

## Articles

# A Response to *BIO 2010: Transforming Undergraduate Education for Future Research Biologists*, from the Perspective of the Biochemistry and Molecular Biology Major Program at Kenyon College

Received for publication, August 26, 2003, and in revised form, February 25, 2004

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**The National Research Council completed a major study of undergraduate biology education, *BIO 2010-Transforming Undergraduate Education For Future Research Biologists (BIO 2010)*, funded by the Howard Hughes Medical Institute and the National Institutes of Health. The *BIO 2010* report recommends that biology pedagogy should use an interdisciplinary approach incorporating a strong basis in mathematics and physical sciences. Many of the aims of *BIO 2010* can be met by an interdisciplinary major program such as that of Biochemistry and Molecular Biology at Kenyon College. The Kenyon program effectively encourages students to connect biology with chemistry and mathematics and to develop a sound basis for research in the biological sciences. A continuing challenge is to balance the needs for depth of physical and mathematical understanding and breadth of diversity in biology.**

The intersection of chemistry and biology provides a creative focus for understanding the molecular processes of life. As interdisciplinary research programs became commonplace, universities and funding agencies have explored ways to strengthen the biology-chemistry interface in undergraduate education. In 2002, the National Research Council completed a major study of undergraduate biology education, funded by the Howard Hughes Medical Institute (HHMI)<sup>1</sup> and the National Institutes of Health, *BIO 2010-Transforming Undergraduate Education For Future Research Biologists (BIO 2010)*. The study was conducted by a panel of eminent scientists chaired by Lubert Stryer.

A central recommendation of the *BIO 2010* report is that biology pedagogy should use an interdisciplinary approach incorporating a strong basis in mathematics and physical sciences. The emphasis on interdisciplinary education is in fact a major concern at liberal arts colleges, such as Kenyon, that have developed undergraduate major programs focusing on the intersection of chemistry and biology. We review here the recommendations of *BIO 2010* in light of our experience developing a major program in Biochemistry and Molecular Biology at Kenyon College.

### BIO 2010: RECOMMENDATIONS

A key observation of *BIO 2010* is that at most of the nation's universities, biology and chemistry students take courses in these disciplines but fail to grasp the ways in which chemistry feeds the study of biology. An even

greater divide is seen between biology and physics and mathematics.

To bridge these gaps between biology and the physical sciences throughout the undergraduate curriculum, *BIO 2010* makes a number of recommendations for teaching, which we summarize as follows:

- New teaching approaches should be developed that incorporate rigorous mathematical, physical, and informational sciences into biology. A noted model for the incorporation of this material is the modular approach, in which a case study such as that of the mechanism of influenza infection is used to motivate investigation of carbohydrate chemistry.
- In addition to the improvement of disciplinary courses, cross-disciplinary faculty collaborations should facilitate the incorporation of rigorous mathematical, physical, and informational science concepts and topics into biology courses and *vice versa*. Such collaborations require resources and support from administrators and funding agencies.
- Cross-disciplinary study must also extend to the student laboratory. Interdisciplinary laboratory experiments should incorporate a discovery approach.
- Student independent research should be promoted as early as possible. Student scientific communication skills should be enhanced through presentations of their research.
- Implementation of the *BIO 2010* recommendations should be accompanied by proper assessment of achievement of pedagogical goals.

In considering the *BIO 2010* recommendations, we note that the main target audience for this report is research universities, whose faculty *BIO 2010* called upon to invest

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<sup>1</sup> The abbreviations used are: HHMI, Howard Hughes Medical Institute; ASBMB, American Society for Biochemistry and Molecular Biology; ACS, American Chemical Society.

TABLE I  
*BIO 2010 Potential Curricula*

Bold titles indicate advanced mathematics and physics courses.

