SCIENCE EDUCATION

Educating Future Scientists

Nancy S. Sung,[1] Jeffrey I. Gordon,[2] George D. Rose,[3] Elizabeth D. Getzoff,[4] Stephen J. Kron,[5] David Mumford,[6] José N. Onuchic,[7] Norbert F. Scherer,[8] DeWitt L. Sumners,[9] Nancy J. Kopell[10]*

The most exciting science in the 21st century is likely to evolve among, not within, traditional disciplines. Physical scientists, mathematicians, and engineers, concerned with understanding and designing complex systems, can offer invaluable viewpoints and approaches to biologists. Conversely, biological systems provide new challenges for mathematics and physics, and they catalyze technology development in engineering and computer science. Yet the education of scientists has historically been constrained by disciplines, paralleling patterns of science funding.

Enhanced online at www.sciencemag.org/cgi/content/full/301/5639/1485

Lately, most research universities have softened disciplinary boundaries by creating multidepartmental graduate programs in biomedical science. Authentic interdisciplinary programs that reach beyond the biomedical sciences are still rare, however, and they present new challenges. When physical science and mathematics departments recruit bright students to serve as teaching or research assistants, they are not always eager to relinquish them to courses and laboratories in biomedical departments. Furthermore, there is strong economic pressure for graduate students to complete coursework quickly and to move into a laboratory, where, typically, they work on a specific project funded by a mentor's research grants. The need to produce results to ensure renewal of these grants constrains the trainees' freedom to take courses in other departments or to explore novel questions in the laboratory. Young, pretenure faculty may not receive credit for developing or teaching innovative interdisciplinary courses, or permission to substitute such teaching efforts for standard ones. Training funds that reward cooperation across traditional academic boundaries can provide freedom and incentive.

The cultural barriers are at least as great as the institutional barriers. A scientific language, approach, and training style are passed from mentor to student within disciplines, like a tribal culture. By the time a Ph.D. is earned, formerly undifferentiated students may have lost the plasticity to develop a deep appreciation of the insights and approaches of other disciplines. Hence, the Burroughs Wellcome Fund (BWF) in 1996 began supporting a series of "social experiments" to take students and fellows with backgrounds in the physical, computational, or mathematical sciences and to educate them to tackle biological questions. Ten programs were funded over three cycles of grant awards (*1*). Although the career outcomes of the program participants will take years to emerge, a few principles are already clear.

Since 1996, pre- and postdoctoral fellows in the multi-institutional La Jolla Interfaces in Science program have had to propose research projects that require the participation of two mentors—one from the quantitative sciences and one from the biological sciences—before being awarded financial support. Participation in two group meetings has proven more effective than coursework at assuring immersion of the fellows in the culture, language, technology, and literature of two scientific disciplines, as well as familiarity with the key players in two fields. A similar strategy was used by the University of Chicago's Institute for Biophysical Dynamics when faced with the opportunity afforded by construction of a $200M interdisciplinary research building.

In both programs, shared trainees are the catalysts bringing research groups together. Because trainees are funded from nondepartmental sources, barriers for mentor participation are lower. Another advantage for faculty is the enhanced probability that new areas of research will be established and perpetuated. The fellow provides the necessary link; thereafter, the active involvement of faculty from different disciplines contributes to institutional change, and their collaboration will likely outlive the trainee's tenure. BWF now recommends that all programs it supports implement dual mentorship.

The interdisciplinary culture should be as influential in the lives of the young scientists as their primary departments. Directors of the Program in Mathematical and Computational Neuroscience at Boston University created a new "interdisciplinary" structure using elements of three preexisting interdisciplinary programs within the university. The founding faculty were members of collaborative networks across departments, with a demonstrated commitment to interdisciplinary education. All community-building need not occur within one institution, however. The Program in Mathematics and Molecular Biology (PMMB), funded since 1987 by both the National Science Foundation and BWF, is based at Florida State University but supports fellows at 15 institutions nationwide. These and nascent scientific communities in other BWF programs have grown stronger through the use of BWF funds for Internet resources, retreats, symposia, and social events designed to "enculturate" trainees.

