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Integrated Biology and Undergraduate Science Education: A New Biology Education for the Twenty-First Century?

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INTRODUCTION

Given the radical changes in the nature of the science of biology and what we have learned about effective ways to teach, this is an opportune time to address the biology we teach so that it better represents the biology we do.

– www.visionandchange.org

For more than a decade, numerous reports have called for a rethinking and restructuring of high school and undergraduate science education to make it more relevant and accessible to a broader spectrum of students (Handelsman *et al.*, 2006; Hulleman and Harackiewicz, 2009; National Research Council [NRC], 1996, 1997, 1998, 2002, 2003a,b,c, 2005, 2008; National Science Foundation [NSF], 1996) and to base our strategies on the expanding body of research on human learning and cognition (NRC, 2000b; Allen and Tanner, 2007; Morse and Jutras, 2008; DeHaan, 2009; Pfund *et al.*, 2009; Labov *et al.*, 2009). In 2009, several important publications, conferences, and events have pointed toward confluence around more interdisciplinary and interconnected approaches and themes for undergraduate education in the life sciences. These events have included the following:

- Release of draft curriculum frameworks in biology for the College Board's multiyear restructuring of advanced placement courses in science for high school students (see http://apcentral.collegeboard.com/apc/public/repository/draft_revised_ap_biology_curriculum.pdf). This restructuring closely follows the recommendations of a report from the NRC (2002) and calls for teaching fewer concepts in greater depth. Restructuring also requires developing and implementing

means to measure students' level of conceptual understanding (Mervis, 2009a; Wood, 2009).

- Publication of *Scientific Foundations for Future Physicians*, a joint report from the Howard Hughes Medical Institute (HHMI) and the Association of American Medical Colleges, which calls for a change in undergraduate science education away from a system based on courses to one based on "competencies." According to the committee, "A competency-based approach will give both learners and educators more flexibility in the premedical curriculum and allow the development of more interdisciplinary and integrative courses that maintain scientific rigor, while providing a broad education." (Executive Summary, p. 1)¹
- Convening of "Vision and Change in Undergraduate Biology Education," a summit held in Washington, DC, in July 2009 that was organized by the American Association for the Advancement of Science with support from the NSF. This summit brought together >500 people to consider future pathways for undergraduate education in the life sciences (Mervis, 2009b; Woodin *et al.*, 2009).² A report from the summit is planned for release in 2010.
- Publication in September 2009 of *A New Biology for the Twenty-First Century* by a committee under the aegis of the NRC's Board on Life Sciences (NRC, 2009; a podcast about the report is available at <http://dels.nas.edu/dels/viewreport.cgi?id=5953>). The report proposes a bold new integrated research agenda, with important implications for the future of undergraduate and K–12 science education.
- Convening in November 2009 of an interdisciplinary forum on synthetic biology as part of the annual National Academies Keck Futures Initiative.³ Consistent with calls to find ways to develop science curricula in conjunction with cutting-edge scientific discoveries (Jurkowski *et al.*, 2007), the forum actively considered issues of education and communication about synthetic biology in conjunc-

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¹ A separate Executive Summary for this report is available at www.hhmi.org/grants/pdf/08-209_exec_summary.pdf.

² Additional information is available at www.visionandchange.org.

³ Additional information is available at www.keckfutures.org/conferences/synthetic-biology.html.

tion with discussions of scientific, legal, and ethical aspects. A report from this event will be published by the National Academies in 2010.

Thus, throughout this past year, the life sciences community has focused its attention on where biological research is likely to progress over the next several decades and how education in the life sciences might keep pace with this rethinking of research priorities and progress. The NRC (2009) report offers the most comprehensive review of these sets of issues; its recommendations for research and education agendas are summarized below.

A NEW BIOLOGY FOR THE TWENTY-FIRST CENTURY: OVERVIEW AND IMPLICATIONS FOR BIOLOGICAL RESEARCH

Biological research is in the midst of a revolutionary change due to the integration of powerful technologies along with new concepts and methods derived from inclusion of physical sciences, mathematics, computational sciences, and engineering. As never before, advances in biological sciences hold tremendous promise for surmounting many of the major challenges confronting the United States and the world. Historically, major advances in science have provided solutions to economic and social challenges. At the same time, those challenges have inspired science to focus its attention on critical needs. Scientific efforts based on meeting societal needs have laid the foundation for countless new products, industries, even entire economic sectors that were unimaginable when the work began . . .

