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Pre-publication copy

BIO2010:

Undergraduate Education to Prepare Biomedical Research Scientists

Committee on Undergraduate Biology Education to Prepare Research Scientists for the 21st Century

Board on Life Sciences
Division on Earth and Life Studies

This pre-publication version of the report has been provided to the public to facilitate timely access to the committee's findings. Although the substance of the report is final, editorial changes may be made prior to publication. The final report will be available through the National Academies Press later this year.

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Committee on Undergraduate Biology Education to Prepare Research Scientists for the 21st Century, Board on Life Sciences, National Research Council

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EXECUTIVE SUMMARY

The interplay of the recombinant DNA, instrumentation, and digital revolutions has profoundly transformed biological research. The confluence of these three innovations has led to important discoveries, such as the mapping of the human genome. How biologists design, perform, and analyze experiments is changing swiftly. Biological concepts and models are becoming more quantitative, and biological research has become critically dependent on concepts and methods drawn from other scientific disciplines. The connections between the biological sciences and the physical sciences, mathematics, and computer science are rapidly becoming deeper and more extensive. The ways that scientists communicate, interact, and collaborate are undergoing equally rapid and dramatic transformations, which are driven by the accessibility of vast computing power and facile information exchange over the Internet.

In contrast to biological research, undergraduate biology education has changed relatively little during the past two decades. The ways in which most future research biologists are educated are geared to the biology of the past, rather than to the biology of the present or future. Like research in the life sciences, undergraduate education must be transformed to prepare students effectively for the biology that lies ahead. Life sciences majors must acquire a much stronger foundation in the physical sciences (chemistry and physics) and mathematics than they now get. Connections between biology and the other scientific disciplines need to be developed and reinforced so that interdisciplinary thinking and work become second nature. Connections within biology are equally important and the relevance of fields such as population biology, plant biology, and cognitive science to biomedical research should not be ignored. Equally important, teaching and learning must be made more active to engage undergraduates, fully prepare them for graduate study, and give them an enduring sense of the power and beauty of creative inquiry. In light of these realities, this report describes changes in undergraduate education designed to improve the preparation of students in the life sciences, with a particular emphasis on the education that will be needed in the future for careers in biomedical research.

The Report

This study was conducted at the initiative of its sponsors, the National Institutes of Health (NIH) and the Howard Hughes Medical Institute (HHMI). Both sponsors support numerous diverse projects in biomedical research. They view future research as increasingly interdisciplinary and believe that exposing today's undergraduates to a more interdisciplinary curriculum will help them to better collaborate with their scientific peers in other disciplines as well as to design more interdisciplinary projects on their own. The National Research Council (NRC) convened the Committee on Undergraduate Biology Education to Prepare Research Scientists for the 21st Century to prepare a report addressing issues related to undergraduate education of future biomedical researchers. The committee was charged with examining the formal undergraduate education, training, and experience required to prepare the next generation of life science majors, with a particular emphasis on the preparation of students for careers in biomedical research. One goal of the project was to identify the basic skills and concepts of

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mathematics, chemistry, physics, computer science, and engineering that can assist students in making novel interdisciplinary connections. The complete formal charge to the committee can be found in Appendix A.

Conclusions

To successfully undertake careers in research after graduation, students will need scientific knowledge, practice with experimental design, quantitative abilities, and communication skills. While this study was conducted to consider what is appropriate for the education of future biomedical researchers, the committee recognizes that students with many other career goals will take the same courses and believes that many of the ideas for increasing the interdisciplinary nature of coursework would be equally beneficial for all students. Colleges and universities should reexamine current curricula in light of changing practices in biological research. In addition, faculty should attempt to utilize teaching approaches that are most likely to help students learn these skills. For example, independent or group projects (both library- and laboratory-based) are likely to help foster a sense of ownership by students, which may in turn encourage them to take the initiative to investigate a topic in detail. Presenting examples of current research to show that science consists of unanswered questions will also intrigue and inspire more students to probe problems in depth. It is important for these efforts to start at the very beginning of a student's education in the K-12 years, and for them to be continued and enhanced in the first year of college. (Some ideas for providing this exposure to high school students can be found in a recent NRC report on advanced placement and international baccalaureate courses [NRC, 2002] and in an earlier NRC report, *Transforming Undergraduate Education in Science, Mathematics, Engineering, and Technology* [NRC, 1999b].) Offering exciting introductory courses will help attract more students to enroll in biology courses, increasing the number who might consider biomedical research as a career. Increasing the number of students who consider biology as a major may increase the quality of future biomedical researchers.