	Curriculum A	Curriculum C
First year	Introductory Biology I & II (and lab) Inorganic Chemistry I (and lab) Introductory Math I & II Organic Chemistry I (and lab) Faculty Research Seminar 3 General Education Electives	Introductory Biology I & II (and lab) Inorganic Chemistry I (and lab) Introductory Math I & II <b>Probability and Biostatistics</b> Faculty Research Seminar 3 General Education Electives
Sophomore	Molecular Biology Cell and Developmental Biology Organic Chemistry II (and lab) Introductory Physics I & II (and lab) Biochemistry 4 General Education Electives	Molecular Biology Cell and Developmental Biology Organic Chemistry I (and lab) Introductory Physics I & II (and lab) <b>Differential Equations</b> 4 General Education Electives
Junior	Genetics Evolutionary Biology and Ecology Analytical and Physical Chemistry (and lab) Biology Laboratory course 4 General Education Electives Independent Laboratory Research I & II	Genetics Evolutionary Biology and Ecology Organic Chemistry II (and lab) Biology Laboratory course Biochemistry <b>Physics III</b> 2 General Education Electives Independent Laboratory Research I & II
Senior	2 Biology Electives 2 Science Electives Faculty Research Seminar 3 General Education Electives Independent Laboratory Research I & II	Biology Elective Science/Biology Elective Analytical and Physical Chemistry (and lab) <b>Advanced Mathematics</b> Faculty Research Seminar 2 General Education Electives Independent Laboratory Research I & II

more of their energy and ingenuity in undergraduate teaching. By contrast, the liberal arts colleges such as Kenyon appear to be ahead of universities in implementing some of the recommendations, particularly for cross-disciplinary study and investigative laboratory courses. Liberal arts colleges have long implemented discovery learning and independent investigation in their curricula, from the introductory courses upward.

*BIO 2010* also presents a series of proposed biology curricula including different ranges of content in physical science and mathematics. Two examples of their “potential curricula” are shown in Table I. The content of Curriculum A is consistent with recommendations of the American Society for Biochemistry and Molecular Biology (ASBMB) for a major program in molecular biology, and with the American Chemical Society (ACS) guidelines for a major in biochemistry (Table II). Curriculum C is a more “math-physics”-intensive program that includes advanced mathematics and physics (titles in bold) while delaying the chemistry sequence and limiting electives.

The Potential Curriculum A that *BIO 2010* suggests for consideration as a “biology” major corresponds to what we teach at Kenyon as Biochemistry and Molecular Biology, a major program we developed based on the ASBMB and ACS guidelines. Our program effectively attains several of the goals cited in *BIO 2010*. We discuss below the achievements, as well as the limitations, of our program. We also offer some reflections on the possible consequences of defining biology itself as biochemistry.

#### THE KENYON PROGRAM IN BIOCHEMISTRY AND MOLECULAR BIOLOGY

In the early 1990s, the Departments of Biology and Chemistry at Kenyon experienced increased student inter-

est in molecular biology and biochemistry. Many of our honors and research students at that time chose to conduct molecular/biochemical projects such as gene cloning and gene product expression, and growing numbers of our students began attending graduate school in these fields. But students found it increasingly difficult to obtain sufficient course work in both biology and chemistry while majoring in one of these departments. To meet the student needs, in 1993 we instituted a program enabling students to major in either Biochemistry (BCHM) or in Molecular Biology (MBIO).

Our current course requirements for each major are summarized in Table III. Students in both majors share common core courses in their first 2 years, then diverge at the upper level. The core includes a rigorous chemistry sequence, including physical chemistry (CHEM 335) for all majors. Introductory biology includes a laboratory course culminating in an independent project. For advanced biology, we offer diverse options, including coverage of microbes and plants. Instead of requiring students to take the traditionally animal-centered cell physiology course, as implied by the ASBMB and ACS curricula, we offer the option to focus on other classes of organisms.

Our program offers excellent opportunities for research. Students reading for Honors may conduct a thesis project under the direct supervision of a faculty member in either department (biology or chemistry) for either major (molecular biology or biochemistry).

#### MEETING THE *BIO 2010* RECOMMENDATIONS: STRENGTHS AND AREAS FOR IMPROVEMENT IN KENYON'S PROGRAM

The strengths of our program include the intensive study of both biology and chemistry, the highly investigative laboratory courses, and the availability of high-quality re-

TABLE II  
ASBMB and ACS Curriculum Guidelines

Courses	Semesters hours
ASBMB recommended curriculum for major in Biochemistry and Molecular Biology (simplified)	
Chemistry	
Introductory Chemistry with lab	3–6
Organic Chemistry with lab	6
Biochemistry with lab	9
Biology	
Introductory Biology with Lab	3
Molecular Genetics with lab	3
Allied fields	
Calculus	6
Physics	6
Advanced electives	6
Recommended	
Research Experience with written paper	6
ACS guidelines for a degree in Biochemistry (simplified)	
Chemistry core	
Analytical Chemistry	3
Inorganic Chemistry	3
Organic Chemistry	6
Calculus-based Physical Chemistry	3
Biochemistry	3 +
Laboratory	7 +
Additional for biochemistry degree	
Biology (containing cell biology, microbiology or genetics)	3
Advanced Biochemistry	3
Biochemical Laboratory Methods	3
Biochemical Research with written paper	