. . . the essence of the New Biology is integration—reintegration of the many subdisciplines of biology, and the integration into biology of physicists, chemists, computer scientists, engineers, and mathematicians to create a research community with the capacity to tackle a broad range of scientific and societal problems. NRC (2009), p. viii

. . . the New Biology represents an additional, complementary approach to biological research. Purposefully organized around problem-solving, this approach marshals the basic research to advance fundamental understanding, brings together researchers with different expertise, develops the technologies required for the task and coordinates efforts to ensure that gaps are filled, problems solved, and resources brought to bear at the right time.

— NRC, 2009, p. 3

The committee⁴ that authored *A New Biology* (NRC, 2009; Figure 1) was asked by the National Institutes of Health, NSF, and the U.S. Department of Energy to undertake an appraisal of areas in which the life sciences are poised to make major advances and of how these advances could contribute to practical applications and improved environmental stewardship, human health, and quality of life. It also was asked to examine current trends toward integration and synthesis within the life sciences, the increasingly important role of interdisciplinary teams, and the resultant implications for funding strategies, decision making, infrastructure, and education in the life sciences.

⁴ A list of committee members and their institutional affiliations is available at http://books.nap.edu/openbook.php?record_id=12764&page=R5.

The report states that the life sciences face a moment of opportunity similar to that faced by physics in the twentieth century. The members of the committee identified four major areas of societal challenge where problem-focused research incorporating emerging theory, new technologies, fundamental findings from basic research in the life sciences, and integration into the life sciences of the physical sciences, mathematics, and engineering could enable biology to contribute to rapid progress in practical problem-solving. These broad areas, which are in fact interdependent and must be addressed in parallel, include the following:

- health, with an emphasis on developing the capacity to understand individual health at a level that allows prevention, diagnosis, and treatment to be based on each individual's unique genetic and environmental characteristics rather than statistical probability;
- environment, with an emphasis on developing the means to monitor, diagnose, and restore ecosystem function and biodiversity in the face of rapid environmental change;
- energy, with an emphasis on expanding sustainable alternatives to fossil fuels; and
- food, with an emphasis on developing the capability to adapt any crop plant to sustainable growth under any set of growing conditions. The new biology, if successful, would make it possible to more quickly and predictably breed food plants suitable for cultivation where they are most needed.

The committee envisioned the New Biology as a cycle encompassing four major components (Figure 2):

1. Integration of Scientific Information, Theory, Technologies, and Thinking about Complex Problems. As noted in Figure 2, biology is essential, but in its traditional form is insufficient to confront the key problems that must be addressed in the future. The physical sciences, mathematics, engineering, and information sciences all must be integrated with the traditional discipline to form the New Biology. Importantly, the committee emphasized that science education must be an integral input to this interdisciplinary approach to capacious problems. Science education itself also is envisioned as advancing as a result of the feedback loops that emerge from this integrated approach.
2. Deeper Understanding of Biological Systems. A deeper understanding of biological systems emerges from the multifaceted thinking of experts from a variety of disciplines. This deeper understanding will advance biology from an era of observation and mechanism to one of deciphering design principles for biological processes, making them accessible to manipulation and eventually predictable.
3. Biologically Based Solutions to Societal Problems. For societal problems that may be intractable by other approaches, the deeper understanding that results from the integrated and interdisciplinary collaborations driving the New Biology will allow more rapid progress on complex and interrelated challenges such as those in the areas of health, environment, energy, and food. In this context, the societal issues could be

