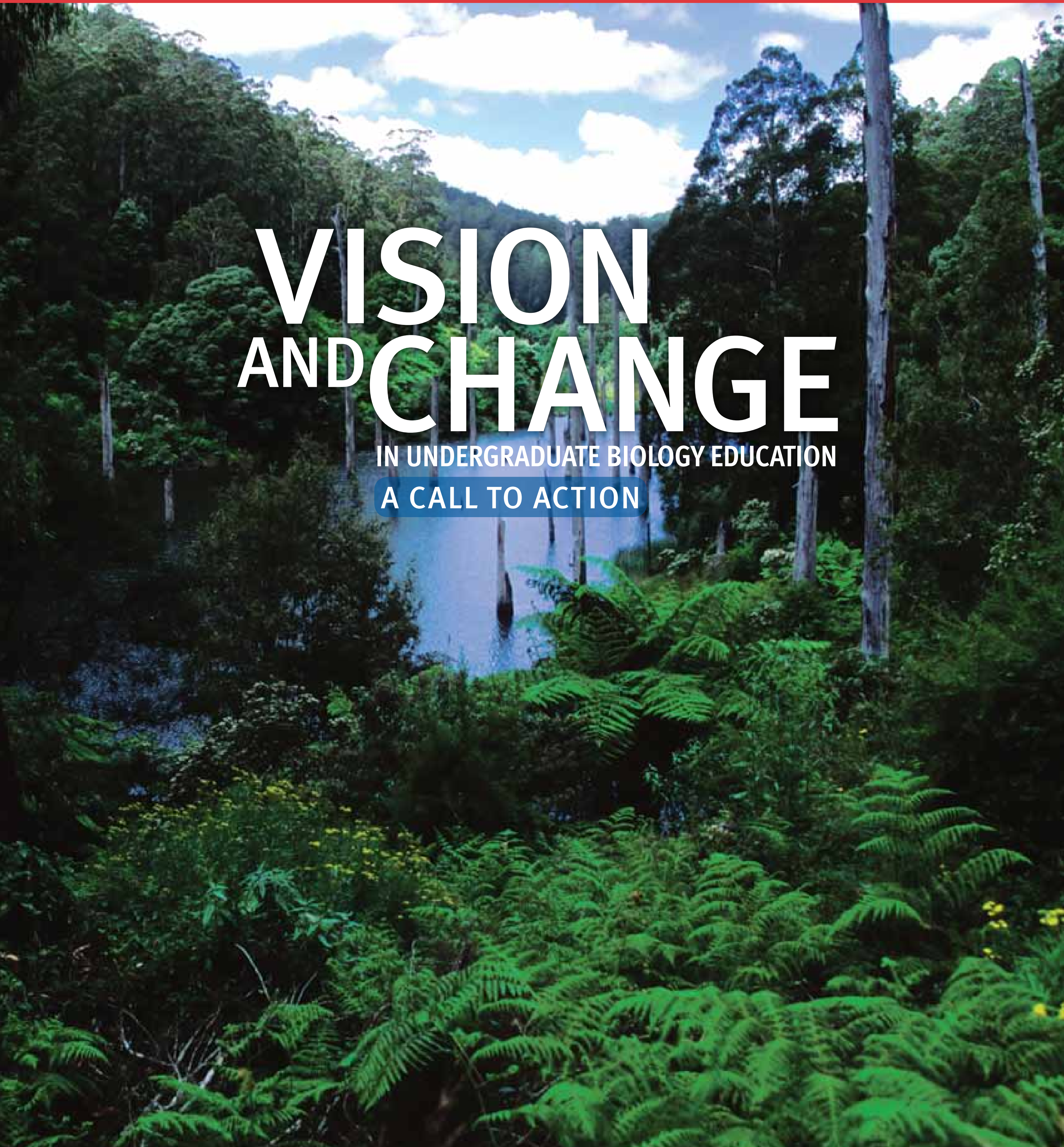

VISION AND CHANGE

IN UNDERGRADUATE BIOLOGY EDUCATION

A CALL TO ACTION

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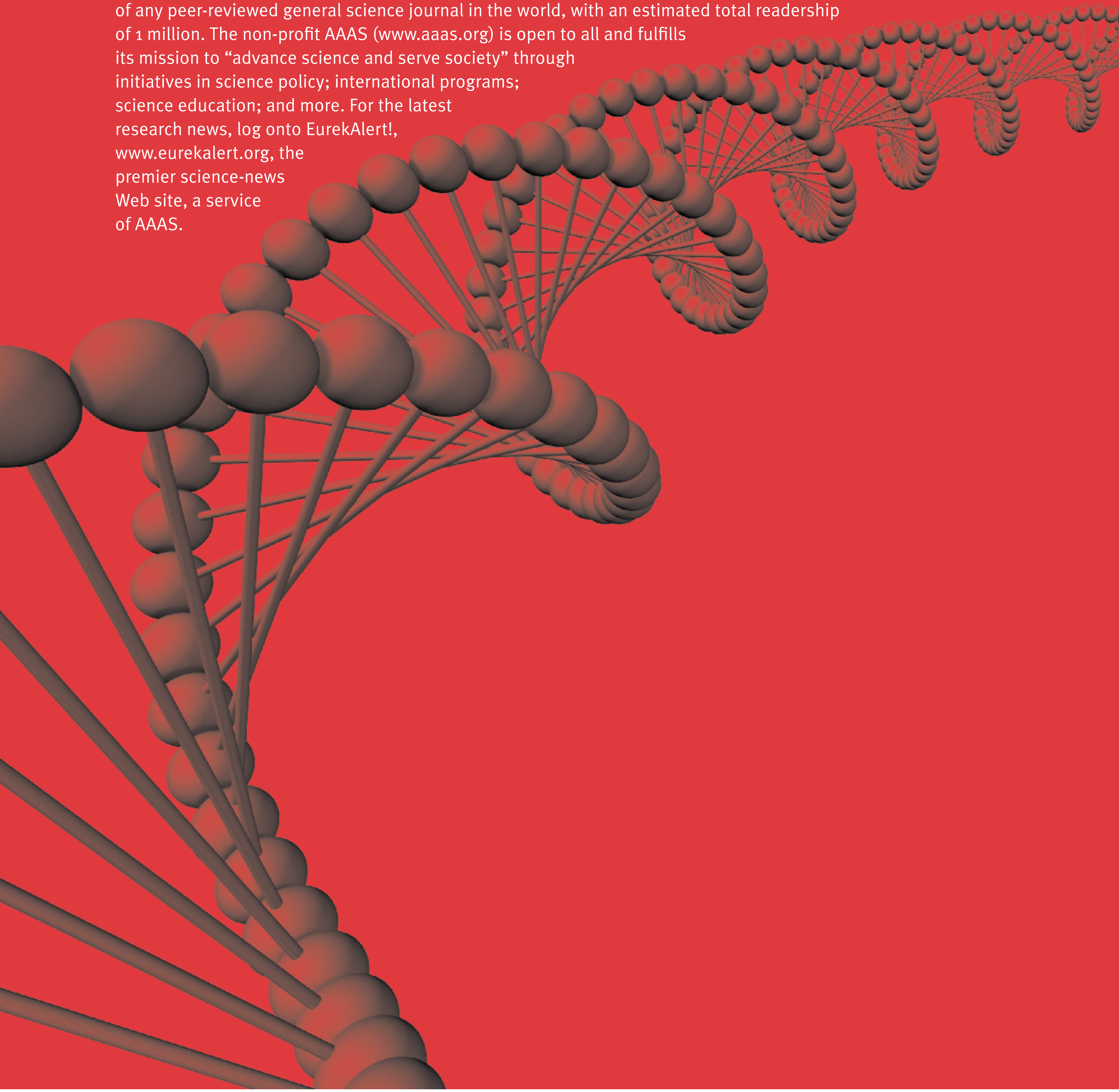
The American Association for the Advancement of Science (AAAS) is the world's largest general scientific society, and publisher of the journal, *Science* (www.sciencemag.org) as well as *Science Translational Medicine* (www.sciencetranslationalmedicine.org) and *Science Signaling* (www.sciencesignaling.org). AAAS was founded in 1848, and includes some 262 affiliated societies and academies of science, serving 10 million individuals. *Science* has the largest paid circulation of any peer-reviewed general science journal in the world, with an estimated total readership of 1 million. The non-profit AAAS (www.aaas.org) is open to all and fulfills its mission to "advance science and serve society" through initiatives in science policy; international programs; science education; and more. For the latest research news, log onto EurekAlert!, www.eurekalert.org, the premier science-news Web site, a service of AAAS.



VISION AND CHANGE

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FINAL REPORT OF A NATIONAL CONFERENCE
ORGANIZED BY THE

AMERICAN ASSOCIATION FOR THE
ADVANCEMENT OF SCIENCE

WITH SUPPORT FROM THE
NATIONAL SCIENCE FOUNDATION
Directorate for Education and Human Resources
Division of Undergraduate Education
and the
Directorate for Biological Sciences

July 15–17, 2009
Washington, DC

For more information on the AAAS Vision and Change in Undergraduate Biology Education Initiative, see http://www.visionandchange.org/.

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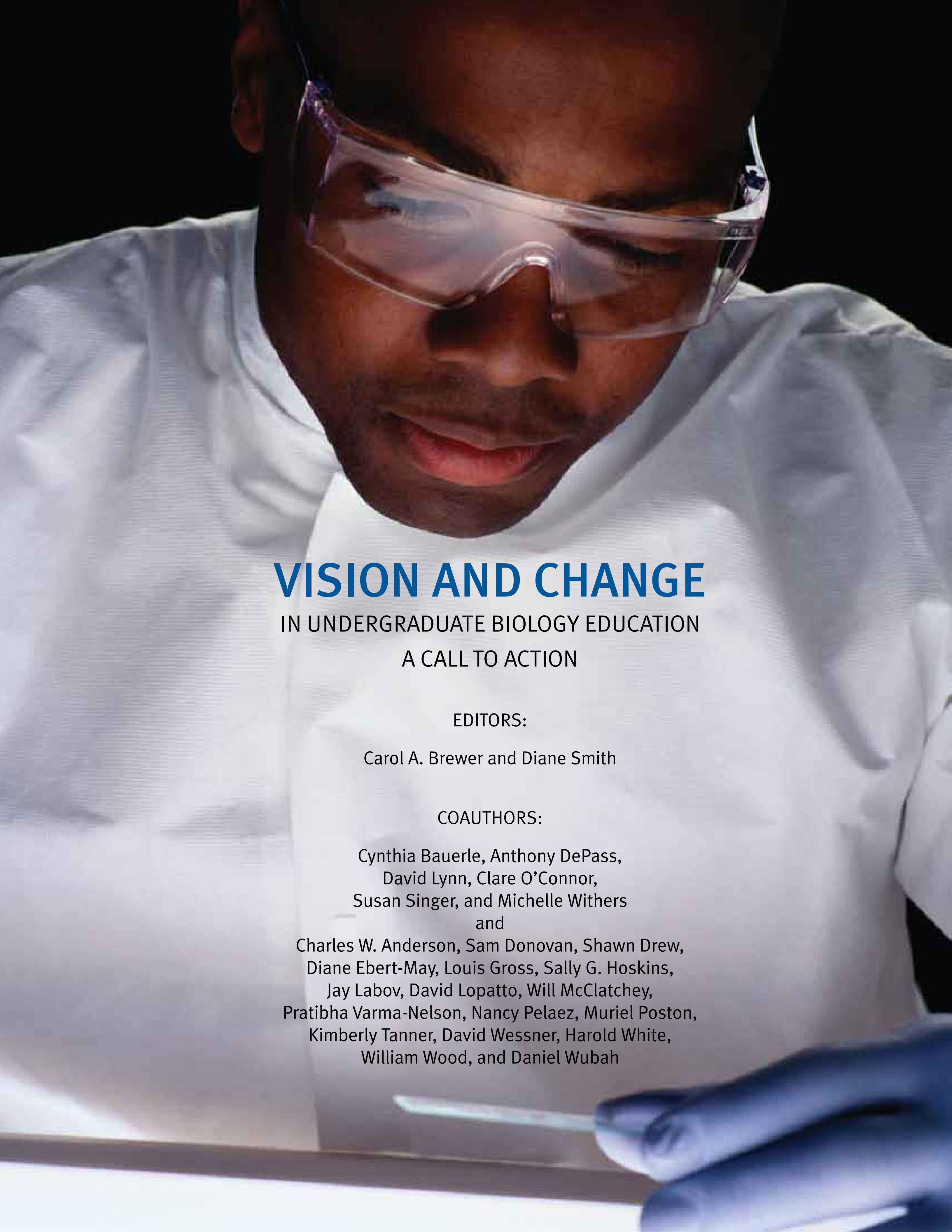

VISION AND CHANGE

IN UNDERGRADUATE BIOLOGY EDUCATION

A CALL TO ACTION

EDITORS:

Carol A. Brewer and Diane Smith

COAUTHORS:

Cynthia Bauerle, Anthony DePass,
David Lynn, Clare O'Connor,
Susan Singer, and Michelle Withers
and
Charles W. Anderson, Sam Donovan, Shawn Drew,
Diane Ebert-May, Louis Gross, Sally G. Hoskins,
Jay Labov, David Lopatto, Will McClatchey,
Pratibha Varma-Nelson, Nancy Pelaez, Muriel Poston,
Kimberly Tanner, David Wessner, Harold White,
William Wood, and Daniel Wubah

CONTRIBUTING AUTHORS

EDITORS: Carol Brewer and Diane Smith

TOPICAL AREAS

(name in ***bold italics*** signifies topical area lead)

Cultivating Scientific Thinking

Clare O'Connor
Michelle Withers
Sam Donovan
Sally G. Hoskins
David Lopatto
Pratibha Varma-Nelson
Harold White

Concepts and Competencies

Cynthia Bauerle
Louis Gross
Jay Labov
Muriel Poston
David Wessner

Implementing Change

David Lynn
Shawn Drew
Kimberly Tanner
William Wood

Assessment

Anthony DePass
Charles A. Anderson
Diane Ebert-May
Will McClatchey
Nancy Pelaez
Daniel Wubah

Strategies and Tools for Change

Susan Singer
Jay Labov

Vision and Change Student Conversations organized and recorded by
Catherine Fry and
Marsha Matyas

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Robert S. Seville, Associate Dean in the Outreach School and Associate Professor of Zoology and Physiology, University of Wyoming

Daniel Udovic, Professor Emeritus of Biology & Environmental Studies, University of Oregon

Thomas A. Woolsey, Professor of Experimental Neurological Surgery, Experimental Neurology, Anatomy and Neurobiology, Cell Biology and Physiology, and Biomedical Engineering, Washington University in St. Louis

Maria Elena Zavala, Professor of Biology, California State University, Northridge