TABLE III  
Kenyon course requirements for Biochemistry and Molecular Biology majors

Courses	Semesters <sup>a</sup>
Courses required for both majors (5 3/4 units)	
BIOL 113, 114 Introductory Cell Biology, Genetics, and Development	2.0
BIOL 109–110 General Biology Lab with Independent Project	1.0
CHEM 111,112 Introductory Chemistry	2.0
CHEM 113,114 Introductory Chemistry Lab	1.0
CHEM 231,232 Organic Chemistry	2.0
CHEM 233,234 Organic Chemistry Lab	1.0
CHEM 256 Biochemistry	1.0
BIOL 363 Molecular Biology and Genomics	1.0
BIOL 364 Gene Manipulation (lab)	0.5
CHEM 335 Chemical Kinetics and Thermodynamics	1.0
Additional courses required for the major in Biochemistry (BCHM) (1 1/4 units)	
CHEM 341 Instrumental Analysis	1.0
CHEM 371 Advanced Laboratory: Biochemistry	0.5
Two advanced chemistry lab courses from (inorganic, advanced organic, photophysics, chemical research)	2.0
One advanced biology course may substitute for general biology lab	1.0
The Senior Exercise is conducted under the Department of Chemistry	
Additional courses required for the major in Molecular Biology (MBIO) (1 1/4 units)	
BIOL 366 Cell Physiology, or other advanced biology course (microbiology, developmental biology, or plant biology)	1.0
Advanced biology elective	1.0
CHEM 371 (Biochemistry Laboratory) or advanced biology lab (microbiology lab, developmental lab, advanced genetic analysis, or advanced microscopy).	0.5
The Senior Exercise is conducted under the Department of Biology.	

<sup>a</sup> Semester courses meet 3 h per week. Laboratory courses meet 3 h per week for a semester, but earn a half-semester of credit.

search experience comparable in some cases to a masters program.

Several factors limit the content of our program, compared with the curricula envisioned by *BIO 2010*. The challenging course content and investigative laboratories at Kenyon make it difficult for the average student to fit more than four or five courses into a semester schedule. Our laboratory courses receive separate credit, equivalent to half a lecture course. The investigative nature of our laboratory courses was cited as exceptional by an external examiner of our program. To maintain this high level of

laboratory work, however, requires considerable time investment by the student. It is simply not practical for most students to undertake four lecture courses and three lab courses in one semester. Thus we do not yet explicitly require the courses in physics and mathematics recommended by *BIO 2010*. We do strongly recommend courses in calculus and introductory physics; most of our BCHM and MBIO majors take them, and some take enough extra mathematics courses to earn a minor concentration. For the future, we are exploring the development of accessory concentrations in biomathematics and biophysics, an ap-

proach that has worked well, for example, at Haverford College.

Another limited resource is staff. Our small departments lack the personnel to offer senior seminars on specialized topics. We do however conduct the Senior Exercise, in which students write an essay integrating a wide range of approaches in biology, and in some cases prepare a presentation on their topic.

*New Teaching Approaches*—As recommended by *BIO 2010*, Kenyon faculty are encouraged to incorporate cross-disciplinary rigor into courses in both MBIO and BCHM curricula. The molecular biology major combines depth in molecular genetics with a strong basis in chemistry, including a semester of physical chemistry. The chemistry background ensures that students recognize the dynamic molecular dimension of biological molecules, more than just strings of bases or amino acids. In the core course BIOL 363 Molecular Biology and Genomics, for example, students combine genomic analysis of sequences with three-dimensional structural analysis of proteins and nucleic acids, including structure and function of the recently solved ribosome. Students author Chime tutorials on biomolecules, providing a continual influx of new three-dimensional teaching tools.

The biochemistry major sequence of courses ensures a rigorous analytical background while integrating a strong component of biology. Instrumental analysis is required for BCHM majors, and advanced courses focus on bioanalytical methodologies and examples. Students choosing the BCHM path have attested to the program's success by effectively tackling intense molecular biology-based literature for their senior exercise.