Courses

Many science and mathematics courses are taught as sets of facts, rather than by explaining how the material was discovered or developed over time. Covering the history of the field, demonstrating the process of discovery, or presenting other stories as examples of how scientists work--while clearly illustrating why the knowledge that has been gained is relevant to the lives and surroundings of the students—is an excellent way to engage undergraduates. The committee believes that success of a future biomedical researcher requires not just expertise in the specific biological system under study, but a conceptual understanding of the science of life and where a specific research topic fits into the overall picture. Teaching undergraduates about the many different ways in which biologists approach research, including lab work, fieldwork, and computer modeling, will help them to understand the unifying themes that tie together the diverse kinds of life on earth. Much of today's biomedical research is at the interface between biology and the physical, mathematical, or information sciences. Most colleges and universities already require their biology majors to enroll in courses in mathematics and physical science.

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However, faculty often do not integrate these subjects into the biology courses they teach. This can result in students with a shortsighted view of the connections between all the scientific disciplines involved in the study of the biological world, and produce students who do not see the relevance of their other science courses to their chosen field of study.

Laboratory Experience

Independent work, both inside and outside the classroom, is a wonderful way to expose students to the world of science. Class projects can provide opportunities for students to analyze original data, experience teamwork, and practice scientific writing and presentation skills. Independent research gives students a real worldview of life as a researcher. Colleges and universities should provide all students with opportunities to become engaged in research, whether that be in an on-campus independent research experience with faculty; an internship at nearby institutions (biotechnology or pharmaceutical companies, national laboratories, government agencies, independent research centers, or other academic institutions); or through an extended research-based project in a course and/or laboratory.

Quantitative Skills

The lack of a quantitative viewpoint in biology courses can result in students who are mathematically talented losing interest in studying the life sciences. While not all students who pursue an education in the biomedical sciences have an equal interest or predilection for mathematics, it is important that all students understand the growing relevance of quantitative science in addressing life-science questions. Thus, a better integration of quantitative applications in biology would not only enhance life science education for all students, but also decrease the chances that mathematically talented students would reject life sciences as too soft. Similar consideration must be given to the integration of physics and chemistry into a life science curriculum. In biomedical research today, complex questions are usually addressed by teams of scientists that bring different perspectives and insights to the issues being studied. Many of today's top biomedical researchers came to their work after undergraduate or graduate education in another field, most notably physics and/or chemistry. However, there is often a profound communication barrier between these researchers and those educated as biologists. Increasing the amount of mathematics and of physical and information sciences taught to new biology students, and the opportunity for physical science majors to take courses with biological content, would improve the possibilities for productive collaborations.

Mathematics teaching presents a special case. Most biology majors take no more than one year of calculus, although some also take an additional semester of statistics. Very few are exposed to discrete mathematics, linear algebra, probability, and modeling topics, which could greatly enhance their future research careers. These are often considered advanced courses; however, many aspects of discrete math or linear algebra that would be relevant to biology students do not require calculus as a prerequisite. While calculus remains an important topic for future biologists, the committee does not believe biology students should study calculus to the exclusion of other types of mathematics. Newly designed courses in mathematics that cover

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some calculus as well as the other types of math mentioned above would be suitable for biology majors and would also prove useful to students enrolled in many other undergraduate majors.