AAAS Education and Human Resources Program Staff

Yolanda S. George, Deputy Director

Shirley M. Malcom, Director

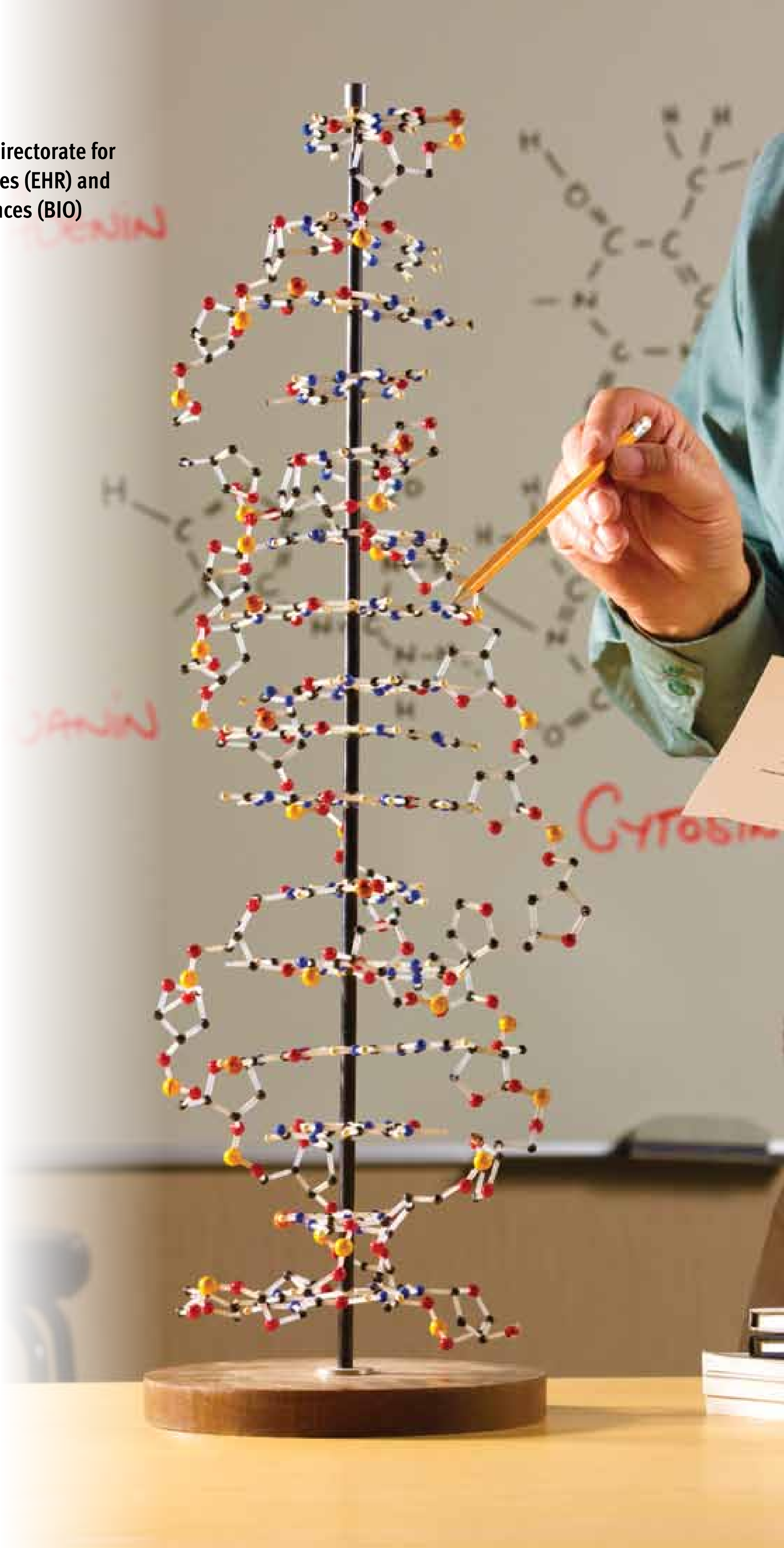
National Science Foundation Directorate for Education and Human Resources (EHR) and Directorate for Biological Sciences (BIO)

Conference Working Group

Deborah Allen, EHR
J. Ellis Bell, BIO
Celeste Carter, EHR
Mary Chamberlin, BIO
Karen Cone, BIO
LaJoyce Debro, BIO
Penelope Firth, BIO
Linnea Fletcher, EHR
Catherine Fry, EHR
Richard Inouye, BIO
Emily Leichtman, BIO
Daniel Litynski, EHR
Al Savitzky, BIO
Judith Skog, BIO
Daniel Udovic, EHR
Cynthia Wei, EHR
Terry Woodin, EHR
Kasey Yturralde, BIO
William Zamer, BIO

Contributors

Dondra Bailey, BIO
James Collins, BIO
Brian Gates, EHR
Elizabeth Gaige, BIO
Gera Jochum, BIO
Wesley Lumpkin, EHR
Elizabeth Lawrence, BIO
Richard McCourt, BIO
Linda Slakey, EHR
Jessica Slater, EHR



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VISION AND CHANGE

PREFACE

> ***"Appreciating the scientific process can be even more important than knowing scientific facts. People often encounter claims that something is scientifically known. If they understand how science generates and assesses evidence bearing on these claims, they possess analytical methods and critical thinking skills that are relevant to a wide variety of facts and concepts and can be used in a wide variety of contexts."***
>
> **—National Science Foundation, Science and Technology Indicators, 2008**

In 2006, staff from the National Science Foundation's (NSF) Directorates for Education and Human Resources (EHR) and for the Biological Sciences (BIO), prompted by changes in the discipline, formed a working group that recognized the need within the biology community to discuss a shared vision for undergraduate biology education and the changes needed to achieve that vision. This led to the idea of a series of conversations culminating in a large conference that could crystallize the vision and change(s) and give momentum to any community initiatives that would follow. The NSF asked the American Association for the Advancement of Science (AAAS) if they could implement the conversations and conference and develop related resources.

In 2007, the AAAS, with principal support from NSF and additional support from the Howard Hughes Medical Institute (HHMI) and the National Institutes of Health (NIH), initiated a series of regional conversations with more than 200 leading biology faculty, administrators, and other stakeholders from around the country. The conversations sought direction on how to improve undergraduate biology education to better prepare all undergraduates for the biology-related challenges of the 21st century. Workshop participants were diverse in several dimensions, representing institutions from community colleges to research universities, as well as many subdisciplines in the life sciences. They included traditional researchers, faculty, pedagogy experts, and undergraduate and graduate students, as well as representatives of professional societies and agencies, all of whom came together in small venues around the country to address the national need to nurture biological literacy and to prepare the next generation of life scientists, educators, and citizens.

In July 2009, using the findings of these regional conversations as a starting point, NSF and AAAS, with the guidance of an advisory board, hosted an invitational conference on *Vision and Change in Undergraduate Biology Education* that attracted more than 500 biology faculty, college and university administrators, representatives of professional societies, and students and postdoctoral scholars from around the country. During the national conference, participants built on the earlier conversations to make recommendations about (1) what students should know and be able to do in the set of courses that make up the biology curriculum; (2) innovative pedagogy and the integration of authentic research experiences into individual courses and biology programs overall; (3) assessment; (4) professional development for both current and future faculty; (5) the kinds of changes that are needed at the institutional level; and (6) tools to facilitate and support change at various levels (e.g., courses, programs, institutions, etc.). The coauthors of this report used the recommendations that arose from these deliberations as the foundation for the report. Thus, cutting across diverse subdisciplines and institutions, *Vision and Change in Undergraduate Biology Education* represents the collective wisdom of hundreds of leading life scientists who contributed to the conversations around the country and then joined with other leading biology faculty, administrators, and undergraduates at the invitational conference.

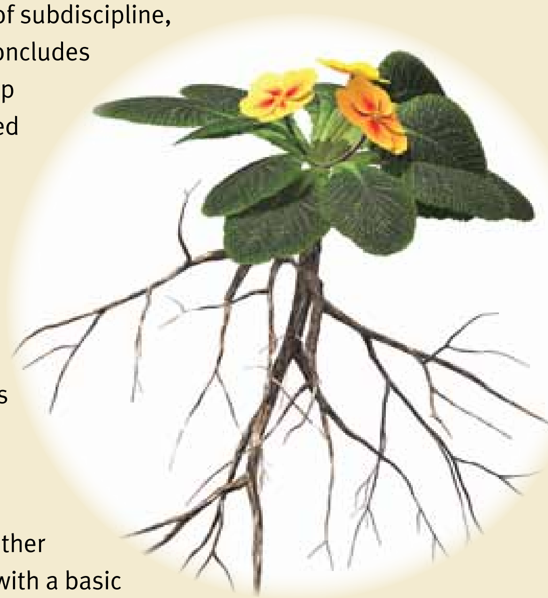
Chapter 1, "Undergraduate Biology Education for All Students," sets the context for the changes needed in undergraduate biology courses and curricula to ensure that the biology we teach reflects the biology we practice. Today's biologists need new skills, including the ability to think and contribute outside their disciplinary boundaries. Tomorrow's researchers will face even more daunting challenges. Recent advances throughout the life sciences require new approaches to preparing biology majors and premedical students. These advances in the discipline also call out for new ways to prepare all undergraduates, regardless of their eventual career paths.

Biology in the 21st century (NRC, 2009) requires that undergraduates learn how to integrate concepts across levels of organization and complexity and to synthesize and analyze information that connects conceptual domains. Chapter 2, "Cultivating Biological Literacy," proposes the presentation of five core concepts and the development of six core competencies as the distinguishing features of, and framework underlying, undergraduate biology education for all students. Rather than identify a "one-size-fits-all" directive, this framework can serve as a useful resource for curricular development based on the collective experience and wisdom of a broad national community of leading biology scientists and educators.

Over the past decade, innovators in both the life sciences and education research have been exploring new models of course and curriculum design, looking at teaching from a scientific perspective, an approach that mirrors the conduct of scientific research. Chapter 3, "Student-centered Undergraduate Biology Education," reviews innovations for making undergraduate courses more student centered and relevant. Having data available to make wise instructional decisions is the key. Case studies highlight some of these innovations around the country.

The success of the nation's biology faculty and their undergraduate students depends on broad institutional support. Chapter 4, "Preparing Campuses for the Challenges Ahead," calls on students, faculty, deans, provosts, and college and university presidents to make a commitment to recognizing the importance of improving biology and other science-related educational outcomes on their campuses. Such improvement will involve (1) advocating for increased status, recognition, and rewards for faculty and departments engaged in innovative teaching and (2) promoting scholarly activities in science education.

Chapter 5, "Unity of Purpose," is a call to action. Transforming undergraduate biology education requires a concerted and sustained effort by *all* stakeholders in the life sciences, regardless of subdiscipline, unified by a common vision of first-rate, student-centered learning. This chapter concludes with a set of recommendations for action to ensure that all undergraduates develop the level of biological literacy needed to understand, help solve, and make informed decisions about the complex problems facing the world today and tomorrow.



A Note about Terminology

The Vision and Change Initiative focuses on improving undergraduate biology education for *all students.* Throughout this report, we use the term "all students" to reflect the growing social, economic, and ethnic diversity of today's undergraduates. We also use "all students" to remind readers that undergraduates arrive at a four-year campus with diverse levels of preparation, having recently graduated from high school, transferred from a community college, or returned to complete a degree (or initiate a new one) later in life. Finally, while the term "all students" includes biology majors, it also refers to undergraduates who major in other disciplines. The coauthors want to ensure that *all students* graduate from college with a basic understanding of biology.

That brings up another important note about terminology: The Vision and Change Initiative focuses on undergraduate *biology education.* Within this context, we include courses and curricula for both biology majors and majors in other disciplines, from traditional introductory biology courses to the full spectrum of subdisciplinary coursework associated with the life sciences. Throughout this report, we use the terms "biology," "biological sciences," and "life sciences" interchangeably. This usage is intended not to obfuscate, but to ground the argument in the traditional terminology of the undergraduate curriculum while still reflecting the growing interdisciplinary nature of the numerous life science subdisciplines. This broader view of biology is also reflected in the report's overarching recommendations.

Letter From the National Science Foundation Directorates

Colleagues,

It is a daunting challenge to transform long institutionalized patterns of instruction so that they align with what we have come to understand about how learning takes place. That challenge is heightened for the life sciences by the burgeoning of new information and new insights, and the increased requirement that practitioners of biology master approaches from other disciplines. In recognition of these challenges, the National Science Foundation (NSF) funded a series of stakeholder conversations and the July 2009 conference, Transforming Undergraduate Education in Biology: Mobilizing the Community for Change. *These investments provided opportunities to listen for shared vision and the changes needed to achieve it and to crystallize initiatives and partnerships.*

The report from this conference articulates that vision and clearly identifies strategies for change. It is encouraging to see the unanimity of purpose the report manifests in establishing consensus around core learning goals for students across the subdisciplines of the life sciences and connecting to the growing understanding of effective teaching practice achieved across multiple scientific disciplines. We are particularly pleased by the inclusion of students' voices in the conversations we held in preparation for the conference, during the conference itself, and in this report.

This effort has also manifested the power of collaboration among funding agencies, both federal and private. We gratefully acknowledge the participation by the National Institutes of Health and the Howard Hughes Medical Institute, and the leadership of the American Association for the Advancement of Science in managing the preparation for the conference and the actual event, as well as overseeing the development of this report. We look forward to continuing to work with our colleagues at AAAS on these critical issues.

We also look forward to working with you as you translate these recommendations into the changes necessary to bring about a true transformation of undergraduate biology education. These efforts will help students better understand the natural world—knowledge that is so necessary in addressing contemporary social challenges.

Sincerely,

Linda L. Slakey
Division Director
Division of Undergraduate Education
Education and Human Resource Directorate
National Science Foundation

Judith A. Verbeke
Acting Division Director
Division of Biological Infrastructure
Biological Sciences
National Science Foundation

ACKNOWLEDGMENTS

With funding from the National Science Foundation (NSF) and contributions from Howard Hughes Medical Institute (HHMI) and the National Institutes of Health (NIH), AAAS was able to bring together some of the best minds to offer guidance to faculty and administrators on new directions for teaching in the biological sciences. We are grateful to these funders for providing the opportunities for faculty leaders from all types of colleges and universities to have conversations and meetings with their peers in order to share their approaches and reflect on how the lessons they have learned could be used as A *Call to Action* to transform teaching in the biological sciences.

Leaders of professional societies for the biological sciences also participated in conversations and several special meetings. We would like to thank these officers and staffs from our affiliated societies. Professional societies have long played, and are committed to playing, a continuing role in undergraduate biological sciences education via publications, programs, meetings and conferences, and board statements.