*Cross-disciplinary Faculty Collaborations*—The core courses for Biochemistry and Molecular Biology are designed to complement one another so as to maximize student-made connections between disciplines. For example, students enjoy taking Molecular Biology and Genomics concurrently with the Chemistry Department's Biochemistry because both courses emphasize fundamental structure of molecules. Biochemistry focuses on the essential chemistry of the building blocks, whereas Molecular Biology puts together complex structures within the framework of genomics and evolution and provides an excellent foundation for more advanced study in either department.

Nevertheless, we feel a need for more cross-departmental collaborative discussions between the biology and chemistry faculties. At our most recent program retreat, we discussed ways to decrease redundancy and develop complementary curricular materials for courses serving BCHM and MBIO majors to free up time for even more advanced and rigorous topics to be covered.

Faculty from the two departments have succeeded in working together to obtain resources from administrators and funding agencies in support of the joint program. Funding has been obtained through the National Science Foundation, the HHMI, and internal Kenyon Faculty Development grants. Kenyon offers a competitive Teaching Initiatives Grant for development and implementation of innovative teaching methods. One faculty member, for example, recently received funds to set up a cell culture laboratory in chemistry teaching and research laboratories

to enhance the biochemistry major.

*Interdisciplinary Laboratory Experiments Should Incorporate a Discovery Approach*—The experimental foundation of the MBIO major is BIOL 364 Gene Manipulation. This laboratory course applies techniques of gene cloning and RNA expression to a research system, study of dioxin receptor metabolism in *Xenopus*. The course became so popular with students in other majors as well, such as biology, chemistry, and neuroscience, that we had to add a new section to accommodate student demand.

Another exciting interdisciplinary development was the creation of a shared position in Mathematics and Biology, initiated on a grant from the HHMI. The holder of this position, biostatistician Michael Radmacher, helped us to developing a new emphasis on bioinformatics and global expression systems such as microarrays. Radmacher now offers an advanced course on analysis of microarrays.

In the Chemistry department, laboratory courses in Biochemistry complement the physical nature of the general and advanced biochemistry courses, focusing not only on the fundamentals of protein isolation and reactivity, but also on protein structure analysis using circular dichroism, ultraviolet-visible, and stopped-flow spectrophotometry and protein gel electrophoresis. Cell culture is used in the inorganic laboratory elective to test cytotoxicity of medically important metal complexes synthesized and characterized by the students.

Outcomes assessment has indicated that techniques learned by the students in both MBIO and BCHM laboratories serve them well in Honors research and in postgraduate work. Furthermore, students bring cross-disciplinary laboratory expertise to our own research programs. For example, cross-disciplinary students brought DNA electrophoresis techniques to a mechanistic inorganic research laboratory, resulting in two publications.

*Student Independent Research Should Be Promoted as Early as Possible*—Both departments have mechanisms for continual research offerings throughout all four semesters, and both departments encourage first-year students to join research programs. The opportunity for students of either major to do research in either department remains a strength of our program. One BCHM major, who carried out her research with a mentor in biology, comments, "By being a biochemistry major I felt I had the tools to really attack the toughest problems in molecular biology." This student has gone on to Berkeley for a Ph.D. in molecular biology. In 2004, an MBIO major conducting microarray research with mentors in biology and in mathematics was accepted into several MD/Ph.D. programs. To enhance student opportunities for research, liberal arts colleges such as Kenyon commonly provide mechanisms to offer faculty credit for research courses.

As with our teaching efforts, more cross-departmental collaborations in our research program are desirable. The number of such collaborations is increasing. One biologist is working with a chemist to conduct proteomic studies of bacterial metabolism of short-chain organic acids. Another collaboration between a biologist and a chemist involves epi-fluorescence microscopy. These research projects have attracted several talented undergraduates majoring in BCHM or MBIO.

Student communication skills are emphasized by many of our courses, which contain an oral presentation component. Furthermore, all of our research students give in-house talks, and those doing Honors research do so before an outside examiner. Many students present their work at regional and national conferences. For example, BCHM and MBI0 majors have presented orally at the Annual Argonne Symposium for Undergraduates in Science, Engineering, and Mathematics (Chicago, IL) and the National Conference on Undergraduate Research, as well as national professional meetings such as the American Society for Microbiology.