Role of Medical School Requirements

Another special issue is the impact of medical school admissions requirements on undergraduate biology curriculum. The committee did not specifically address the needs of premedical students in making its recommendations. However, the committee recognizes that specific courses are currently required for medical school admission and that the need to prepare students for the Medical College Admissions Test (MCAT) constrains course offerings and content at most institutions. Departments of physics, chemistry, and mathematics, as well as departments of biology, feel pressure to cover the material tested on the MCAT in their introductory courses to the exclusion of other potential topics.

Implementation

Incorporating mathematics, physical science, and emerging fields such as the information sciences into a biology curriculum is not easy, especially for faculty who do not consider themselves well versed in those topics. One way to start is to add modules into existing biology courses. Throughout this report, modules are mentioned as a way to modify courses without completely revamping the syllabus. The committee uses the word "module" to mean a self-contained set of material on a specific topic that could be inserted into various different types of preexisting courses. For example, modules can provide opportunities to add quantitative examples or experimental data to a course. The modules would demonstrate the necessity of using mathematics and physical and information sciences to solve biological problems. Administrators, funding agencies, and professional societies should all work to encourage the collaboration of faculty in different departments and the development of teaching materials, including modules of the type mentioned above, that incorporate mathematics, physical science, or information science into the teaching of biology. The creation of new teaching materials is a significant undertaking. It will require a major commitment from college and university administrators and funders to be successful. Faculty must feel encouraged to spend the time necessary to dedicate themselves to the task of understanding the integrative relationships of biology, mathematics, and the physical sciences, and how they can be combined into either existing courses or new courses. In addition, faculty development opportunities must be provided so that faculty can learn from each other and from experts in education about the best approaches for facilitating student learning.

The following box presents a summary of the most important recommendations in this report. Throughout the text of the report, other recommendations are made and other ideas are presented. Not all of the ideas presented here are proven approaches. In any new educational effort it is important to define goals and create an assessment plan to determine if the student learning goals are being met. The committee believes that the general recommendations presented here are appropriate for all institutions, while recognizing that not all institutions will use the same mechanisms to achieve these goals. The specific mechanisms appropriate for each

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individual institution of higher education will depend on the skills and interests of both their students and their faculty. This report presents numerous ideas in the belief that each institution will identify for itself the most relevant options. The recommendations that follow are directed at the next generation of life science majors, particularly those preparing for careers in biomedical research.

Recommendations

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. (pages 21, 24, 26, 28, 30, and 31)

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. (page 37)

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. (page 47)

4. Laboratory courses should be as interdisciplinary as possible, since laboratory experiments confront students with real-world observations do not separate well into conventional disciplines. (page 59)

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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. (page 69)

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. (page 73)

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. (page 87)

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. (page 88)

The ideas presented here for transforming the undergraduate education of life science majors are demanding, but the committee believes that significant change is realizable within this decade if these recommendations are acted upon. Reform will require concerted action by faculty, administrators, professional societies and other educational organizations, foundations, industry, and government. The process begins with faculty and administrators. The committee urges each academic institution to critically review how it educates its future biologists. Departmental retreats are a good setting for an initial examination of current educational objectives, practices, and outcomes. The circle should eventually be broadened by inviting faculty from different departments to come together with administrators and discuss aspirations and goals for the coming decade. The resources needed to effect these changes must be clearly defined and a realistic path must be charted to complete the planning stage. University administrators will need to actively support faculty development and remove barriers to interdisciplinary teaching, a key aspect of enhancing undergraduate education. Departments and colleges must find new ways to help individual faculty and academic departments innovate and reward their efforts in creating, assessing, and sustaining new educational programs. For example, faculty interested in adapting teaching approaches for their own use or in creating new teaching materials should have lighter than normal requirements for teaching, research, or service while actively engaged in such projects. Also, travel funds earmarked especially for faculty development or education meetings should be provided to enable faculty to participate in meetings that enhance their teaching capabilities. These funds must be targeted towards faculty who are specifically seeking to build and sustain high-quality programs that can be assessed and demonstrated as effective.