This report represents the collective wisdom of more than 500 biological sciences faculty and administrators who participated in conversations, meetings, and writing teams to produce this document. We would like to express our gratitude to all the faculty and administrators who attended conversations and meetings, sponsored conversations on their campus, led working groups, and contributed to the writing and reviewing of the chapters. We thank Terry Woodin for coordinating the review of this document with her colleagues at NSF.

We would also like to acknowledge the more than 200 students, both biological sciences majors and those majoring in other disciplines, from 13 colleges and universities who participated in campus-based conversations or the national meeting. Their perspectives about biological sciences education are highlighted in this report. One of the major lessons learned from this work is to pay more attention to the perspectives of the students we teach.

We would particularly like to thank Marsha Matyas, Director of Education Programs for the American Physiological Society (APS), and Catherine Fry, a former AAAS Science & Technology Policy Fellow in the Division of Undergraduate Education at the National Science Foundation, for writing the reports on the conversations and working with the student group that attended the national meeting. These reports helped to guide the framework and working groups of the national conference.

This report would not be possible without the diligence of the editors, Carol A. Brewer and Diane Smith. Succinctly writing and pulling together the ideas, strategies, practices, actions, and references highlighted in this report took months of work.

Finally, we would like to thank Brian Baker (copy editor), Stacey Pasco (reference checker), Marilyn Fenichel (publications management), and Gail Peck, Peck Studios, Inc. (graphic design) for helping to finalize the report.

We sincerely hope that this report will provide biological sciences faculty with ideas to prepare the new biologist for the 21st century, as well as those majoring in other subjects who will need a sound biological sciences education to face the daily decisions and many societal challenges that are bound to be connected to a comprehension of the biological sciences.

Yolanda S. George Shirley M. Malcom

Yolanda S. George and **Shirley M. Malcom,**
AAAS Education & Human Resources Programs

http://visionandchange.org/files/2010/03/VC-Prelimary-Reports-from-Conversations1.pdf

LETTER FROM COCHAIRS

These are exciting times for biologists, with changes occurring in all areas of the life sciences, from breakthroughs in genomics and neuroscience to a deeper understanding of the effects of global climate change on Earth's ecosystems. And yet, many of these new areas of biology, and the skills needed to understand and engage effectively in them, typically do not appear in science classrooms and textbooks until many years after their inception, leaving undergraduate biology education lagging behind these exciting scientific advances. As a consequence, too many students never learn about the cutting-edge discoveries that make biology so exciting to professional scientists, or engage in the kinds of active participation in science that will better prepare them to be informed citizens and—for those choosing to go on—to succeed as modern scientific researchers.

Starting in 2007, the American Association for the Advancement of Science (AAAS) and the National Science Foundation (NSF) initiated a series of national conversations to envision what undergraduate biology education should look like in the 21st century. These conversations culminated in an invitational conference in July of 2009, at which more than 500 leading biologists, educators, administrators, and students built on the conversations to create a blueprint for real change. During the conference, there was overwhelming excitement from faculty about the revolution underway in the biological sciences, and we sensed an eagerness among faculty members to share their passion with their students. And conference speakers urged participants to design innovative courses and materials to engage all students, not just biology majors, with important concepts to better prepare them to work and participate in an increasingly scientific and technological society.

The result of these deliberations is a series of recommendations aimed at ensuring that all students—biology majors and those majoring in other fields—gain a better understanding of the nature of science and the living natural world. But it is not just about the content of biological science: A key recommendation is that biology courses and curricula must engage students in how scientific inquiry is conducted, including evaluating and interpreting scientific explanations of the natural world. In this volume, you will find the consensus framework that emerged to produce core concepts and competencies that can serve as the distinguishing features of undergraduate biology education.

As cochairs of the Vision and Change initiative, we would like to thank our Steering Committee for its guidance, and all the groups, including NSF, the National Institutes of Health, and the Howard Hughes Medical Institute, for their ongoing encouragement and support. We would also like to thank the hundreds of biologists, administrators, students, and others who helped us envision what undergraduate biology should look like in the 21st century and who made informed and thoughtful recommendations on how to achieve the requisite changes. And we extend our special thanks to the authors of this report.

Clearly, this ongoing commitment to vision and change did not end at the close of the meetings. As noted throughout the report, if we expect our students to be engaged with the subject matter of biology, we must ensure that all of our undergraduate courses and curricula be designed to reflect the best of what our science has to offer and that we do not attempt to "cover" all there is to know. Indeed, given the explosion of new knowledge in the biological sciences, attempting to "cover it all" can be counterproductive and turn away even the most talented and interested students.

Meeting participants agreed that these are indeed exciting times, but they also stressed that all biologists, particularly those of us who introduce the life sciences to undergraduates, are facing major challenges. The time has never been more critical to rethink what and how we teach to ensure that the biology we teach engages all students and reflects the biology we practice in the laboratory and in the field.

Carol Brewer, Conference Cochair
Professor Emeritus of Biological Sciences
University of Montana

Alan Leshner, Conference Cochair
CEO of AAAS

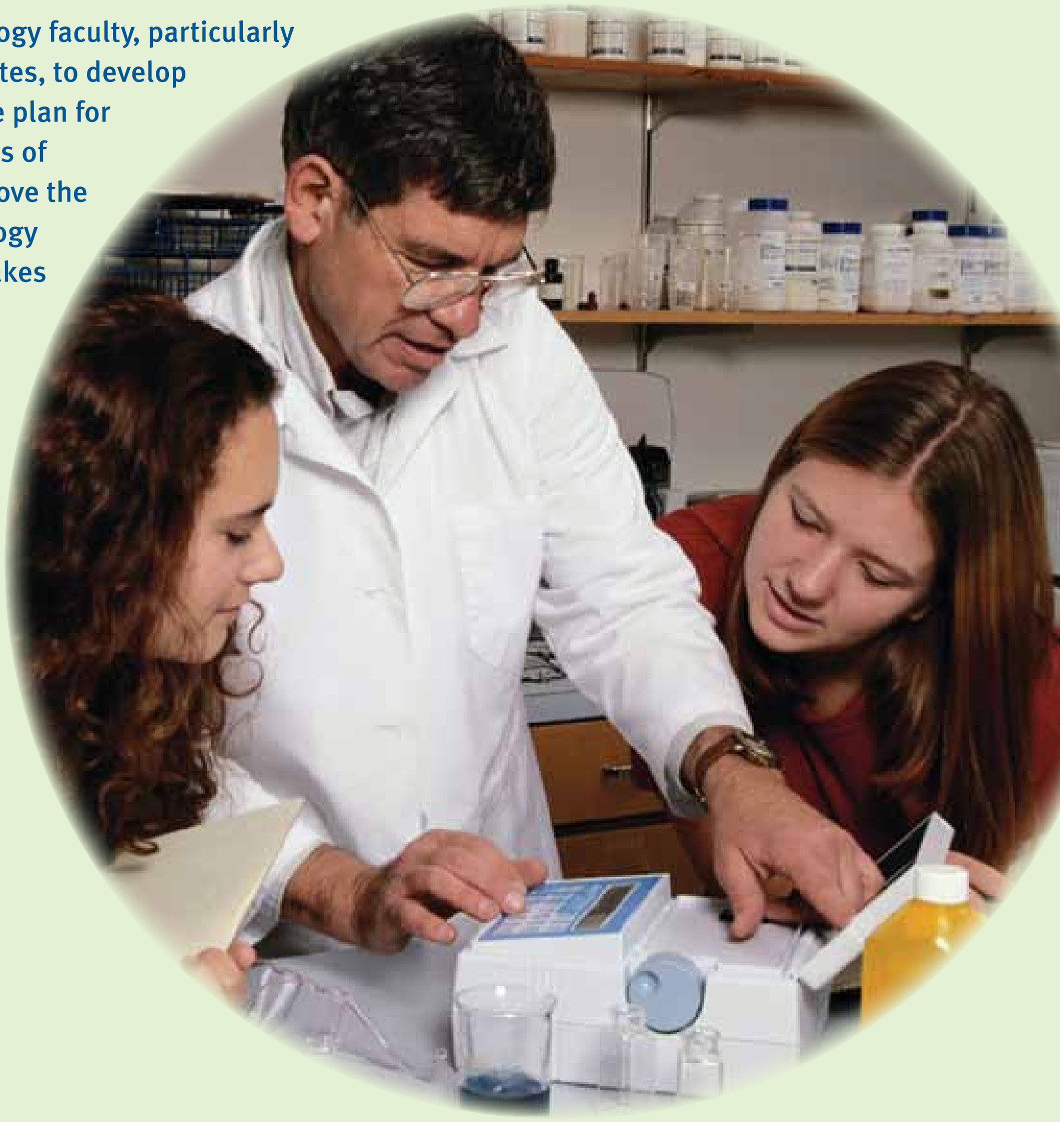
A VISION FOR IMPLEMENTING CHANGE

The recommendations discussed in this report include the following action items aimed at ensuring that the vision of the conference becomes an agenda for change:

1. **Integrate Core Concepts and Competencies throughout the Curriculum**
    - Introduce the scientific process to students early, and integrate it into all undergraduate biology courses.
    - Define learning goals so that they focus on teaching students the core concepts, and align assessments so that they assess the students' understanding of these concepts.
    - Relate abstract concepts in biology to real-world examples on a regular basis, and make biology content relevant by presenting problems in a real-life context.
    - Develop lifelong science-learning competencies.
    - Introduce fewer concepts, but present them in greater depth. Less really is more.
    - Stimulate the curiosity students have for learning about the natural world.
    - Demonstrate both the passion scientists have for their discipline and their delight in sharing their understanding of the world with students.
2. **Focus on Student-Centered Learning**
    - Engage students as active participants, not passive recipients, in all undergraduate biology courses.
    - Use multiple modes of instruction in addition to the traditional lecture.
    - Ensure that undergraduate biology courses are active, outcome oriented, inquiry driven, and relevant.
    - Facilitate student learning within a cooperative context.
    - Introduce research experiences as an integral component of biology education for all students, regardless of their major.
    - Integrate multiple forms of assessment to track student learning.
    - Give students ongoing, frequent, and multiple forms of feedback on their progress.
    - View the assessment of course success as similar to scientific research, centered on the students involved, and apply the assessment data to improve and enhance the learning environment.
3. **Promote a Campuswide Commitment to Change**
    - Mobilize all stakeholders, from students to administrators, to commit to improving the quality of undergraduate biology education.
    - Support the development of a true community of scholars dedicated to advancing the life sciences and the science of teaching.
    - Advocate for increased status, recognition, and rewards for innovation in teaching, student success, and other educational outcomes.
    - Require graduate students on training grants in the biological sciences to participate in training in how to teach biology.
    - Provide teaching support and training for all faculty, but especially postdoctoral fellows and early-career faculty, who are in their formative years as teachers.

4. **Engage the Biology Community in the Implementation of Change**
    - Promote more concept-oriented undergraduate biology courses, and help all students learn how to integrate facts into larger conceptual contexts.
    - Ensure that all undergraduates have authentic opportunities to experience the processes, nature, and limits of science.
    - Provide all biology faculty with access to the teaching and learning research referenced throughout this report, and encourage its application when developing courses.
    - Create active-learning environments for all students, even those in first-year biology courses.
    - Encourage all biologists to move beyond the "depth versus breadth" debate. Less really is more.

The time has come for all biology faculty, particularly those who teach undergraduates, to develop a coordinated and sustainable plan for implementing sound principles of teaching and learning to improve the quality of undergraduate biology education nationwide. The stakes are too high for all biologists not to get involved with this national call for change.



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"Innovation in life science will be the major driver of meeting four major societal challenges: challenges of climate, challenges of food, challenges of energy, and challenges of health."

—Phillip A. Sharp, MIT,
Cochair, NRC Committee
A New Biology for the 21st Century

CHAPTER 1

BIOLOGY EDUCATION FOR ALL STUDENTS

A revolution is underway in biology. The major focus of the biological sciences—understanding life—remains the same, but the science has experienced a major transformation. Many of the most exciting discoveries in the biological sciences during the second half of the 20th century occurred at the intersections of established disciplines. Emerging interdisciplinary fields such as genomics, proteomics, metagenomics, synthetic biology, biochemistry, bioinformatics, computational biology, and systems biology are leading to new discoveries, and some are changing the ways we think about and engage in biological research and explore established biological fields (such as evolutionary biology). These new integrated fields, spread across the diversity of life sciences, are opening up a vast array of practical applications, ranging from new medical approaches, to alternative sources of energy, to new theoretical bases in the behavioral and social sciences.

Breakthrough discoveries at the boundaries of traditional biology disciplines also have changed the nature and the kinds of questions researchers can ask about living systems, while emerging technologies have opened new opportunities for biologists to investigate questions we never thought could be addressed or even asked. Real-time molecular imaging, bioinformatics approaches to generating molecular phylogenies, the sequencing of ancient DNA from extinct mammals, and the use of global information systems (GIS) to aggregate and present data from sensors monitoring the environment are just a few examples of how new technologies have advanced the life sciences. These new areas of research are expanding at breathtaking speed and providing opportunities for investigators to contribute their specific expertise to research questions as they collaborate with people from other disciplines to address complex and increasingly interdisciplinary problems.

To contribute effectively to this "New Biology" (NRC, 2009), scientists need to interact with information in new ways, including being able to manage large, complex data sets. Systems approaches and biological modeling rely on the application of mathematics and statistical analysis, while the explosive generation of larger and larger data sets demands increasingly sophisticated computational knowledge (Brewer and Gross, 2003). Studying biological dynamics requires a greater emphasis on modeling, computation, and data analysis tools than ever before.

Clearly, today's biologists require new skills to address the challenges of the 21st century, including the ability to think and contribute outside their disciplinary boundaries. Tomorrow's researchers will face even more daunting challenges. While these advances in the life sciences require new approaches to preparing biology majors and premedical students, they also call out for new ways to prepare all undergraduates, regardless of their eventual career paths. As a growing number of societal challenges, from preserving the environment to advancing human health and the quality of life, intersect with biology, future scientists and nonscientists alike must become adept at making connections among seemingly disparate pieces of information, concepts, and questions, as well as be able to understand and evaluate evidence. In addition, they must possess enough knowledge about related disciplines (e.g., chemistry, geology, physics, computer science, engineering, and the social sciences) to bring the requisite expertise to address complex issues.

Many college students, regardless of their majors, take at least one biology class as an undergraduate. For some students, introductory biology classes are gateways into science; for others, these classes are the only science course they will take in college. Indeed, entry-level biology courses serve as the first and perhaps only chance to introduce the latter students to scientific inquiry, the use of evidence, and the core biological concepts that will help them make informed decisions about the many biology-related problems they are bound to encounter in their daily lives. Biology faculty, therefore, have a unique opportunity and responsibility to ensure that all undergraduates taking their courses gain a basic understanding of science as a way to learn about the natural world.