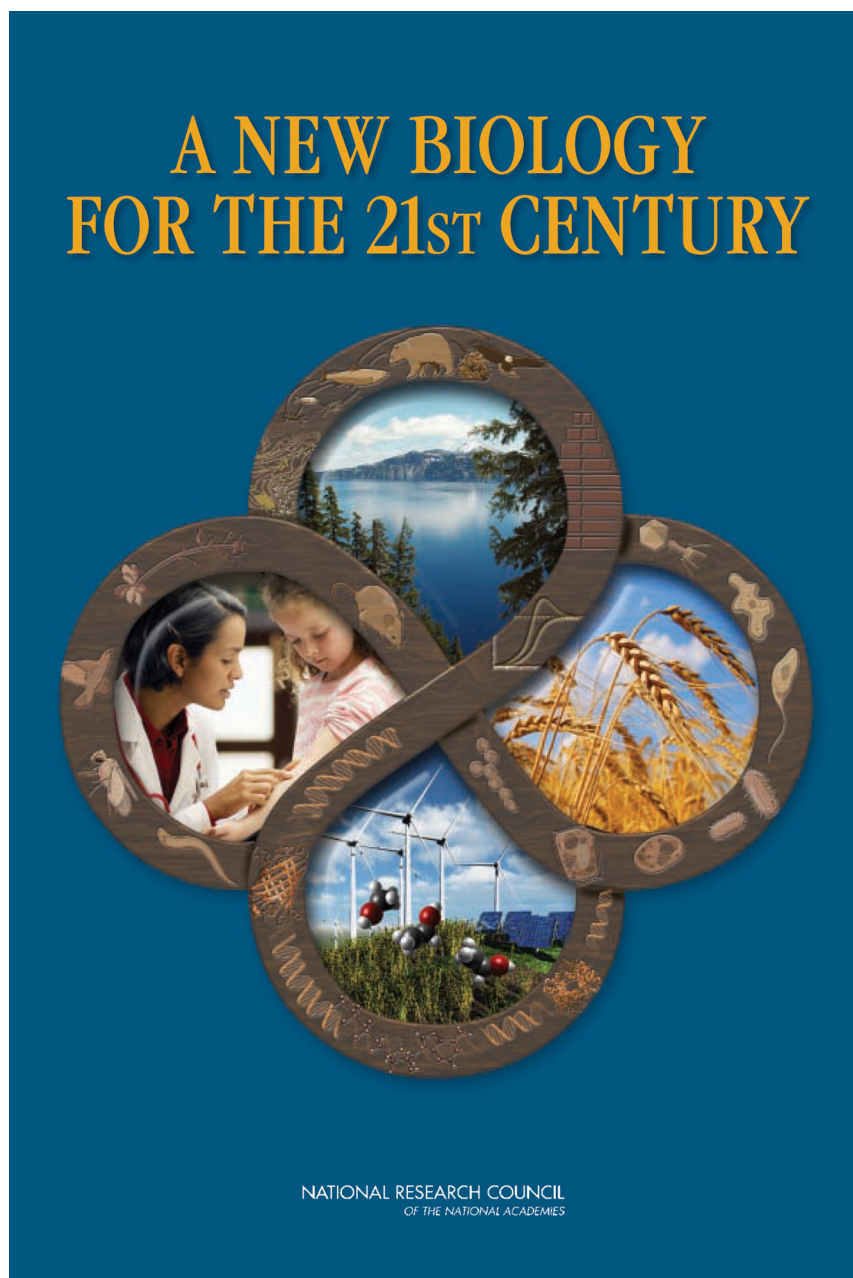


Figure 1. Report cover for *A New Biology for the 21st Century*.

considered as interactive drivers on a very large scale, spurring the development of enabling technologies and new discovery.

4. Feedback and Benefits to Contributing Disciplines and to Education. The collective, synergistic knowledge and thinking that emerge from integrated approaches to biological research and their applications to societal challenges will, in turn, inform and stimulate fundamental research across the scientific spectrum and in science education. If education tracks the projected trajectory of research that is encompassed by the New Biology, individual disciplines are also likely to con-

verge around the idea of integrated and interconnected science, technology, engineering, and mathematics (STEM) education.

A NEW BIOLOGY FOR THE TWENTY-FIRST CENTURY: OVERVIEW AND IMPLICATIONS FOR BIOLOGICAL EDUCATION

The committee observed that the New Biology presents unprecedented opportunities to draw attention to the excitement of biology but will require new ways of thinking about

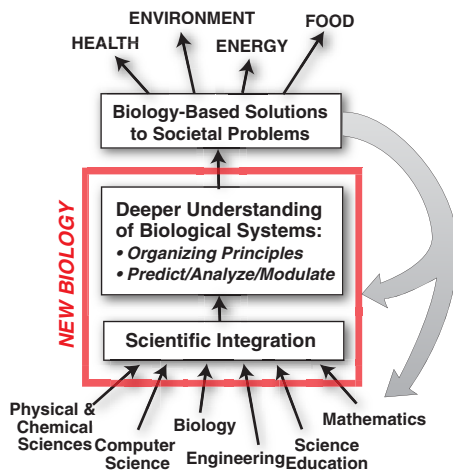


Figure 2. The inputs to and outcomes of a new integrated approach to biological research in the twenty-first century (NRC, 2009, p. 18).

how to attract, educate, and retain undergraduates as detailed below.

