – recombinant DNA, new instrumentation and the digital revolution – have combined to make biomedical research more quantitative and more closely connected to concepts in the physical, mathematical and information sciences. Researchers who once dedicated their lives to the study of a single gene, can now use sophisticated instrumentation and computer analysis to study the complex interactions of the more than 30,000 genes that make up the human genome.

In contrast, undergraduate biology education is still geared to the biology of the past. Although most colleges and universities require biology majors to enroll in courses in math, chemistry and physics, these subjects are not well integrated into biology courses. Furthermore, most courses, especially those for first-year students, are still primarily lecture-based, and do not convey the exciting reality of biology today.

What qualifications should a graduating biology major possess? What are the fundamental concepts of mathematics, chemistry, physics, computer science and engineering that will assist students in making interdisciplinary connections? How can universities implement new programs and what institutional barriers must be overcome?

The National Academies' report, *Bio2010: Transforming Undergraduate Education for Future Research Biologists*, identifies potential changes in undergraduate education designed to improve the preparation of students in the life sciences, with a particular emphasis on the education needed for future careers in biomedical research. The report looks at content, teaching approaches, curriculum requirements, funding and other issues.

Biology in Context: An Interdisciplinary Curriculum

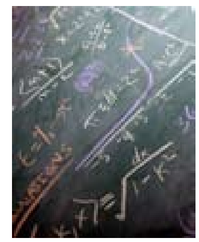
The modern biologist uses a wide array of advanced techniques, such as measuring instruments, novel imaging systems, computer analysis, and modeling that are rooted in the physical and information sciences. Focused laser beams allow manipulations of single molecules. X-ray sources are used to determine three-dimensional structures of proteins. Functional magnetic resonance imagers map activated regions of the brain. Computers now play a central role in the acquisition, storage, analysis, interpretation and visualization of vast quantities of biological data.

Understanding and applying these techniques requires access to a broader range of concepts and skill than past generations, much of it outside the traditional realm of biology education. Numerous studies and workshops have addressed the growing body of research at the intersection of biology with other disciplines, further supporting the need for more interdisciplinary education. Already, multidisciplinary projects are emphasized in solicitations for research grants.

The *Bio2010* report provides a consensus list of the central concepts of biology, chemistry, physics, math and computer science, and engineering that life science students should master in order to make novel interdisciplinary connections to address the reality of research today.

Central Concepts in Biology. Knowledge of diverse genomes, from bacteria to worms to flies to humans, is revealing recurring motifs and mechanisms and strengthening our appreciation for the fundamental unity of life. Variations on this unity lead to the extraordinary diversity of individual organisms. To understand this unity and diversity, teaching of biology students should focus on several central themes in multiple contexts. For example, the central theme of equilibria could be taught in a variety of contexts:

Living systems are far from equilibrium. They utilize energy, largely derived from photosynthesis, which is stored in high-energy bonds or ionic concentration gradients. The release of this energy is coupled to thermodynamically unfavorable reactions to drive biological processes.



Central Concepts in Math and Computer Science. The elucidation of the human genome has opened new vistas and highlighted the increasing importance of mathematics and computer science in biology. The current intense interest in genetic, metabolic and neural networks reflects the need of biologists to view and understand the coordinated activities of large numbers of components of the complex systems underlying life.

It is essential that biology undergraduates become quantitatively literate, studying the mathematical concepts of change, modeling, equilibria and stability, structure of a system, interactions among components, data and measurement, visualization, and algorithms. Every student should acquire the ability to analyze issues in these contexts in some depth, using analytical methods (e.g., pencil and paper) and appropriate computational tools. An appropriate course of study would include aspects of probability, statistics, discrete models, linear algebra, calculus and differential equations, modeling and programming.

Though all of these topics are offered in most universities and colleges, it is difficult for life science students to master the most essential concepts without taking a larger number of courses than can be accommodated in a biology major. The report recommends the creation of new courses that will cover the most relevant math concepts in less time in the context of biological problems.

As a good example, the University of Tennessee offers a two-semester course designed for life science majors that replaces the traditional calculus course (see Box 1). It introduces topics such as the mathematics of discrete variables, linear algebra, statistics, programming and modeling as applied to biological problems.