NEW CHALLENGES FOR BIOLOGY FACULTY

At the same time, biology faculty face a unique challenge. Undergraduates are more diverse than ever, coming from a variety of social, economic, and ethnic backgrounds. They enter institutions of higher education from a variety of entry points: directly from high school, as transfer students from community colleges, or as students starting their college career after military service or other postsecondary life experiences. Some nontraditional students return to college to complete a college education started years earlier or to explore new educational goals. Transfer patterns are equally diverse. For example, faculty at four-year institutions often interact with transfer students from community colleges, while faculty at community colleges may work with students from four-year institutions completing required coursework at their campus. Although the educational and career paths these students follow are as diverse as the students themselves, all students should graduate with a basic level of biological literacy in order to participate as informed citizens and thrive in the modern world.

In attempting to address these challenges and opportunities, biology faculty have a number of resources available. A growing body of research now exists on how students learn (e.g., NRC, 2000), and over the last two decades leading scientists, science educators, and policymakers have given much thought to improving teaching and learning. Their recommendations and calls for change have been published by a number of organizations committed to the advancement of science and science education. (See “National Context for Improving Undergraduate Science Education.”)

Building on these recommendations, life sciences faculty from around the country have started to develop, adapt, implement, and assess biology course units and modules, entire courses, curricula, and pedagogical approaches at two- and four-year colleges and research universities. New biology course designs have helped students develop critical-thinking skills and have resulted in increased interest among undergraduates in general and biology majors in particular. Some approaches have even been helpful in improving the participation of underrepresented groups and in increasing students’ confidence in their ability to understand and excel in the study of biology (Summers and Hrabowski, 2006; Laursen et al., 2010). A spectrum of assessments, such as Conceptual Assessment in the Biological Sciences (CABS—Michael et al., 2008; D’Avanzo, 2008) and assessment tools that pose problems or questions similar to those faced by those outside and inside the field of biology (Wiggins, 1993), has been developed to measure both student understanding and the ability to apply knowledge. These instruments help faculty document the learning outcomes of student-centered classes and research experiences. Excellent curricular models also exist (e.g., Handelsman et al., 2007; Ebert-May and Hodder, 2008).

Because of their unique focus on living systems and the exciting techniques available today for asking and answering complex questions, the biological sciences have the potential to contribute significantly to understanding and addressing many of the challenges the nation faces, from climate change and declining biological diversity to improving human health and widening access to safe food and clean water. Indeed, as *A New Biology for the 21st Century* (NRC, 2009) and other reports (NRC, 2003a, b) point out, these problems cannot be solved without a comprehensive understanding of—and advances in—the life sciences.

The participants at the Vision and Change national conference and the coauthors of this report understand that their recommendations will not result in overnight change. However, it is our hope that those biologists who read this report will make a concerted effort to ensure that all of *their* undergraduate students, regardless of their majors or eventual careers, graduate with a well-defined level of functional biological literacy and critical-thinking skills. Each of us in the life sciences community must be up to this challenge. Because if not us, who? And if not now, when?

UNDERGRADUATE STUDENT VOICES

As part of the National Conversations on Undergraduate Biology Education, NSF and biology faculty participating in Vision and Change activities held conversations with undergraduates during the spring of 2009. A total of 231 undergraduates participated, representing 13 institutions from around the country. Among the participants were 99 biology majors, along with majors from 36 other disciplines, including other STEM fields, the humanities, and the arts (Fry, 2009).

During the focus groups, organizers presented undergraduates with a series of questions, followed by representative student responses drawn directly from the NSF/AAAS report of national conversations with undergraduates (Fry, 2009; available at http://visionandchange.org/files/2010/03/VC-Prelimary-Reports-from-Conversations1.pdf). These “student voices”—direct quotes in all cases—offer important insights into the thoughts and concerns of today’s students and tomorrow’s leaders, researchers, teachers, and citizens.

DISCUSSION QUESTION

Professors and biologists care about biology, but what do students think about biology?

STUDENT RESPONSES

- Biology can connect many topics, both within STEM and more broadly; “biology is life.”
- Innovation in other fields often depends on biology.
- Everyone needs some knowledge of biology in order to make informed decisions as adults—about health, nutrition, the environment, conservation, “green” living, etc.
- Biology can teach problem-solving skills and an understanding of the scientific method in general; everyone should understand what does and doesn’t constitute evidence for a claim.
- Biology can help make connections between self and society.
- “Facts are at our fingertips”; biology can help illustrate the context and connections.
- Biology presents a good way to communicate about science, because many biology topics are immediately relevant and relatable to anyone’s life.
- An understanding of biology can make people feel more engaged with Earth and its environment and more inclined to take steps to protect it.
- Good biology education is needed for global competitiveness.
- Biology education is needed to provide solutions for diminishing resources/sustainability issues.
- Since many nonmajors take biology as their required lab science course, it’s a gateway to get more students interested in science.

NATIONAL CALL FOR IMPROVING UNDERGRADUATE SCIENCE EDUCATION

For more than 25 years, the scientific community, senior science educators, and public policy leaders have called upon colleges and universities to better prepare their undergraduates for the difficult social, economic, and environmental challenges of the 21st century. The resulting reports raised questions about declines in science and technology comprehension, workforce capabilities, and national competitiveness and suggested solutions to the problems noted. The following list provides a brief overview of some of the reports that have called for improving how the nation educates students in science and technology:

YEAR REPORT

1986 ***Undergraduate Science, Mathematics and Engineering Education,*** National Science Board, calls for strengthening collegiate education to better prepare the next generation of U.S. leadership in science and technology.

1989 ***Private Universe,*** a 20-minute film produced by the Harvard–Smithsonian Center for Astrophysics (Science Media Group), illustrates what graduates (and some faculty) of this university believe causes the seasons. The film emphasizes the importance of addressing student misconceptions before introducing new concepts and demonstrates how hands-on approaches can help improve learning in the classroom.

1989 ***Science for All Americans,*** American Association for the Advancement of Science, advocates for the need for all students to understand science and paved the way for much of the subsequent thinking about the role and future of science education.

1989 ***Report on the National Science Foundation Disciplinary Workshops on Undergraduate Education,*** NSF Directorate for Science and Engineering Education, makes recommendations for improving science education, including biology education. The biology workshop recommended that "[t]he main target of reform must be introductory biology," since these "courses are confusing, aimless, and generally negative stimuli to career choice or selection of electives." In addition, the workshop noted, undergraduate biology curricula "don't address [the] increasing multidisciplinary nature of biology."

1990 ***Scholarship Reconsidered: Priorities of the Professoriate,*** Ernest L. Boyer, Carnegie Foundation for the Advancement of Teaching, argues for reintroducing the scholarship of teaching to those engaged in the education of undergraduates, as well as including it among the key components for how faculty are evaluated.

1990 ***The Liberal Art of Science: Agenda for Action,*** American Association for the Advancement of Science, discusses undergraduate education in the 21st century and the level of understanding required in the natural sciences today.

1991 ***What Works: Building Natural Science Communities*** (Volume 1), Project Kaleidoscope (PKAL), focuses on collecting and disseminating knowledge about effective practices in teaching and learning at the course, departmental, and institutional levels in undergraduate STEM education. This was the first in a series of publications from PKAL on teaching and learning at the university level.

1996 ***Shaping the Future: New Expectations for Undergraduate Education in Science, Mathematics, Engineering, and Technology,*** National Science Foundation, calls for all undergraduates to have access to excellent science, mathematics, engineering, and technology education, and recommends that undergraduates “learn these subjects by direct experience with the methods and processes of inquiry.”

1997 ***Minds of Our Own,*** a follow-up film produced by the Harvard–Smithsonian Center for Astrophysics (Science Media Group), reveals that a new generation of graduates from a prestigious university repeatedly identify soil and water as the primary contributors to the mass of wood in a tree trunk, even though photosynthesis is one of the most widely taught science topics throughout all levels of a student’s education in biology. As one commentator in the film notes, this lack of understanding of a core biological principle “is symbolic of the state of the nation.”

1998 ***Beyond Bio 101: The Transformation of Undergraduate Biology Education,*** Howard Hughes Medical Institute (HHMI), recounts the innovations at many of the colleges and universities supported by HHMI, including expanding research opportunities for undergraduates, updating teaching equipment and science curricula, and attracting new faculty in emerging fields.

1999 ***Transforming Undergraduate Education in Science, Mathematics, Engineering, and Technology,*** National Research Council, offers a series of recommendations for faculty and senior academic administrators to improve undergraduate STEM education. This report was one of the first to focus on introductory courses and how they can be made more relevant to a broader number of students, both those who intend to major in sciences and those who elect to pursue studies in other fields.

2000 ***How People Learn: Brain, Mind, Experience, and School,*** National Research Council, summarizes and synthesizes emerging research from the cognitive and learning sciences about human learning. The report also points out that many current education practices are inconsistent with what research suggests could promote student learning through more effective teaching.

2002 ***Preparing Future Faculty in the Sciences and Mathematics,*** Council of Graduate Schools and the Association of American Colleges and Universities, points out that most graduate students who earn PhDs at research universities will not obtain faculty positions at any of those institutions. Thus, preparing graduate students to become faculty in a variety of academic settings is paramount.

2002 ***Learning and Understanding: Improving Advanced Study of Mathematics and Science in U.S. High Schools,*** National Research Council, calls for substantial changes in college-level courses taught in high schools as Advanced Placement (AP) courses, which many students take for college credit. Many of the recommended reforms, now being implemented, are congruent with the changes in undergraduate courses recommended in the reports listed next.

2003 ***Bio 2010: Transforming Undergraduate Education for Future Research Biologists,*** National Research Council, proposes that biology majors acquire stronger foundations in the physical sciences, mathematics, and interdisciplinary problem-solving abilities. “[T]eaching and learning must be made more active to engage undergraduates … and give them an enduring sense of the power and beauty of creative inquiry.”


WF10X-18MM

2003 ***Evaluating and Improving Undergraduate Teaching in Science, Technology, Engineering, and Mathematics,*** National Research Council, focuses on how various kinds of assessments can be used to improve student learning and to help faculty improve their teaching approaches. The report calls for measures of effective teaching to be based at least in part on evidence that students are learning and emphasizes formative assessments as a way to offer continual feedback to both students and their instructors.

2004 ***Math and Bio 2010: Linking Undergraduate Disciplines,*** Mathematical Association of America, argues that biology is becoming increasingly interdisciplinary, that it is relying more heavily on mathematics and computer science, and that these changes are dictating a need to modify the undergraduate curriculum.

2009 ***Scientific Foundations for Future Physicians,*** Association of American Medical Colleges and Howard Hughes Medical Institute, calls for restructuring undergraduate science education away from a system based on courses to one based on "competencies." The report also recommends "the development of more interdisciplinary and integrative courses that maintain scientific rigor, while providing a broad education."

2009 ***A New Biology for the 21st Century,*** National Research Council Board on Life Sciences, promotes a bold new integrated research agenda and includes recommendations for improving undergraduate biology education.

2010 ***Synthetic Biology: Building on Nature's Inspiration,*** National Academy of Sciences, calls for, among other things, educating "young scientists in new ways, [breaking] down divisions in academic institutions, and [improving] general science communication."

For more information, see

A New Biology for the 21st Century

http://www.nap.edu/catalog.php?record_id=12764

CULTIVATING

"As we think about the content that must be introduced in undergraduate biology education, we really are talking about the need to teach future biologists, doctors, chemists, and poets, my grandchildren's future science teachers, US presidents and members of Congress and state legislators, and school board members."

—Alan Leshner, AAAS, Vision and Change Conference Cochair

CHAPTER 2

BIOLOGICAL LITERACY

Because of the extraordinary pace of changes in the science of biology, keeping the undergraduate biology classroom current and dynamic without overwhelming students is a constant challenge. And yet, the cutting-edge discoveries that make biology so exciting to professional scientists can also excite undergraduates. All of us who teach undergraduates, therefore, need to find a balance between providing the depth of coverage required to promote appropriate student conceptual understanding while still providing needed factual knowledge. To meet this challenge, we can no longer rely solely on trying to cover a syllabus packed with topics to be covered in lecture and guided laboratory sessions—an approach that can be counterproductive and can often leave students with a misguided and, possibly, negative impression of biology. Rather, we all need to rethink what we teach—what has been historically significant in biology, what key research is being carried out today, and what implications that research may have in the future—while meeting the needs of an ever more diverse student population.

The intent of the Vision and Change conversations and national conference was to move toward a consensus framework in the biology community that would be broadly adaptable, given the unique structures, capacities, and constraints of individual life science programs. Building on the recent work of others (e.g., Association of American Medical Colleges and Howard Hughes Medical Institute, 2009; Wood, 2009a), participants proposed the core concepts and competencies described in this chapter as the distinguishing features of undergraduate biology education, providing a strong foundation to guide the development of curricular frameworks. Clearly, the utility of any proposed framework depends on its potential to be adapted to meet the local needs and resources of diverse colleges and universities. So, rather than offer a "one-size-fits-all" directive, we pose these core concepts and competencies as a resource and starting point based on the collective experience and wisdom of a broad national community of biological scientists and educators. The core concepts and competencies, outlined below, closely mirror those recently posed by others

In our discussions, we came to a consensus that five organizing themes describe lines of inquiry in modern biology and, thereby, help define *core concepts* for the discipline. These concepts provide an organizational model for improving undergraduate biology education generally and designing curricula to meet the needs of the "New Biology" (NRC, 2008, 2009) in particular. The concepts also help provide a set of overarching principles that are important throughout the living world, and their use in teaching biology lends meaning to the multitude of facts that the student encounters in any undergraduate biology course. However, we agreed that the practice of biology requires more than just understanding core concepts. To understand, generate, and communicate knowledge about the living world, students need to develop and apply relevant skills. Therefore, in addition to understanding concepts, undergraduates must have opportunities to develop *core competencies* to better prepare them to practice biology, as well as to address the complex biology-related issues that our society faces. The core concepts and competencies, derived from general features of the discipline, together offer a framework informed by modern themes in biology that reflect disciplinary practice and are flexible enough to be useful in informing course design in diverse academic contexts.

Meeting participants also noted that, even though life sciences curricula typically serve biology majors, introductory courses help prepare *all* students to understand the natural world and many significant challenges of the 21st century. Although instructors teaching an introductory course cannot be expected to present the same material that will be developed in a full curriculum for majors, an introductory course should still use the core concepts and competencies to provide a solid foundation for all students. The five core biological concepts and six core competencies proposed here can serve as the basis for any undergraduate biology course, whether it is for those students who take only one or two introductory biology courses to satisfy core requirements or for biological science majors who pursue advanced studies.