The New Biology Initiative Provides an Opportunity to Attract Students to Science Who Want to Solve Real-World Problems

This approach may be especially attractive to those students who would otherwise become disenfranchised from science through traditional approaches to teaching and learning. Emerging research is demonstrating that allowing students to make connections between the science they study and the problems that they, their families, and their communities face can encourage greater interest in science as well as the motivation to learn scientific concepts more deeply (NRC, 2000b; Hulleman and Harackiewicz, 2009).

The New Biologist Is Not a Scientist Who Knows a Little about All Disciplines, but One with Deep Knowledge in One Discipline and a “Working Fluency” in Several

Although this vision of scientists who participate in the New Biology may seem to support the current structure of science majors, it actually would require very different thinking about how scientists are educated. Solving complex, interdisciplinary problems will require that students go far beyond their life science majors both in understanding what connections exist across disciplines and how to make those connections. Requiring separate courses in other natural and behavioral sciences with no attempt to help students make specific connections among them will probably be insufficient. Preparing future life scientists without offering them exposure to and experience with engineering, design, computer science, and an appreciation of the broader connections between science and technology (NRC, 1998, 2003; National Academy of Engineering, 2002, 2007, 2009) will not constitute adequate preparation. And mere exposure (by requiring students to

take courses in these other areas) most likely will not prepare them to make and understand the connections among these disciplines; specific efforts must be made to help students learn these skills (NRC, 2000b).

Highly Developed Quantitative Skills Will Be Increasingly Important

Mathematics and other quantitative tools are becoming increasingly important to the work of biologists and to the advancement of the field, and these areas need to become a larger part of undergraduate biology education (NRC, 2003a; Bialek and Botstein, 2004⁵; Brent, 2004; Cohen, 2004; Hoy, 2004; Gross, 2004; Steen, 2005). However, there are many structural and systemic impediments that limit true integration of mathematics and quantitative literacy into undergraduate biology education. These include lack of communication between biology and mathematics departments to better integrate mathematical concepts and examples into biology courses and more appropriate examples involving biology in mathematics courses in which biology majors enroll. There are also persistent misperceptions about the kinds of mathematics that are required to prepare pre-medical students for the Medical College Admission Test (currently none are specifically required⁶) or for entrance to medical schools (requirements vary widely from urging preparation in mathematics, to one or two semesters of calculus or to algebra or statistics⁷). The recent report from the Association of American Medical Colleges and HHMI (2009) recommends that students should be able to “Apply quantitative reasoning and appropriate mathematics to describe or explain phenomena in the natural world.” (p. 22). This competency could be demonstrated by students who are able to

- demonstrate quantitative numeracy and facility with the language of mathematics,
- interpret data sets and communicate those interpretations using visual and other appropriate tools,
- make statistical inferences from data sets,
- extract relevant information from large data sets,
- make inferences about natural phenomena using mathematical models,
- apply algorithmic approaches and principles of logic (including the distinction between cause/effect and association) to problem-solving,
- quantify and interpret changes in dynamical systems (pp. 22–24).

⁵ This editorial is part of a special issue of *Science* on “Mathematics in Biology.” All relevant papers in this issue are available through links at www.sciencemag.org/sciext/mathbio.

⁶ According to the Association of American Medical Colleges, “The Medical College Admission Test (MCAT) is a standardized, multiple-choice examination designed to assess the examinee’s problem solving, critical thinking, writing skills, and knowledge of science concepts and principles prerequisite to the study of medicine. Scores are reported in Verbal Reasoning, Physical Sciences, Writing Sample, and Biological Sciences. Medical colleges consider MCAT exam scores as part of their admission process.” See www.aamc.org/students/mcat/about/start.htm.

⁷ For a listing of entry requirements in mathematics for medical schools in the United States, see www.cse.emory.edu/sciencenet/additional_math_reqs.pdf.

New thinking about ways to integrate and connect these two disciplines can serve as the basis for departments of biology and mathematics, and for professional societies in these disciplines, to work together toward the improvement of undergraduate education as envisioned by the *New Biology*.