Box 1: Teaching that Works
Quantitative Life Sciences Education
at the University of Tennessee

This course sequence, developed by Dr. Louis Gross, provides an introduction to a variety of mathematical topics of use in analyzing problems arising in the biological sciences. The goal of the course is to show how mathematical ideas such as linear algebra, statistics and modeling can provide answers to key biological problems and to provide experience using computer software to analyze data and investigate mathematical models. Students are encouraged to formulate hypotheses that test the investigation of real world biological problems through the use of data.

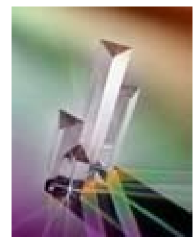
Each class session begins with students generating one or more hypotheses regarding a biological or mathematical topic germane to that day's material. For example, students go outdoors to collect leaf size data; they are then asked, Are leaf width and length related? Is the relationship the same for all tree species? What affects leaf size? Why do some trees have larger leaves than others? Each of these questions can generate many hypotheses, which students can evaluate after analyzing their data.

The program makes extensive use of graduate students in Tennessee's mathematical and computational ecology program because they are well positioned to explain the connections between mathematics and biology. More information on a quantitative curriculum for life science students can be found at www.tiem.utk.edu/~gross/quant.lifesci.html.

Central Concepts in Chemistry. Chemistry has always been an important sister science to biology, biochemistry, and medicine. Today, modern molecular and cell biology focuses on understanding the chemistry of genes and of cell structure. In the applied area, chemistry is central to modern agriculture, and biomedical engineering draws on chemistry for new materials. A thorough grounding in general and organic chemistry has historically required four semesters of chemistry courses, but could require fewer following an integrated restructuring.

The report recommends that biology majors receive a thorough education in chemistry, including aspects of organic, physical and analytical chemistry as well as biochemistry incorporated into new courses. Biology faculty could work in concert with chemistry colleagues to design curricula that will not only foster growth for aspiring chemists but also stimulate biology majors and those majoring in other disciplines. Core concepts include atoms, molecules, aqueous solutions, chemical reactions, energetics and equilibria, reaction kinetics, biomolecules, and materials.

Central Concepts in Physics. There is a set of basic physics concepts on which an understanding of biology can be built and that can be of aid in using increasingly sophisticated instrumentation. The typical calculus-based introductory physics course, which allocates a major block of time to electromagnetic theory and to many details of classical mechanics, is often the only option for biology students. The course emphasizes exactly solvable problems rather than the kinds of problems common in the life sciences. Illustrations involving modern biology are rarely given, and computer simulations are usually absent.



The report provides a list of physics concepts that life science majors should master including motion, dynamics and force laws; conservation laws and global constraints; thermal processes at the molecular level; waves, light, optics and imaging; and collective behavior and systems far from equilibrium. A redesigned physics course focused on these concepts would help biology students see how physicists think and how physics informs biology.

Central Concepts in Engineering. Biology increasingly involves the analysis of complex systems. Organisms can be analyzed in terms of subsystems having particular functions. Concepts in engineering can help biology students more easily describe and model how system functions result from constituent elements (see Box 2). For example, an effort to understand the locomotion of insects might be preceded by a laboratory involving an analysis of a simple legged robot, which provides a concrete model of the relation between the laws of physics and the problem of controlling directed movements.

The report recommends that life science majors be exposed to engineering principles and analysis that could include topics such as:

- the blood circulatory system and its control; fluid dynamics; pressure and force balance.
- material properties of biological systems and how structure relates to their function (e.g., wood, hair, cells).

Box 2: Teaching That Works
On The Mechanics of Organisms

An upper-level course developed by Mimi Koehl at the University of California, Berkeley, brings biology and engineering together. It teaches functional morphology (how things move) in terms of mechanical design principles. Organisms are introduced as "Living Machines" and their abilities to fly, swim, parachute, glide, walk, run, buckle, twist and stretch are evaluated in the context of physics and engineering principles.

Students learn about the different types of fluid flow, the fluid dynamic forces of drag and lift, and how organisms live on wave-swept shores. They consider how mechanical properties change during the life of an organism, and the physics of shape change in morphogenesis, among other topics.