FOUNDATIONS OF UNDERGRADUATE BIOLOGY

The practice of identifying key concepts and competencies for student learning is well established in science education. As early as 1985, The American Association for the Advancement of Science (AAAS) proposed a conceptual framework in its *Benchmarks for Science Literacy*. This proposal was followed by the National Research Council (NRC) report, *National Science Education Standards,* in 1996. Also, the identification of biology-specific concepts has been described in *BIO 2010* (NRC, 2003); the Association of American Medical Colleges, (2009); and the College Board Advanced Placement Study Program (2009). In concert with these efforts, the core concepts and competencies identified next form the backbone of a relevant, exciting 21st century biology education for undergraduates.

Core Concepts for Biological Literacy

After much discussion and debate, Vision and Change participants agreed that all undergraduates should develop a basic understanding of the following core concepts:

1. EVOLUTION:

The diversity of life evolved over time by processes of mutation, selection, and genetic change.
Darwin's theory of evolution by natural selection was transformational in scientists' understanding of the patterns, processes, and relationships that characterize the diversity of life. Because the theory is the fundamental organizing principle over the entire range of biological phenomena, it is difficult to imagine teaching biology of any kind without introducing Darwin's profound ideas. Inheritance, change, and adaptation are recurring themes supported by evidence drawn from molecular genetics, developmental biology, biochemistry, zoology, agronomy, botany, systematics, ecology, and paleontology. A strong preparation in the theory of evolution remains essential to understanding biological systems at all levels.

Themes of adaptation and genetic variation provide rich opportunities for students to work with relevant data and practice quantitative analysis and dynamic modeling. Principles of evolution help promote an understanding of natural selection and genetic drift and their contribution to the diversity and history of life on Earth. These principles enable students to understand such processes as a microbial population's ability to develop drug resistance and the relevance of artificial selection in generating the diversity of domesticated animals and food plants.

2. STRUCTURE AND FUNCTION:

Basic units of structure define the function of all living things.
Structural complexity, together with the information it provides, is built upon combinations of subunits that drive increasingly diverse and dynamic physiological responses in living organisms. Fundamental structural units and molecular and cellular processes are conserved through evolution and yield the extraordinary diversity of biological systems seen today.

Understanding of biological regulatory systems and communication networks has become increasingly sophisticated, yielding knowledge about the functional responses of the components of those systems and networks at differing scales, from the molecular to the ecosystem level of organization. Knowledge of relationships between biological structure and function is informed by design approaches from engineering and from models based on the quantitative analysis of data. The application of tools from the physical sciences often facilitates our understanding of biological structure–function relationships. For example, anatomical analysis of body morphology and function by means of a biomechanics approach and robotics (e.g., Spenko et al., 2008) provides a venue for discussing the interface between applied physics and biology in an undergraduate biology course. Rational drug design strategies offer useful case studies emphasizing the importance of the basic structure–function concept. For instance, elucidating the molecular structure of a target protein such as HIV protease has provided the basis for novel approaches to the discovery of drugs, leading to important antiretroviral therapies to treat AIDS.

3. INFORMATION FLOW, EXCHANGE, AND STORAGE:

The growth and behavior of organisms are activated through the expression of genetic information in context.

The convergence of systems approaches and powerful bioinformatics tools has dramatically expanded our understanding of the dynamics of information flow in living systems. From gene expression networks to endocrine mechanisms for physiological regulation, and from signal transduction and cellular homeostasis to biogeochemical cycling, all may be understood in terms of the storage, transmission, and utilization of biological information. Moreover, the collection, archiving, and analysis of information about living organisms and their components has created an extraordinary breadth and diversity of data that facilitate analyses of how information flows through systems. Real-time analytical approaches facilitate the study of cellular dynamics in response to environmental changes. Studies of the dynamics of information flow raise questions about topics such as the storage of genetic information and the transmission of that information across generations.

All students should understand that all levels of biological organization depend on specific interactions and information transfer. Information exchange forms the basis of cell recognition and differentiation, the organization of communities from microbial assemblages to tropical forests, and the mating behavior of animals. The introduction of the topic of information exchange offers undergraduates many opportunities to learn how scientists apply quantitative skills and tools in the management and analysis of large data sets.

4. PATHWAYS AND TRANSFORMATIONS OF ENERGY AND MATTER:

Biological systems grow and change by processes based upon chemical transformation pathways and are governed by the laws of thermodynamics.

The principles of thermodynamics govern the dynamic functions of living systems from the smallest to the largest scale, beginning at the molecular level and progressing to the level of the cell, the organism, and the ecosystem. An understanding of kinetics and the energy requirements of maintaining a dynamic steady state is needed to understand how living systems operate, how they maintain orderly structure and function, and how the laws of physics and chemistry underlie such processes as metabolic pathways, membrane dynamics, homeostasis, and nutrient cycling in ecosystems. Moreover, modeling processes such as regulation or signal transduction requires an understanding of mathematical principles.

For example, knowledge of chemical principles can help inform the production of microorganisms that can synthesize useful products or remediate chemical spills, as well as the bioengineering of plants that produce industrially important compounds in an ecologically benign manner. These are topics of intense current interest.

5. SYSTEMS:

Living systems are interconnected and interacting.

As defined in *A New Biology for the 21st Century* (NRC, 2009), systems biology seeks a deep quantitative understanding of complex biological processes through an elucidation of the dynamic interactions among components of a system at multiple functional scales. A systems approach to biological phenomena focuses on emergent properties at all levels of organization, from molecules to ecosystems to social systems. Mathematical and computational tools and theories grounded in the physical sciences enable biologists to discover patterns and construct predictive models that inform our understanding of biological processes. Through these models, researchers seek to relate the dynamic interactions of components at one level of biological organization to the functional properties that emerge at higher organizational levels.

Systems biology provides rich opportunities for all students to learn about scientific inquiry and, because of the complex nature of the research involved, to practice in a multidisciplinary context. For example, early applications of systems biology to ecosystem processes resulted in useful simulation models.

Core Competencies and Disciplinary Practice

Knowledge of *concepts* and the development of *competencies* form the bases for the practice of any discipline, but particularly in the sciences. All students need to develop the following competencies:

1. ABILITY TO APPLY THE PROCESS OF SCIENCE:
Biology is evidence based and grounded in the formal practices of observation, experimentation, and hypothesis testing.
All students need to understand the process of science and how biologists construct new knowledge by formulating hypotheses and then testing them against experimental and observational data about the living world. Studying biology means practicing the skills of posing problems, generating hypotheses, designing experiments, observing nature, testing hypotheses, interpreting and evaluating data, and determining how to follow up on the findings. In effect, learning science means learning to *do* science. For example, authentic research experiences in undergraduate biology through course-based projects, independent or summer research, community-based student research, or other mechanisms can be a powerful means of providing students with opportunities to learn science by doing it (Mulnix, 2003; Sadler and McKinney, 2010).

2. ABILITY TO USE QUANTITATIVE REASONING:
Biology relies on applications of quantitative analysis and mathematical reasoning.
The application of quantitative approaches (statistics, quantitative analysis of dynamic systems, and mathematical modeling) is an increasingly important basic skill utilized in describing biological systems (Jungck, 1997; Brewer and Gross, 2003). Advances in several fields of the biological sciences provide opportunities for students to appreciate the impact of mathematical approaches in biology and the importance of using them. For example, the dynamic modeling of neural networks helps biologists understand emergent properties in neural systems. Systems approaches to examining population dynamics in ecology also require sophisticated modeling. Advances in understanding the nonlinear dynamics of immune system development have aided scientists' understanding of the transmission of communicable diseases.

All students should understand that biology is often analyzed through quantitative approaches. Developing the ability to apply basic quantitative skills to biological problems should be required of all undergraduates, as they will be called on throughout their lives to interpret and act on quantitative data from a variety of sources.

3. ABILITY TO USE MODELING AND SIMULATION:
Biology focuses on the study of complex systems.
All students should understand how mathematical and computational tools describe living systems. Whether at the molecular, cellular, organismal, or ecosystem level, biological systems are dynamic, interactive, and complex. As new computational approaches improve our ability to study the dynamics of complex systems, mathematical modeling and statistical approaches are becoming an important part of the biologist's tool kit. Biologists must understand both the advantages and the limitations of reductionist and systems approaches to studying living systems. Also important is the advantage of qualitative analyses, including steady-state behaviors (e.g., homeostasis) and associated stability analyses (e.g., responses to perturbations). A combination of these approaches is essential to teasing apart the complexities of biological systems.

A variety of computational educational tools is readily available to examine complexity as it arises in biological systems. These tools can simulate many interacting components and illustrate emergent properties that allow students to generate and test their own ideas about the spatiotemporal complexity in biology. Today, modeling is a standard tool for biologists, so basic skills in implementing computational algorithms for models are increasingly being incorporated into the undergraduate curriculum (Rowland-Godsmith, 2009; NetLogo, n.d.).

4. ABILITY TO TAP INTO THE INTERDISCIPLINARY NATURE OF SCIENCE:

Biology is an interdisciplinary science.

Integration among subfields in biology, as well as integration between biology and other disciplines, has advanced our fundamental understanding of living systems and raised a number of new questions. As exciting new areas of study emerge from the interstices, solid grounding in the sciences, including computer science and social science, can advance the practice and comprehension of biology. Accordingly, all students should have experience applying concepts and subdisciplinary knowledge from within and outside of biology in order to interpret biological phenomena.

Interdisciplinary science practice may be achieved in several ways. For future biologists, one way is through developing expertise not just in an area of biology, but also in a related discipline. That way, students will develop the vocabulary of both disciplines and an ability to think independently and creatively in each as well. A second, less intensive approach is to develop deep expertise in one area and fluency in related disciplines. A third option is to serve as a biologist on a multidisciplinary team. All of these routes develop a student's facility to apply concepts and knowledge across traditional boundaries. For those not majoring in biology, the inherent interdisciplinary nature of biology practice lends itself to forming connections between biology and other sciences and, in so doing, can help all students understand the way science disciplines inform and reinforce each other.

5. ABILITY TO COMMUNICATE AND COLLABORATE WITH OTHER DISCIPLINES:

Biology is a collaborative scientific discipline.

Biological research increasingly involves teams of scientists who contribute diverse skills to tackling large and complex biological problems; therefore, all students should have experience communicating biological concepts and interpretations. As the science of biology becomes more interdisciplinary in practice and global in scope, biologists and other scientists need to develop skills to participate in diverse working communities, as well as the ability to take full advantage of their collaborators' multiple perspectives and skills.

Effective communication is a basic skill required for participating in inclusive and diverse scientific communities. Communicating scientific concepts through peer mentoring helps students solidify their comprehension and develop the ability to communicate ideas not only to other biology students, but also to students in other disciplines. Practicing the communication of science through a variety of formal and informal written, visual, and oral methods should be a standard part of undergraduate biology education.

6. ABILITY TO UNDERSTAND THE RELATIONSHIP BETWEEN SCIENCE AND SOCIETY:

Biology is conducted in a societal context.

Biologists have an increasing opportunity to address critical issues affecting human society by advocating for the growing value of science in society, by educating all students about the need for biology to address pressing global problems, and by preparing the future workforce. Biologists need to evaluate the impact of scientific discoveries on society, as well as the ethical implications of biological research. Cross-disciplinary opportunities for students to explore science in a social context may be generated through real-life case studies embedded in biology courses, or in social science courses designed specifically to explore the effect of science and technology on human beings (e.g., Fluck, 2001; Pai, 2008).

Table 2.1 describes the core competencies as sets of skills linked to disciplinary practice. The development of these skills will enable students to better understand the core concepts presented earlier and, consequently, will advance their ability to practice biology. Biology majors achieve an increasing understanding of the core concepts and greater proficiency in doing biology as they proceed down their chosen academic path, but all students should have opportunities to develop these basic competencies.

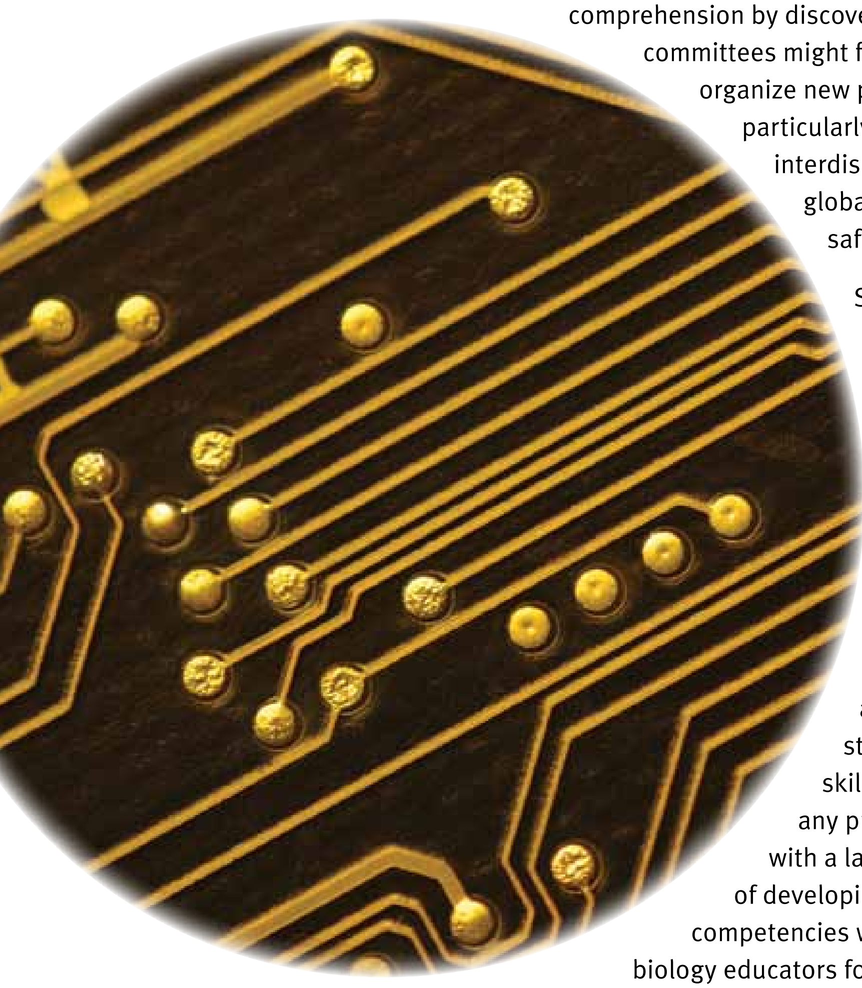
Table 2.1: Core Competencies and Disciplinary Practices. A competency-based approach to undergraduate biology education focuses on demonstrating analytical, experimental, and technical skills as measurable outcomes of student learning. Biology literacy is defined primarily in terms of acquired competencies, demonstrated within the context of fundamental biology concepts.