Development and Implementation of Genuinely Interdisciplinary Undergraduate Courses and Curricula Will Both Prepare Students for Careers as New Biology Researchers and Educate a New Generation of Science Teachers Who Will Be Well Versed in New Biology Approaches

The preparation of future science teachers must become a joint responsibility between faculties in science departments and schools of education (NRC, 1998, 2000a, 2003a). Templates and syllabi for interdisciplinary undergraduate courses that would benefit teachers of science (especially those in the elementary and middle grades) have been published.⁸ But science, mathematics, and engineering faculty and academic leaders in higher education must recognize their roles in preparing future teachers as well as future researchers. Consideration must be given to what undergraduates will need to learn to teach science in the way envisioned in *A New Biology*, both with respect to the necessary scientific knowledge base and to familiarity with scientifically based pedagogical techniques that are most effective in teaching science.

Similar attention needs to be paid to preparing graduate students to become the next generation of faculty who will, in turn, assume some of the responsibility for K–12 teacher preparation. Are graduate students being encouraged to pursue quality teaching experiences? Are they being provided with training in new approaches to teaching and learning and exposure to the research literature about human learning and cognition as part of that preparation?

What characteristics might undergraduate courses have that emphasize an interdisciplinary approach as envisioned in *A New Biology*? The report provides an example of introductory courses at Harvard University (see Box 2). Additional models are offered by SENCER (see footnote 9) and include courses with biological emphases such as

- Cellular and Molecular Biology: Cancer
- Life Science in Context: SubSaharan Africa & HIV/AIDS
- The Science of Sleep
- Slow Food
- Addiction: Biology, Psychology, and Society
- Environment and Disease
- Nutrition & Wellness and the Iowa Environment
- Human Genetics
- Tuberculosis
- Biomedical Issues of HIV/AIDS
- Mysteries of Migration

⁸ For example, model courses have been developed with support from the NSF as part of the Science Education for New Civic Engagements and Responsibilities (SENCER); see www.sencer.net/Resources/models.cfm and the Mathematics/Science Partnerships (see <http://mspnet.org>) initiatives.

Box 1: Connecting *Bio 101* to Real-World Issues: An Interdisciplinary Approach

In 2005–2006, Harvard University launched two semester-long introductory courses that provide an interdisciplinary introduction to biology and chemistry. The first course synthesizes essential topics in chemistry, molecular biology, and cell biology, and the second course synthesizes essential topics in genetics, genomics, probability, and evolutionary biology. Scientific facts and concepts are introduced in the context of exciting and interdisciplinary questions, such as understanding the possibility of synthetic life, the biology and treatment of AIDS and cancer, human population genetics, and malaria. Through interdisciplinary teaching, students' grasp of fundamental concepts is reinforced as they encounter the same principles in multiple situations. Each course is taught by a small team of faculty from multiple departments. Members of each teaching team attend all lectures and participate for the entire term. The preparation for and teaching effort in each course offering is integrated. Teaching assistants are also drawn from different departments and work in small interdepartmental teams.

Development of these courses required institutional support. The president, dean of the faculty, and the chair of the life sciences council all provided funds to support a one-year curriculum development effort, lab renovations, lower teaching fellow-student ratios, equipment, and development of teaching materials. One of the founding faculty member's HHMI undergraduate education award contributed to developing specific sets of teaching materials.

Success depended on finding faculty members with personal commitments to the principles of the courses and willingness to work as a team to build the new courses from scratch. This effort was rewarded as individual departments agreed to count these interdepartmental and interdisciplinary courses toward their respective departmental teaching expectations.

Since the courses were implemented, undergraduate enrollment in introductory life sciences courses is up >30% and the number of life sciences majors has risen 18%. NRC (2009) p. 80

The life sciences and science education communities have made significant advances in articulating how undergraduate biology education can be made accessible to more students with varying education needs and learning styles. The beginnings of real consensus about the future course for life sciences education is emerging. As the year 2010 opens, the ideas for "transforming undergraduate education for future research biologists" that were envisioned in the *Bio 2010* report are being considered more seriously and implemented more widely than many had imagined when the report was published in 2003 (e.g., Pfund *et al.*, 2009). The *New Biology* report emphasized the ongoing and lasting relevance of *Bio 2010* but also noted the incomplete implementation of its recommendations to date. Much work remains.

The findings and recommendations that emerged in 2009 again offer a collective and coherent vision for improving undergraduate science education in general, and biology education specifically. As a community, we must work toward implementation of the visions articulated in *A New Biology* and other recent initiatives, scaled to encompass all areas of biology and all undergraduates who enroll in biology courses and programs.

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