Energizing the Curriculum: New Content and Approaches

Successful interdisciplinary teaching will require both new materials and approaches. The need for teaching materials that will inform, enlighten and empower the next generation of researchers is crucial. New course designs and materials that encompass the highly interdisciplinary character of biology can accelerate the learning process and enable students to exercise their talents earlier in their careers.

An increasing number of today's college faculty recognize the significance of incorporating inquiry-based teaching and learning into their courses. The approach helps students to learn in the same way that scientists learn through research. Scientists ask questions, make observations, take measurements, analyze data, and repeat this process in an attempt to integrate new information. Teachers can use the approach in the classroom, labs, and the field.

The report presents several examples of ways to integrate two or more sciences together into one course as well as innovative teaching approaches that help communicate the excitement of science.

Modules for Course Enrichment

A logical first step in providing interdisciplinary course material is to use modules. The use of biological examples as modules in courses on chemistry, physics, computer science, and mathematics could help make those courses more relevant to future biological research scientists. Well-chosen examples that vividly present the biological pertinence of the physical or mathematical concepts under study can help students connect material taught in different courses.

A module can be presented in a single lecture or laboratory session, or over several sessions (see Box 3). Adaptable modules for course enrichment that take full advantage of interactive computer programs and multimedia educational tools are a very attractive complementary means of strengthening undergraduate biology education. Modules have been developed and integrated into science curricula with success at some institutions, but this approach has not been widely adopted at a majority of institutions nationwide.

Multiple independent groups have published modules or resources that can be used to enhance the teaching of undergraduate biology students. One group that has developed numerous modules for biology courses and laboratories is the BioQUEST Curriculum Consortium. The BioQUEST library is a peer-reviewed publication of computer-based curricular materials for biology education. The current volume contains more than 75 software simulations and supporting materials from diverse areas of biology.

Box 3: Teaching that Works:
The "Flu Module" at Carleton College

In his organic chemistry course, Dr. Jerry Mohrig introduced a "Flu Module" as a capstone, with a question that informs and drives the course. The capstone he presented was "Why do we get the flu every year?" Because a lot is known about the viral system, this capstone provides a modern, familiar context in which students can learn the basic chemistry of carbohydrates, proteins, molecular recognition, and cell-cell interactions. The module has been so successful, it is now used as a cohesive storyline every year.

Although most second-term organic chemistry courses include the basics of carbohydrate and amino acid chemistry, most students would be hard pressed to recognize or appreciate the great importance that carbohydrates have in biochemical recognition. The flu module focuses on how the interaction of carbohydrates and amino acids allow viral invasion of cells and also how therapeutic agents can be developed. Students are able to relate complex organic molecules to biological questions and they develop the confidence to do so.

Since he has been teaching the flu module, Dr. Mohrig has seen a significant increase in the interest in organic chemistry from the many biology students in the course.

The report offers ideas for potential modules, including:

What determines whether an epidemic waxes or wanes? In a simple model, a population consists of susceptibles who can contract a disease, infectives who can transmit it, and removals who have had the disease and are neither susceptible nor infective. Given an infection rate, a removal rate, and initial sizes of the three groups, one can calculate how the population evolves.

How do leopards get their spots and zebras get their stripes?
In 1952, Alan Turing published a seminal paper showing that an initially homogeneous distribution of chemicals can give rise to heterogeneous spatial patterns by reaction and diffusion.

Box 4: Teaching That Works
First-Year Seminar on Plagues

In the University of Oregon's first-year seminar, Plagues: The Past, Present, and Future of Infectious Diseases, professor Dan Udovic helps communicate the excitement of science. The course examines diseases such as malaria, bubonic plague, smallpox, polio, measles, and AIDS. In addition to the biology of the diseases, it also addresses their effects on populations and the course of history. Students investigate the conditions that influence the rate of spread of contagious diseases, and ways to prevent it. They discuss a number of ethical issues that arise in treating the sick, as well as development of policies intended to halt epidemics.