Core Competency	Ability to apply the process of science	Ability to use quantitative reasoning	Ability to use modeling and simulation	Ability to tap into the interdisciplinary nature of science	Ability to communicate and collaborate with other disciplines	Ability to understand the relationship between science and society
Instantiation of Ability in Disciplinary Practice	Biology is an evidence-based discipline	Biology relies on applications of quantitative analysis and mathematical reasoning	Biology focuses on the study of complex systems	Biology is an interdisciplinary science	Biology is a collaborative scientific discipline	Biology is conducted in a societal context
Demonstration of Competency in Practice	Design scientific process to understand living systems	Apply quantitative analysis to interpret biological data	Use mathematical modeling and simulation tools to describe living systems	Apply concepts from other sciences to interpret biological phenomena	Communicate biological concepts and interpretations to scientists in other disciplines	Identify social and historical dimensions of biology practice
Examples of Core Competencies Applied to Biology Practice	Observational strategies Hypothesis testing Experimental design Evaluation of experimental evidence Developing problem-solving strategies	Developing and interpreting graphs Applying statistical methods to diverse data Mathematical modeling Managing and analyzing large data sets	Computational modeling of dynamic systems Applying informatics tools Managing and analyzing large data sets Incorporating stochasticity into biological models	Applying physical laws to biological dynamics Chemistry of molecules and biological systems Applying imaging technologies	Scientific writing Explaining scientific concepts to different audiences Team participation Collaborating across disciplines Cross-cultural awareness	Evaluating the relevance of social contexts to biological problems Developing biological applications to solve societal problems Evaluating ethical implications of biological research

NEXT STEPS

The core concepts and competencies described in this chapter serve as a framework for initiating conversations about curricular evaluation and revision within biology departments and for catalyzing cross-departmental discussions about interdisciplinary programming. As a first step, this framework provides departments with a structure for using biology curricula to identify learning outcomes appropriate for the students they serve and for their institutions' academic objectives. Such a framework can reveal a strategy for designing and applying learning assessments appropriate to varied types of programs. In turn, standards for student learning can inform discussions focused on revising existing curricula or creating new ones.

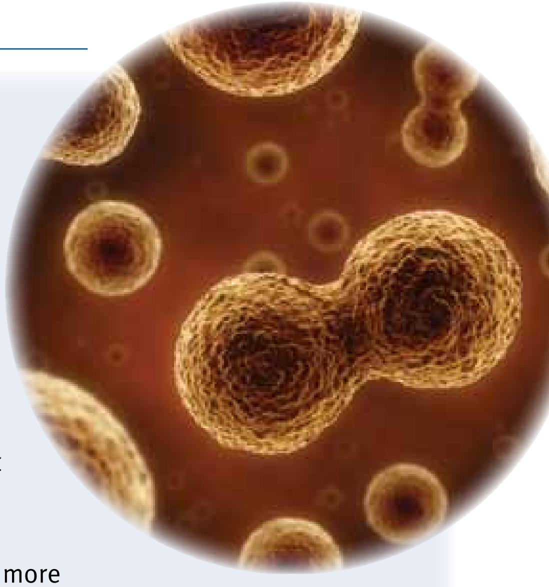
For instance, curricular discussions may focus on questions concerning (1) the types of linkages that exist or that should exist between concepts and competencies, (2) the best time to introduce specific competencies, (3) ways of increasing the depth and sophistication of the competencies, and/or (4) ways of supporting the integrated development of student competencies throughout the academic curriculum. Departments and programs may incorporate core concepts into theme-based curricula that enable students to develop comprehension by discovery or application in hands-on courses. Curriculum committees might focus on strategies for utilizing core concepts to organize new programs that integrate various disciplines or, particularly for those not majoring in biology, that address an interdisciplinary problem (e.g., the study of biodiversity, global climate change, or local or regional access to safe water).



Shifting the framework for biology education and learning also entails changing the ways in which student learning is evaluated and progress is measured. Scientific literacy includes the acquisition of skills that enable the productive use of experimentally generated data sets and scientific information. These competencies and others cannot be adequately measured solely by correct answers on multiple-choice tests, but must be assessed through demonstrations of students' thinking and scientific problem-solving abilities. Curriculum revision must involve giving students regular opportunities to demonstrate their skills in controlled contexts—a challenging task for any program, especially an undergraduate program with a large and diverse student enrollment. The challenge of developing effective strategies for assessing scientific competencies will undoubtedly occupy the creative efforts of biology educators for some time to come.

ACTION ITEMS

- Introduce the scientific process to students early, and integrate it into all undergraduate biology courses.
- Define learning goals so that they focus on teaching students the core concepts, and align assessments so that they assess the students' understanding of these concepts.
- Relate abstract concepts in biology to real-world examples on a regular basis, and make biology content relevant by presenting problems in a real-life context.
- Develop lifelong science learning competencies.
- Introduce fewer concepts, but present them in greater depth.
- Stimulate the curiosity students have for learning about the natural world.
- Demonstrate both the passion scientists have for their discipline and their delight in sharing their understanding of the world with students.



UNDERGRADUATE STUDENT VOICES

DISCUSSION QUESTION

In what ways can biology education be improved?

STUDENT RESPONSES

Introductory courses are too broad

- Give entering Bio 101 students a diagnostic test, and split them into three groups: the ones who really need more basics to supplement what they didn't get in high school, the ones ready for 101, and the ones ready for something more advanced. Stop the "one-size-fits-all" Bio 101.
- Reduce the amount of information in classes; teach students how to learn so they can gain depth on their own.
- Have more topic-based or concept-oriented courses, especially for nonmajors.

Less emphasis on memorization

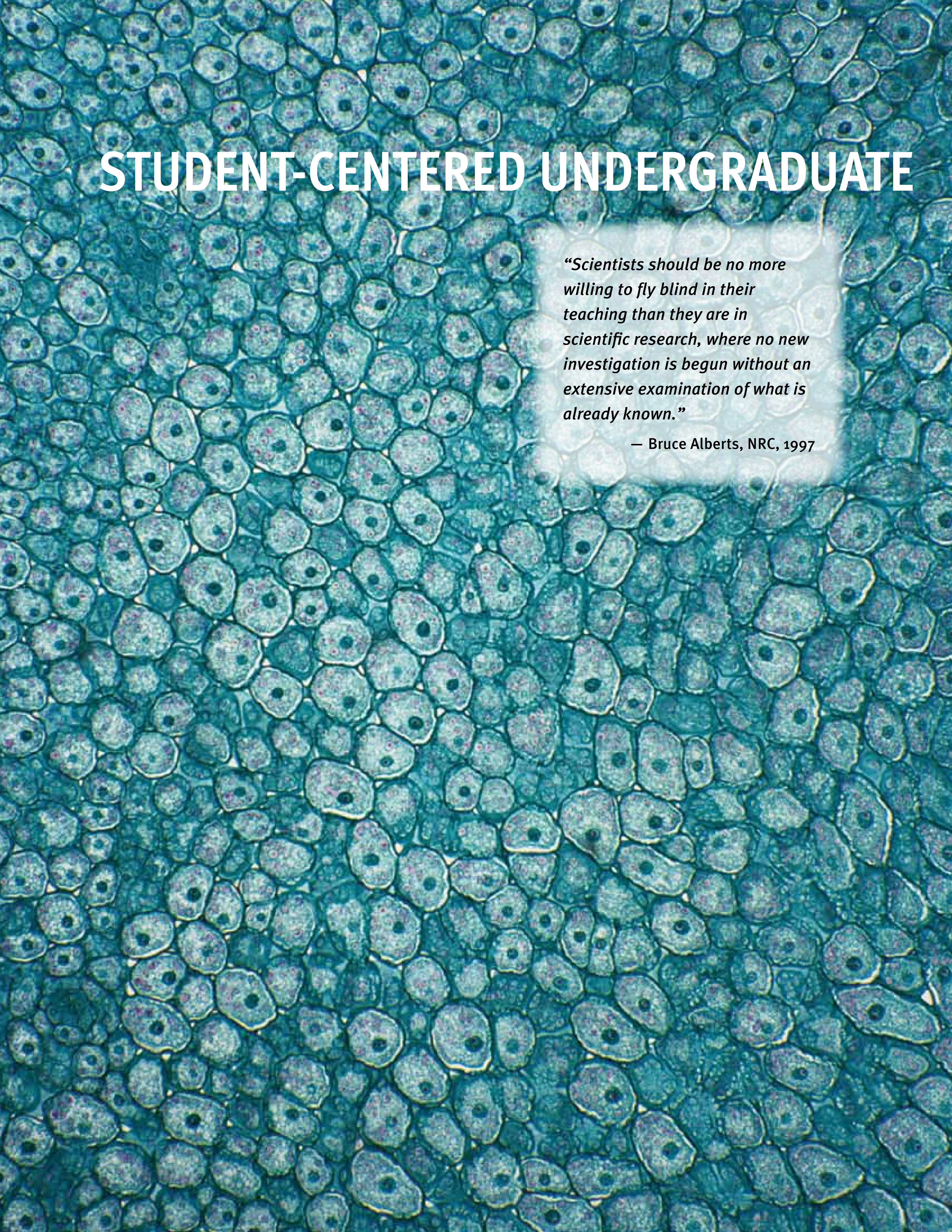
- More emphasis on application and problem solving—if science changes so much, why are we trying to memorize everything?
- More emphasis on the "how" of science: what is the evidence and how did we obtain it?
- Have projects where knowledge needs to be applied instead of exams where facts are regurgitated.
- More essay questions on exams. Even in classes where we discuss broader concepts, we are still tested on the fine details.
- Use case studies where the professor facilitates a discussion about them.

More connections across the curriculum

- Professors should be more explicit about what they want students to get out of the course and why it's necessary to know those things.
- More connections between lecture and lab components within an individual course.
- More connections across the disciplines (e.g., between chemistry and biology and between physics and biology).
- There should be greater discussion of the curriculum as a whole with the students: why you need this course, that technique, etc., and how it all fits together; have a short seminar course before or with introductory biology for those who know they want to be biology majors.
- More interdisciplinary courses.

For more information, visit
http://media.collegeboard.com/digitalServices/pdf/ap/10b_2727_AP_Biology_CF_WEB_110128.pdf

STUDENT-CENTERED UNDERGRADUATE



"Scientists should be no more willing to fly blind in their teaching than they are in scientific research, where no new investigation is begun without an extensive examination of what is already known."

— Bruce Alberts, NRC, 1997

CHAPTER 3

BIOLOGY EDUCATION

A number of reports over the last two decades (e.g., Labov et al., 2010) have called for renewed attention to undergraduate science education in general and to the life sciences in particular. In light of the ongoing genesis and maturation of exciting new areas in biology (e.g., NRC 2008, 2009), the time has never been better to focus on student learning and to integrate research and education to attract more students to explore the life sciences, both for career options and to better understand the complex world in which they live.

Traditionally, introductory biology courses have been offered as three lectures a week, with, perhaps, an accompanying two- or three-hour laboratory. This approach relies on lectures and a textbook to convey knowledge to the student and then tests the student's acquisition of that knowledge with midterm and final exams. Although many traditional biology courses include laboratories to provide students with hands-on experiences, too often these "experiences" are not much more than guided exercises in which finding the right answer is stressed while providing students with explicit instructions telling them what to do and when to do it. As one writer quipped, introductory science courses can be like a "travelogue through a myriad of topics that educators, exam manufacturers, and textbook authors have determined to be essential to every student's college experience" (Tobias, 1997).

First science courses do not need to be stuffed with facts. Indeed, most of the recent reports on the status of undergraduate science education (e.g., see "National Calls for Improving Undergraduate Science Education" in Chapter 1) recommend inquiry-rich, investigative experiences for all students, from their first year through graduate school.

So how can a biology curriculum be organized to "induce students to enjoy science from the first day" of their academic experience in a biology course (Project Kaleidoscope, 1991)? Powerful approaches to this challenge include connecting the student to a community of scholars, personalizing the learning experience, placing science in context with events in students' lives, developing a curricular sequence organized around widely agreed upon content themes, and designing the curriculum so that it develops student competencies. (See Chapter 2.) Making undergraduate courses and teaching methods more student centered and relevant, and providing authentic research experiences as part of an undergraduate education, also can help to achieve these ends, as can providing opportunities for faculty and students to work in a collaborative learning community from matriculation through graduation.

RETHINKING THE CURRICULUM: THE STUDENT-CENTERED CLASSROOM

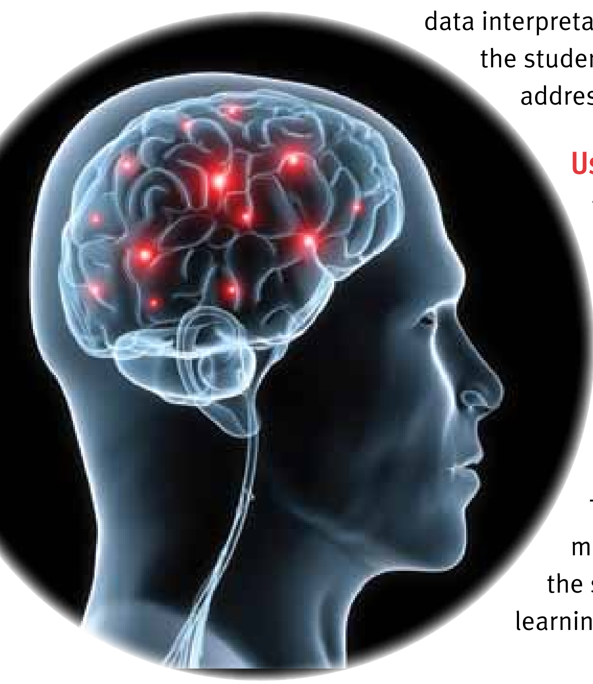
During the Vision and Change conversations and discussions at the national conference, participants noted that biology faculty at campuses around the country are increasingly engaged in discussions about what and how they teach, and that many departments encourage discussions about how their curricula can best serve both life sciences majors and the other undergraduates who take their courses. However, many faculty still express uncertainty over how to better connect teaching with learning, how to make approaches to teaching biology align better with the practice of science, and how to fine-tune undergraduate biology courses to better meet the needs of the diverse student bodies we all serve. Faculty who teach introductory biology also observed that it is easy to fall into the trap of offering lecture-based courses that emphasize rote memorization of isolated facts, rather than designing a course that uses those same facts to promote a deeper understanding of basic concepts.

To address these concerns, meeting participants recommended that instructors shift their focus from faculty-centered teaching to student-centered learning, and away from presenting all the facts (i.e., “covering the material”) toward clearly articulating expected student learning outcomes and following the students’ progress in achieving those outcomes. Ideally, these learning outcomes should include the competencies to be developed, the concepts to be understood, and the factual knowledge to be acquired. This simple shift of focus can provide faculty and students alike with measurable outcomes that can be tracked within individual courses and throughout the curriculum. The following questions can be very helpful in developing a new biology course or redesigning an existing one (see Wiggins and McTighe, 2005; adapted from Handelsman et al., 2007):

1. What knowledge and skills are relevant to the subject area? What should students know and be able to do at the end of the unit or course?
2. What do proficiency and mastery in the subject area at this level in the curriculum (e.g., an introductory course or capstone seminar) look like?
3. What evidence would I accept that a student has achieved proficiency or mastery across the relevant content and skills identified in item 1? What evidence would convince my colleagues?