*Assessment of Pedagogical Goals—BIO 2010* emphasizes the importance of expected student outcomes. The statement of such goals facilitates program assessment, which is critical for promptly pinpointing problems and implementing curricular change in response to such a rapidly changing field. The Kenyon program has begun a regular schedule for external review. Our assessment tools include a review of student presentations and coursework, including literature analysis, oral presentations, and scientific writing, as well as alumni career tracking and a survey of summer research participants. Special attention is paid to the performance of nonresearch *versus* research-active students for assessing the impact of research on student education. Throughout the academic year, faculty members of the Biology and Chemistry departments hold general meetings to discuss any issues that arise, and at the end of the year, participating faculty meet for a day-long retreat to discuss more fully the interdisciplinary program and assessment outcomes.

Our current assessment outcomes indicate that the Biochemistry and Molecular Biology program successfully instills skills into our students as recommended by *BIO 2010*:

- Understanding of the fundamentals of chemistry and biology and the key principles of biochemistry and molecular biology.
- Awareness of the major issues at the forefront of the discipline.
- Ability to assess primary papers critically.
- Good “quantitative” skills such as the ability to accurately and reproducibly prepare reagents for experiments.
- Ability to dissect a problem into its key features.
- Ability to design and interpret experiments and understand the limitations of the experimental approach.
- Ability to work safely and effectively in a laboratory.
- Ability to use computers as information and research tools.
- Ability to collaborate with other researchers.
- Ability to use oral, written, and visual presentations to present their work to both a science literate and a science nonliterate audience.
- Ability to think in an integrated manner and look at problems from different perspectives.

- Awareness of the ethical issues in the molecular life sciences.

In conclusion, an interdisciplinary program such as Kenyon’s Program in Biochemistry and Molecular Biology provides an effective way to achieve many of the goals of state-of-the-art biology education as outlined by *BIO 2010*. While we consider this approach extremely valuable for students interested in molecular biology, it is less clear whether such a program can replace more traditional biology programs. The proposed topics for *BIO 2010* say little about biology at the level of organism and population, or about diversity within the three major domains. What will become of the old courses on zoology and botany; will they be replaced by diversity electives? Will students continue to receive exposure to a wide range of organisms, beyond the model systems? Diversity has significance for fundamental questions. For example, the protist *Oxytricha trifallax* fragments its macronuclear genome into 20,000 chromosomes, each encoding one or two genes. The study of this obscure species is providing key insights on expression regulation and telomere function.

For Kenyon, the most valuable recommendation of *BIO 2010* has been to attempt incorporation of more physics and mathematics into our majors. One approach that has succeeded elsewhere, for example in the biophysics program at Haverford College, is to create supplemental cross-disciplinary course concentrations. Students may elect to use a course concentration in biology-mathematics or biology-physics to supplement the biology major (or the majors in mathematics or physics). We have approached this challenge by instituting a new faculty position in biology and mathematics with start-up support from an HHMI award, and by planning for a new position in biological physics. These colleagues will help develop new coursework at the interface of biology and physical science, as well as to develop cross-disciplinary modules in our current courses.

Overall, Kenyon’s interdisciplinary program provides a broad spectrum of choice for students across the span of biology and chemistry, as well as growing connections with mathematics. We encourage diverse choices of focus on classes of organism, including microbes, plants, and animals. With the encouragement of the *BIO 2010* report, we are venturing to expand our connection with physics and mathematics in our Biochemistry and Molecular Biology program.

#### REFERENCES

- BIO2010: Transforming Undergraduate Education for Future Research Biologists. (2003) National Academies of Science. [www.nap.edu/books/0309085357/html/](http://www.nap.edu/books/0309085357/html/).
- ASBMB Recommended Curriculum for Program in Biochemistry and Molecular Biology. (1992) American Society for Biochemistry and Molecular Biology. [www.asbmb.org/asbmb/site.nsf/Sub/Undergrad-Curriculum?opendocument](http://www.asbmb.org/asbmb/site.nsf/Sub/Undergrad-Curriculum?opendocument).
- American Chemical Society. (2003) Curriculum Guidelines. [www.chemistry.org/portal/a/c/s/1/educatorsandstudents.html](http://www.chemistry.org/portal/a/c/s/1/educatorsandstudents.html).
- Biochemistry and Molecular Biology Major Program, Kenyon College. (2003) [www2.kenyon.edu/Depts/Biochem./index.html](http://www2.kenyon.edu/Depts/Biochem./index.html).
- Biochemistry and Biophysics Concentration, Haverford College. (2002) [www.haverford.edu/biochem-biophys/welcome.html](http://www.haverford.edu/biochem-biophys/welcome.html).