One segment of the course uses readings, discussions, computer modeling and lab activities to help students understand: (1) how the immune system works and why in some cases it doesn't; (2) why antibiotics work with some organisms but not others, and why many organisms are becoming resistant to antibiotics; (3) why so many new diseases seem to be suddenly appearing; (4) how vaccines work and why in some cases they don't; (5) how infectious diseases are transmitted; (6) why and how disease-causing organisms make humans sick; and (7) why most infectious diseases are usually not lethal.

Interdisciplinary Lectures and Seminars

In addition to modules, interdisciplinary lecture and seminar courses can give students a more realistic picture of how the sciences fit together. The report recommends that such courses be made available to students starting in their first year. At one end of the spectrum could be a first-year seminar with relatively few details and no prerequisites designed to "whet the appetite" of students who may or may not be majoring in biology. One excellent example is a first-year seminar on plagues that draws on disciplines outside the sciences (see Box 4).

At the other end of the spectrum is a capstone course for seniors with extensive prerequisites such as the "Mechanics of Organisms" course described in Box 2. At intermediate levels, a variety of course plans could incorporate material from the physical sciences and the underlying mathematical concepts and skills. A possible example is a course in quantitative physiology that explores blood circulation, gas exchange in the lung, control of cell volume, electrical activity of neurons and muscle mechanics.

Building on Concepts Through Laboratories

Laboratories can illustrate and build on the concepts covered in the classroom. Some concepts – such as error analysis, uncertainty, fluctuations and noise – are best learned through laboratory experiences. Once students have time to examine the specimens, materials, and equipment described in class, they are better prepared to carry out experiments. Project based laboratory work helps to stimulate student interest and participation, and is a choice arena to develop scientific writing, speaking, and presentation skills.

Interdisciplinary laboratories are a promising means of strengthening the physical sciences and quantitative background of life sciences majors and of introducing biology to students majoring in other fields. Harvey Mudd College has developed an introductory lab course designed to help students understand the research approach in science and the natural relationship between biology and other sciences (see Box 5).

The report proposes ideas for new labs in four disciplines: Physics, Engineering, Chemistry and Genomics, using a "crawl, walk, run" approach that helps students progress from step-by-step instructions to guidelines and examples, and finally to finding independent solutions to open-ended questions.

Box 5: Teaching that Works
Interdisciplinary Lab, Harvey Mudd College

In this team-taught course, students are led to understand the research approach in science. All experiments include technique development, instrumental experience, question formation and hypothesis testing, data and error analysis, oral and written reporting and most importantly, the opportunity to explore in an open-ended way details of phenomena that are familiar and of interest to students. Students are paired with a different partner for each experiment, developing teamwork skills in the process. Lab exercises include:

- Thermal properties of an ectothermic animal: Are lizards just cylinders with legs?
- Molecular weight of macromolecules: Is molecular weight always simple?
- Photosynthetic electron transport: How do biological systems convert physics into chemistry?

Incorporating Undergraduate Research

Many research scientists regard their undergraduate research experience as a turning point that led them to pursue research careers. By working as a partner in an active research group, undergraduates experience the rewards and frustrations of original research. Colleges and Universities should strive to make opportunities for independent research available to all students. They should regard the time faculty spend mentoring students one-on-one as teaching.

In spite of the overwhelming broad-based agreement that undergraduate research is good pedagogy, the educational value of undergraduate research for students and the impact of undergraduate research on faculty development as scholars and educators, has not been assessed in a systematic and intensive way. The report calls for further study on this important topic; assessment should be an integral part of the introduction of any new teaching approach.

Many schools have trouble finding the resources to offer independent research experiences to all students. A host of infrastructure limitations as well as an overwhelming number of biology students can combine to limit the number of students who can have opportunities for research experiences with independent work, at least early in an undergraduate career. One way to share the excitement of biology with students is to replicate the idea of independent work within the context of courses by incorporating inquiry-based learning, project labs, and group assignments. Although these methods have been used for ages, they can be "discovered" as new by successive generations of teachers and students.

MCAT: A Constraint on Curriculum Change

Innovation in undergraduate biology education is constrained by medical school admission requirements and specifically by the MCAT exam. The report recommends conducting an independent review of medical school admission requirements and testing in light of the rapidly changing nature of biological research, and the consequent need to transform undergraduate science education. A change in the MCAT itself, or in the way it is used for medical school admissions, would allow the biology curriculum to develop in a way that is beneficial to all students (including pre-med students) instead of allowing MCAT content to dictate what all students are taught.