In addition, faculty should ask themselves whether the learning experiences they offer to all undergraduates meet the foundational goals addressed in Chapter 2 and are sufficient to address future questions, issues, and problems.

Although the definition of student-centered learning may vary from professor to professor, faculty generally agree that student-centered classrooms tend to be interactive, inquiry driven, cooperative, collaborative, and relevant. Three critical components are consistent throughout the literature, providing guidelines that faculty can apply when developing a course (e.g., NRC, 2000). Student-centered courses and curricula take into account student knowledge and experiences at the start of a course and articulate clear learning outcomes in shaping instructional design. Then they provide opportunities for students to examine and discuss their understanding of the concepts presented, offering frequent and varied feedback as part of the learning process. As a result, student-centered science classrooms and assignments typically involve high levels of student–student and student–faculty interaction; connect the course subject matter to topics students find relevant; minimize didactic presentations; reflect diverse aspects of scientific inquiry, including data interpretation, argumentation, and peer review; provide ongoing feedback to both the student and professor about the student’s learning progress; and explicitly address learning how to learn (reviewed in Wood, 2009b).



Using Scientific Teaching to (Re)Envision a Life Sciences Course

The process of making courses and curricula more student centered might not be as foreign to life scientists as it might seem at first glance. Over the past decade, innovators in both the life sciences and education research have been exploring new models of course and curriculum design, as well as examining teaching from a scientific perspective (e.g., Handelsman et al., 2004, 2007; Labov et al., 2009). Figure 3.1 diagrams the close connection between assessment, learning outcomes, and instruction embedded in the “backward design approach” to instruction. This approach mirrors the conduct of scientific research as articulated by many science educators (e.g., Wiggins and McTighe, 2005) and emphasizes the systematic collection of data on how a course is conducted and on learning outcomes.

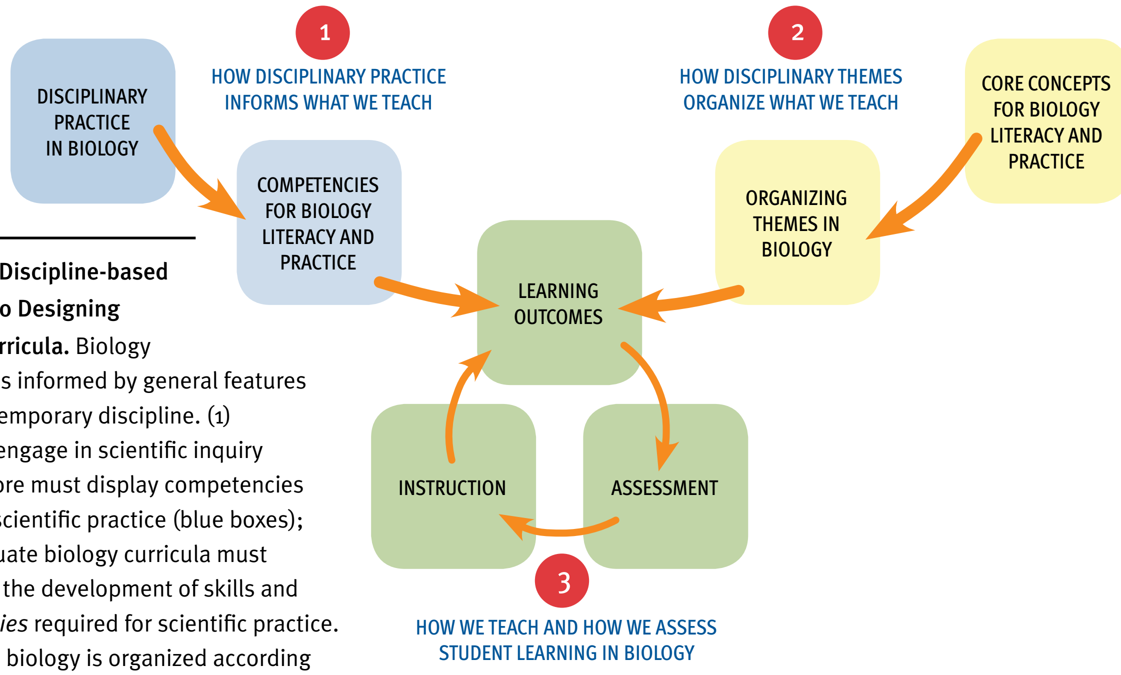


Figure 3.1: **Discipline-based Approach to Designing Biology Curricula.** Biology education is informed by general features of the contemporary discipline. (1) Biologists engage in scientific inquiry and therefore must display competencies related to scientific practice (blue boxes); undergraduate biology curricula must emphasize the development of skills and *competencies* required for scientific practice. (2) Modern biology is organized according to fundamental themes reflected in a set of *core concepts* in the discipline (yellow boxes); the organization of undergraduate biology curricula must reflect the structure of the discipline and provide a scaffold for student learning. (3) The identification of specific learning outcomes informs the development of appropriate assessment and instructional strategies for undergraduate biology curricula (green boxes).

"Scientific teaching" (as described by Handelsman et al., 2007) recommends that faculty iteratively review and revise a course or curriculum on the basis of evidence that students are learning the ways of science and developing defined concepts and competencies. In this model and that of backward design, student-centered courses begin with the articulation of clear, measurable learning goals, followed by the adoption of assessment tools that are appropriate for evaluating the extent to which students have achieved these goals. The tools assess students' mastery of facts, conceptual understanding, and acquisition of competencies and skills, as well as their attitudes and motivation (Baldwin et al., 1999; Ebert-May et al., 2003). By following the progress of student learning, faculty can continually select and adjust their teaching strategies to engage the students and help them deepen their understanding of the topics presented in the course. Well-defined learning outcomes explicitly stating what students should know and be able to do at the end of a course can also aid the development of effective instructional materials (e.g., see Figure 3.1).

The assessment techniques used, both quantitative and qualitative (e.g., objective questions, surveys, extended responses, problems, models, projects, laboratory investigations), should be valid measures of learning, attitudes, and behaviors. The data obtained can then be employed to guide decisions about the course (e.g., what do students understand, what is difficult for them to learn, what motivates the students, how should instruction be modified to better facilitate student learning). Most biology faculty already have the research skills needed to initiate these kinds of scientific approaches to improved learning outcomes. However, as the Vision and Change participants noted, they sometimes need help applying those skills to undergraduate education.

Frequent assessment activities also provide students with feedback about how well they are doing so that they can monitor their own progress toward their learning goals. In addition, ongoing course assessment helps faculty focus on the connection between their teaching and student learning as a course proceeds. Thus, faculty can identify gaps and misconceptions in student learning and, as a result, shift their teaching strategies to support student learning more effectively (e.g., Brewer, 2004; Smith et al., 2005; Cotner et al., 2008; Mayer et al., 2009).

As they develop course goals and identify appropriate assessment tools, faculty need to recognize that students have different background knowledge, experiences, beliefs, and cultural contexts, all of which they bring to the classroom and from which they try to learn. Student-centered learning recognizes that students are not blank slates, but rather "construct" their own knowledge (Fosnot, 1996; Ausubel, 2000) by integrating new knowledge into what they already know. It is, therefore, useful to find out what students know (or think they know) on the first day of class or on the first day of a new instructional unit, after which the course content can be designed accordingly. For example, to find out if various instructional goals were appropriate for their students, Berger et al. (1999) designed and implemented a survey to measure student perceptions of their knowledge about, experience with, and confidence in dealing with the various topics to be taught in a course.

Upfront planning helps ensure that assessment aligns with a course's objectives and with the strategies employed to foster learning. Assessments that do not align with learning goals and class activities undermine both student learning and faculty evaluation of the effectiveness of classroom teaching. For example, if instructional materials emphasize deep conceptual understanding, but multiple-choice exams are used to test only fact-based learning, students will focus mostly on learning facts divorced from concepts. Conversely, if classroom activities are primarily fact based, but exams test for higher order thinking skills, students will likely find that their studying has been in vain, become frustrated, and lose interest in the course, and abandon any plans they had for taking higher level courses in biology. A student-centered approach that uses well-articulated learning outcomes to align assessments with learning activities (i.e., the "backward design" of planning for assessment from the very beginning of a course; see Wiggins and McTighe, 2005) can give faculty a critical framework for designing a student-centered classroom for learning (Handelsman, et al., 2007; Ebert-May and Hodder, 2008).

Identifying Appropriate Assessment Tools

Assessment may be characterized as applying data collection tools on a scale with two measures: ease of administration and potential for correctly evaluating student achievement. (See Figure 3.2.) For example, multiple-choice questions are relatively easy to grade, yet have a low potential for revealing higher level cognitive thinking; by contrast, oral interviews and essays take more time to evaluate, but provide greater insights into student understanding (Pelaez et al., 2005).

Many excellent references are available to assist faculty with designing student-centered courses in the life sciences that converge with recommended assessment approaches (e.g., NRC, 1997, 2003; Wiggins and McTighe, 2005; Handelsman et al., 2007; Ebert-May and Hodder, 2008; Labov et al., 2009). Ultimately, the kinds of assessments used and data collected depend on the goals the faculty member sets for the students in the course, with different kinds of assessments having different potentials for measuring whether the student has met those goals. Table 3.1 gives an overview of some assessment instruments and what they measure.

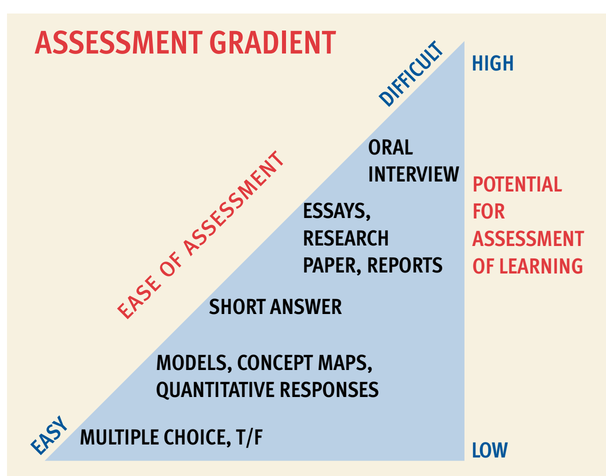


Figure 3.2: **Assessment Gradient** (from Janet Batzli, Biology Core Curriculum, University of Wisconsin–Madison and Tammy Long, Plant Biology, Michigan State University).

Table 3.1: **Examples of Assessment Instruments and Instructional Methods for College and University Biology Faculty**

ASSESSMENT INSTRUMENT/ INSTRUCTIONAL METHOD	PURPOSE	CITATION
Authentic research: open-ended, student-designed, inquiry-driven, mentored research activities	Students carry out ongoing potentially publishable research in undergraduate laboratory courses to enhance their conceptual understanding and their factual and procedural knowledge related to biological processes and research activities.	Bednarski et al., 2005; Dymond et al., 2009; Roth, 1995
Case studies/scenarios in the classroom	Students work through scenarios that require them to apply the biology they are learning to social, ethical, political, or research-related dilemmas.	Allen & Tanner, 2003; Boehrer & Linsky, 1990; Clancy & Linn, 1992
Calibrated Peer Review	Students write papers, and then an integrated set of network tools manages the peer review of written student work. Writing and reviewing assignments can be shared across institutions.	Pelaez, 2002 Hartberg et al., 2008
Gowan's V diagrams	Graphic organizing tools that allow students to demonstrate their thinking skills and knowledge.	Mintzes et al., 2001
Immediate Feedback Assessment Technique (IFAT)	Interactive testing system with immediate feedback for students; intended to enhance learning rates.	Epstein et al., 2002
Immediate response systems Personal response systems Clicker systems	Classroom or online systems for enhancing small-group discussions and faculty–student interaction in large classes. Provides feedback to instructors and students that is immediate enough to be useful during a given class period.	Guthrie & Carlin, 2005; Hall et al., 2005; Brewer, 2004
Inquiry-based learning Inquiry-driven learning	Instruction designed around student questions in order to facilitate the process of learning to discover knowledge.	Bruner, 1961; O'Donnell et al., 1997; Ebert-May et al., 1997
Model-based learning	Relatively simple mental models are developed for students to work with in order to represent and comprehend complex biological phenomena.	Gilbert & Boulter, 1998; Buckley, 2000
Novak's concept mapping	A method for developing graphic tools that allow students to explore, demonstrate, and share their understanding of a set of concepts and the nature of the interrelationships among those concepts.	Novak & Gowin, 1984; Novak, 1998
Outcomes-based education	Analysis of relative success in achieving specific predetermined measured (quantified) learning outcomes.	Castleberry, 2006
Peer-led Team Learning (PLTL); learning by teaching	Strategies for recruiting, preparing, and supporting students who have previously taken a course to serve as guides and mentors (peer leaders) for current students. Peer leaders facilitate small-group discussions.	Roscoe & Chi, 2004; Gafney & Varma-Nelson, 2008; Eberlein et al., 2008
Portfolios, reflections, journals, websites, etc.	A collection of related strategies that allow for analysis of work samples.	Vitale & Romance, 2000
Problem-based Learning (PBL)	Student-centered learning, with students working through a cycle of evaluating a problem, collecting data, recommending solutions, and evaluating the process of coming up with a solution.	Allen & Tanner, 2003; Waterman & Stanley 1998; Eberlein et al., 2008
Process-oriented Guided Inquiry Learning (POGIL)	Student-centered learning, with students assigned to specific roles within small groups so that all are actively engaged in the process of learning.	Farrell et al., 1999; Eberlein et al., 2008
Pyramid exams, collaborative exams	Small groups of students are engaged and assessed as they collaborate on examinations.	Cortright et al., 2003; Eaton, 2009
Team-based learning	Small groups of students work together as high-performance teams to accomplish learning through structured tasks.	Michaelsen et al., 2004; Michaelsen et al., 2002; Treisman, 1992

Implementing Effective Instructional Practices

Once course goals are established and a strategy for collecting assessment data is in place, the next step is to choose the best instructional practices for helping students achieve those goals. Traditional science instruction has relied on a lecture format as the primary teaching tool. This approach assumes that every student needs the same information, presented orally, at the same pace, and in a manner that limits interaction among students and between students and faculty. But relying solely on lectures, especially in introductory courses, tends to promote low-level learning, focused on memorization of factual information, and student attention tends to decrease as the lecture proceeds. Not surprisingly, many students dislike lecture-only courses (e.g., see the "Undergraduate Student Voices" highlighted throughout this report).