Another community-building method, tried by the BWF Brain Science program at Brown University, was the adaptation of courses to integrate theory and application. As a result, mathematicians were trained to appreciate biological questions, and biologists were better prepared to communicate with mathematicians. Our intent is not to turn all scientists into biologists, rather to encourage development of new directions in physics and mathematics based on the increasingly rich data emerging in biology. To move beyond supplying "technical help" to biologists, we believe that physical, theoretical, and computational scientists need to immerse themselves in biology and to revel a bit in all the mess. Otherwise, they will not be prepared to distinguish important questions from trivial ones.

Bright young scientists will gravitate toward the rich scientific opportunities at disciplinary boundaries, but must cross current institutional and cultural barriers that are neither trivial nor intransigent. Providing scientific trainees with effective preparation to capitalize on these opportunities will depend on the adaptability of their mentors, their institutions, and the funding agencies that support their education and research (*2*).

[1]The Burroughs Wellcome Fund, Research Triangle Park, NC 27709; [2]Department of Molecular Biology and Pharmacology, Washington University School of Medicine, St. Louis, MO 63110; [3]Department of Biophysics, Johns Hopkins University, Baltimore, MD 21218; [4]Department of Molecular Biology, the Scripps Research Institute, La Jolla, CA 92037; [5]Department of Molecular Genetics and Cell Biology, and [6]Department of Chemistry, University of Chicago, Chicago, IL 60637; [7]Division of Applied Mathematics, Brown University, Providence, RI 02912; [8]Department of Physics, University of California–San Diego, La Jolla, CA 92093; [9]Department of Mathematics, Florida State University, Tallahassee, FL 32306; and [10]Department of Mathematics and Statistics, Boston University, Boston, MA 02215, USA.

*To whom correspondence should be addressed. E-mail: nk@bu.edu

References and Notes

1. www.bwfund.org/programs/interfaces/institutional_grant_recipients.html
2. See supporting online material for specific recommendations.
3. The authors thank Q. Bond for helpful comments.

Supporting Online Material
www.sciencemag.org/cgi/content/full/301/5639/1485/DC1

doi: t10.1126/science.10866133

Supporting Online Material for Sung *et al*.

Steps to Promote Cultural Change at the Level of the Mentor, the Institution, and the Funding Agency

1. Just as science evolves, so must the role of the mentor. To facilitate the development of students, mentors must be willing to:

- Share students with faculty from other disciplines.
- Encourage the acquisition of skills that they may not themselves possess.
- Take on the intellectually difficult task of evaluating progress of shared students in areas in which they have not themselves been trained.
- Learn to understand and address the distinct career concerns of "hybrid" trainees.

2. To foster environments and set up educational systems that prepare young scientists to think and ask new questions, institutions must

- Recognize that pressure to maintain traditional standards in departments works against the creation of new more appropriate standards for interdisciplinary scientists and will keep those departments out of the future scientific mainstream.
- Provide a mechanism for dual mentoring of students across departmental and disciplinary lines.
- Provide needed release time for faculty who engage in cross-departmental collaboration, cross-disciplinary curriculum development, and sharing of trainees, and value such activities in tenure review.
- Recognize and foster the development of indigenous scientific communities that cross disciplinary lines.
- Support changes in physical plant that will reduce departmental and disciplinary barriers.

3. To promote cultural change within institutions, funding agencies must

- Provide incentives in the form of grants, to both individuals and institutions that require cross-departmental collaboration.
- Require substantive, but not necessarily local, dual mentoring of all trainees named on "interdisciplinary" training grants.
- Recommend laboratory rotations for all trainees from computational and theoretical backgrounds who wish to address biological questions.
- Require tracking of career outcomes in evaluation of interdisciplinary training grants.
- Allow flexibility in the use of training funds to allow adequate support for trainee-centered convening activities that build community.
- Experiment with nontraditional models for training and expect evolution of the program during the award term.
- Facilitate early independence of young scientists by providing more individual, portable fellowships.