Implementation: Building Momentum

Implementing the recommendations of this report will require a significant commitment of resources, both intellectual and financial. Successful redesign of courses and curricula requires a large investment of faculty time, departmental encouragement, and significant support from the college or university administration. Creation of new interdisciplinary majors is a significant challenge, often necessitating the hiring of new faculty with experience doing interdisciplinary research and teaching interdisciplinary topics.

Administrators need to recognize the time and effort required for change by encouraging faculty to take advantage of campus resources (such as teaching and learning centers and computer services) and supporting them for travel to conferences, workshops, and courses that will develop their teaching. Likewise, creation of new material will require the same commitment of funding and time. Potential formats of these needed teaching materials are diverse and complementary: printed books and guides, CDs and videos, Web sites, and interactive computer programs.

National Networks for Reform

Transformation of the undergraduate biology curriculum is tied to issues that extend beyond the reach of a single campus. Many individuals, institutions, organizations, and informal networks are working to address these issues. Significant change will require cooperation between these diverse groups.

Several disciplinary societies have education committees that address undergraduate teaching. Some, such as the American Society for Microbiology (ASM) and the American Institute of Biological Sciences (AIBS), employ full-time staff to make these efforts more successful. Another national group, Project Kaleidoscope (PKAL), has worked since 1989 to identify and disseminate sound principles and methods on which to base undergraduate education in the natural sciences and mathematics. Its members are faculty from all types of colleges and universities and all disciplines of the sciences. An important feature of PKAL is that participants in disciplinary and interdisciplinary workshops leave with specific action plans to implement on their home campus. It operates by looking for "what works" and encouraging others to apply those approaches in their own teaching.

Sources of Financial Support

Two principal organizations that have funded undergraduate biology education are National Science Foundation (NSF) and the Howard Hughes Medical Institute (HHMI). NSF supports a diverse array of projects in undergraduate science education. These projects fund activities such as research by undergraduates and development of teaching resources. HHMI invested more than $476 million between 1987 and 2001 to support improvements in biology education at 232 colleges and universities (HHMI Annual Report, 2001). Their investment has transformed biology instruction at these institutions, in ways ranging from developing new curricula, hiring new faculty, promoting faculty development, and supporting independent research by undergraduate students. Another private organization, the Whitaker Foundation, has spent considerable time and money on programs that enhance research and education in biomedical engineering.

The Central Role of Faculty Development: A Proposed Summer Institute

Undergraduate biology education can be effectively transformed only through close and sustained collaboration between colleges, universities, government agencies, professional societies, and foundations. It is often assumed that once a useful pedagogical approach is identified, it will be reproducible, easy to disseminate, and simple for another faculty member to implement in his/her home institution. The reality is that in teaching, as in research, faculty need to be trained to carry out new tasks and their efforts to do so need to be recognized.

The report proposes the creation of an annual summer institute dedicated to faculty development for biology professors (and other science faculty as appropriate) as an effective and appropriate means of building on the ideas of Bio2010 and fostering continued innovation in biology education.

The summer institute for biology education would be a venue for faculty to share information and experiences. It would help to increase communication between research universities and primarily undergraduate institutions by bringing faculty from both types of institutions together to learn from each other. It would facilitate the development, adaptation, and dissemination of innovative courses and course materials while providing training workshops for faculty and encouraging the development of a community of scientists/educators.

Potential topics include:

- The integration of quantitative examples into biology courses.
- Presenting examples of recent biological research that relies upon basic principles of chemistry or physics to undergraduate students.
- Ideas for exposing large numbers of students to research (how to think like a scientist): from laboratory courses to computer simulations to conceptual experiments.
- Developing teaching materials for the sharing of innovative approaches.
- Incorporating emerging research on cognition and assessment (See the 1999 NRC report *How People Learn* and the 2001 NRC report *Knowing What Students Know*).

A successful institute would require a partnership among a variety of institutions and organizations. A collaboration between the NAS, NRC, HHMI, and NSF would help to anchor the effort in the research establishment.

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