When implementing a more interactive student-centered approach to teaching, faculty cannot conceivably cover as much material; thus, a key concern is maintaining rigor in the curriculum. Indeed, many faculty express the fear of "dumbing down" the curriculum as they move toward highly interactive class formats that emphasize more time devoted to student involvement in class discussions and less to lecture. And yet, undergraduates who participated in the Vision and Change conversations or attended the national conference clearly place a premium on learning how to think critically, ask informed and insightful questions, find information for themselves, communicate well, and work effectively in groups.

Table 3.2 lists many of the instructional strategies that have been designed to produce a student-centered classroom. These have been developed and tested in colleges and universities around the country and have been found to be effective. Typically, these strategies engage students more actively in every aspect of their learning and are interactive, inquiry driven, cooperative, and collaborative, allowing students to engage with each other and with faculty. For example, the "problem–based model of instruction," or learning cycle (Bybee, 1997; Fuller, 2002), revolves around a series of related questions that first probe what students know about a topic and then move to unfamiliar, new ground, enabling the students to develop a more complete and accurate understanding of the topic. Faculty initiate student interactions with key guiding questions and opportunities for discussion, present a short explanation of the necessary background knowledge, and then have students work together on questions to deepen their understanding through reflection on and application of their knowledge (e.g., Ebert-May et al., 1997). This approach incorporates frequent informal assessment (e.g., Angelo and Cross, 1992) to address misconceptions and provides a balance between direct instruction and student interaction. One or two class sessions using this approach to introduce a topic such as evolution might unfold in the following way (e.g., Ebert-May et al., 2008):

1. ***Engagement Question:*** For example, "What is evolution?" This background question probes student knowledge of the topic.
2. ***Exploration:*** Students share their answers with other students sitting nearby and come to a consensus; volunteers from the groups share their answer with the class, allowing the instructor to listen for misconceptions and depth of understanding.
3. ***Explanation:*** The instructor presents a short interactive lecture (15 minutes) on the topic, providing explanations to help clarify student thinking based on identified misconceptions.
4. ***Extension Question:*** Students work together on a more advanced question that might, for example, call for them to analyze information, formulate critical questions and hypotheses, evaluate and criticize evidence, or propose alternative solutions. In the example of evolution, the extension question, tied to a learning goal, might be *What mechanisms are involved in natural selection, and what role does natural selection play in antibiotic resistance in bacteria today?* Again, groups are called on to explain their answers and how they came to them.
5. ***Quiz Question:*** The final assessment (which may or may not be formally graded) allows both the student and the instructor to chart the effectiveness of teaching and learning.

The preceding example addresses a common misconception that student-centered learning cannot include any lectures. In a student-centered context, however, faculty may use the lecture format as one of many tools for teaching. Ideally, faculty will draw on a variety of instructional approaches in their teaching, including, but not limited to, lecturing. Many of the excellent resources for identifying interactive, student–centered teaching strategies listed in Table 3.2 have been used in, and can be adapted to, even the largest lecture halls (Ebert-May et al., 1997; NRC, 1997, 2003a; Handelsman et al., 2007; Ebert-May and Hodder, 2008).

Table 3.2: **Student-Centered Learning Resources.** Even the largest undergraduate biology classroom can incorporate active learning to enhance student learning. This table provides an overview of places to look for more information on how to integrate student-centered learning throughout the biology curriculum.

STRATEGY	EXAMPLE	REFERENCES FOR EXAMPLE OR FOR THE GENERAL STRATEGY
General biology examples of active learning: "How to" and efficacy resources	Resource guides for getting started	Handelsman et al., 2007; Ebert-May & Hodder, 2008
	Review article on active learning strategies relating to physiology education	Michael, 2006
	Articles describing models for implementing active learning in classrooms	Allen & Tanner, 2005; McClanahan & McClanahan, 2002: Smith et al., 2005
	Research articles on efficacy of active learning strategies in biology classes	Freeman et al., 2007; Knight & Wood, 2005: Walker et al. , 2008
Classroom assessment and immediate response (clicker) systems	Online resource for articles on clickers and other resources	Clicker Bibliography at UMass Amherst http://srri.umass.edu/topics/crs/bibliography
	Research article on efficacy of clickers in classrooms with large enrollment	Mayer et al., 2009
	Research article on Immediate Feedback Assessment Technique (IFAT) and clicker (perception data)	Cotner et al., 2008
	Comprehensive "how to" resource book on classroom assessment ideas	Angelo & Cross, 1993
Case-based learning	"How to" resource book	Herreid, 2007
	Article on how to use clickers to implement case studies in class	Herreid, 2006
	Online resources for case studies	Case It! http://caseit.uwrf.edu/ Investigative Case Based Learning http://www.bioquest.org/icbl/cases.php National Center for Case Study Teaching in Science http://ublib.buffalo.edu/libraries/projects/cases/case.html
Model-based learning	"How to" resource for redesigning courses with model-based instruction	Jackson et al., 2008; NetLogo site: http://ccl.northwestern.edu/netlogo/
Problem-based Learning (PBL)	"How to" guide for PBL	Duch et al., 2001
	Article describing specific bioinformatics example of PBL	White & Dhurjati, 2006
	Online resources for PBL	Interdisciplinary Journal of PBL http://docs.lib.purdue.edu/ijpbl PBL@UD http://www.udel.edu/inst
Peer-led Team Learning (PLTL)	Article comparing PBL, POGIL, and PLTL approaches	Eberlein et al., 2008
	Articles looking at efficacy of PLTL	Gafney & Varma-Nelson, 2007; Gafney & Varma-Nelson, 2008; Gosser et al., 2010; Preszler, 2009
Team-based learning	"How to" resources	Michaelsen et al., 2004; Barkley et al., 2005

INTEGRATING UNDERGRADUATE RESEARCH EXPERIENCES

Many working scientists were first drawn into biology careers by a hands-on experience—a science fair project, an intriguing high school biology laboratory experiment, or an undergraduate research opportunity. For current undergraduates, having an opportunity to experience the allure of the scholarship of research can spark or solidify an interest in biology or even inspire a shift in academic or career objectives toward the sciences. But whether or not undergraduates who participate in research ultimately choose research careers, their participation improves their ability to understand how biologists and other scientists conduct research and better prepares them to evaluate science and scientific claims in their day-to-day lives.

Hands-on research also cultivates scientific thinking, allowing students to experience authentic activities of working scientists, including designing studies, interpreting unexpected outcomes, coping with experiments that fail, considering alternative approaches, and testing new techniques—all activities that are difficult, if not impossible, to replicate in standard lecture or laboratory courses. As practiced, undergraduate research experiences vary widely in their depth, technical sophistication, collaborative nature, and duration, reflecting the nature of the academic institution and the maturity of the student researchers, as well as the kind of course setting. Although independent research projects supervised by faculty mentors (e.g., the long-running NSF Research Experiences for Undergraduates [REU] program) have been the most traditional type of research experience available to undergraduates, aspects of research can be integrated into curricula in a variety of additional ways, in both the short and the long term (CUR, 2007; Healey and Jenkins, 2009).

For example, faculty are finding creative means to incorporate research experiences throughout the undergraduate curriculum, from having students read and evaluate journal articles to dedicating a significant part of the academic term to guided or independent research projects in both courses for majors and courses for nonmajors. Indeed, undergraduate research experiences can go far beyond the traditional apprenticeship model in a research laboratory. Innovative in-course research experiences have been introduced on many two- and four-year campuses as well as into research-oriented institutions (e.g., Snellman, et al. 2006; Hoskins et al., 2007; Karukstis and Elgren, 2007; Cejda and Hansel, 2009). The sidebars within this chapter present some excellent examples of in-course approaches.

In the apprenticeship model, undergraduates participate in, and may even design and conduct, an independent research project related to a faculty member's research interests. Students become members of the laboratory community, which may include postdoctoral fellows, graduate students, and technical assistants. The student attends laboratory meetings and is supervised by the faculty member or a senior lab member. The duration of the project can be quite variable, spanning multiple terms (perhaps including summers) or a single summer. In the best circumstances, the student's results are communicated in a research thesis or a peer-reviewed research publication.

A growing body of literature has found a link between student research and lasting learning (NRC, 2000, 2003b; Lopatto, 2003, 2007, 2009; Laursen et al., 2010). Research experiences can also increase a student's interest in a graduate career in biology or another science. But the benefits of some form of research experience are substantial even for students who do not pursue graduate study. In a survey administered to more than 2000 undergraduates at 66 universities (Survey of Undergraduate Research Experiences [SURE], in Lopatto, 2007), students described the research experience as having produced substantial gains in their "understanding of the research process," "readiness for more demanding research," "understanding how scientists work on problems," "learning lab techniques," and "tolerance for obstacles," as well as numerous other areas related to research. These gains persisted when the same students were surveyed nine months later, suggesting that the benefits of research experiences are long lasting, whether in a classroom setting or as part of a more intensive guided or independent research experience (Lopatto, 2007; Hunter et al., 2007; Laursen et al., 2010).

A separate, detailed ethnographic analysis of student interviews after their research experiences showed a number of student gains, including increased confidence in their ability to “think like scientists”; increased intellectual development, and, for some, reinforcement in their choice of a science-related career (Hunter et al., 2007). Close to 70% of approximately 3400 graduates who recently were surveyed reported that their participation in research increased their interest in science-related fields, awareness of what graduate school would be like, and confidence in their research skills (Russell et al., 2007).

Research experiences for undergraduates energize biology majors to continue majoring in the subject, and the effect is stronger for members of minority groups that are currently underrepresented in academic science in the United States (Jones et al., 2010). Interestingly, *early* participation in research (i.e., during the first or second college year) is particularly influential. Students’ increased understanding of scientific processes and scientific thinking, as well as any gains in confidence in their own ability to think like scientists and contribute to the field, may enhance their overall ability to learn science. If so, then extending some form of biology research experience to general education students as well as life sciences majors, and offering that experience early in students’ college careers, could help to bring about a deeper understanding of science for all students.

Results from the SURE survey, widely used to evaluate summer undergraduate research experiences (most offering the apprenticeship model), indicate that even a short immersion experience is sufficient to effect long-term gains in student motivation for learning, independence and understanding of science (Lopatto, 2007). Undergraduate participation in some kind of research in introductory courses, therefore, may be the key to developing an enduring understanding of core concepts for all undergraduate students.

Recognizing the value of undergraduate research experiences, many universities and colleges have established offices that offer various levels of support to undergraduates who are seeking research opportunities. Given the success of these efforts, more institutions should consider establishing similar offices to better engage students and support student-centered learning. (See the section titled “In Practice” later in this chapter for case studies presenting creative ways to involve students in research across a wide spectrum of institutions.) Vision and Change participants also recommended that biology faculty who teach undergraduates consider the benefits of integrating research components into their classrooms and student laboratories.

ACTION ITEMS

- Engage students as active participants, not passive recipients, in all undergraduate biology courses.
- Use multiple modes of instruction in addition to traditional lecture.
- Ensure that undergraduate biology courses are active, outcome oriented, inquiry driven, and relevant.
- Facilitate student learning within a cooperative context.
- Introduce research experiences as an integral component of biology education for all students, regardless of their major.
- Integrate multiple forms of assessment to track student learning.
- Give students ongoing, frequent, and multiple forms of feedback on their progress.
- View the assessment of course success as similar to scientific research, centered on the students involved, and apply the assessment data to improve and enhance the learning environment.

UNDERGRADUATE STUDENT VOICES

DISCUSSION QUESTION

In what ways can biology education be improved?

STUDENT RESPONSES

"Old school" lecture style is frustrating and not engaging

- Professors should ask open-ended questions where they don't know the answer, so you are defending your answer and not guessing what the professor wants.
- More opportunities for small-group work and chances for discussion (e.g., peer teaching/learning), especially in large-enrollment courses.
- Incorporate demonstrations or media (e.g., YouTube) to illustrate topics.
- Use quizzes during or after each lecture (e.g., with clickers) to keep students engaged and see what they did or didn't learn.
- The information presented should be appropriate for both visual and auditory learners; just putting all the lecture text onto a PowerPoint [presentation] isn't very effective.

"Canned" labs are ineffective/uninteresting

- Have more inquiry-based labs where we don't know the answer ahead of time.
- Let the students engage in more troubleshooting (instead of the TAs) so we understand why something did or didn't work.
- More opportunities for creativity, like designing our own lab experiments, especially early on and not just in upper-level courses.
- Learn how to work with real data; learn to deal with ambiguity and that science can be "messy."

Courses feel disconnected from "real-world" science: more relevance/context needed

- Incorporate more discussion about how biology [affects] our lives.
- Read more primary literature and recent developments: What's going on in the field right now?
- Learn to critically analyze the current literature.
- Biology majors should take a history/philosophy of science or a science and society course.
- Have topic-based courses designed around real-world relevant issues.

IN PRACTICE

INTRODUCING RESEARCH INTO THE UNDERGRADUATE BIOLOGY CURRICULUM

Few biology departments can accommodate all students with an interest in pursuing research projects. Consequently, faculty have devised a range of strategies that incorporate research activities into coursework at both the introductory and advanced levels, for both biology majors and those majoring in other disciplines. For some of these activities, the goal may not be the creation of new knowledge, but simply the development of the student as a scientist or the provision of opportunities to experience the processes of science. The examples that follow are a small sample of the many strategies that faculty have used successfully to incorporate research experiences into coursework. In each case, assessment data attest to the success of these strategies in promoting scientific thinking by students.

LABORATORY RESEARCH COURSES

Laboratory research courses can be designed around a professor's personal research interests—a strategy adopted by many colleges and universities over a range of scales. Students in laboratory courses often work in teams, sometimes in parallel with one another. In many cases, students contribute data to research publications. The next two examples describe very different settings in which faculty have collaborated to incorporate authentic research projects into laboratory courses.

Biology majors at Centenary College, a small, liberal arts college in Louisiana, are required to enroll in BIOL313, an upper-division genetics laboratory course that accompanies a lecture course. Approximately 50 students enroll in three sections of the course each spring. Working in groups of two or three, students identified conserved sequences in yeast casein kinase, introduced site-directed mutations, and functionally tested the mutant alleles by complementation in *yck* mutant strains. Several alleles were selected for further study in independent research projects, which may lead to research publications. In addition to citing specific knowledge gains, students reported that they increased their understanding of the steps involved in the processes of science (Braeme et al., 2008).

Distributed genomics projects offer many opportunities for students at multiple institutions to participate in original research. The Genomics Education Partnership (GEP) at Washington University in St. Louis is based on the successful model of a genomics laboratory class at the university whose data have appeared in a research publication (Slawson et al., 2006). The GEP works at finishing and annotating chromosome 4 sequences from several *Drosophila* species and has developed a repository of curriculum materials that can be tailored to a range of classroom formats and student abilities. Since its inception in 2006, the GEP has recruited faculty from 47 schools. Students upload data to a central server that is accessible to other GEP members. Members use the data to draw conclusions about evolution and heterochromatin structure. By March of 2010, GEP students had finished annotating over two Mbp of DNA sequences to high quality. Evaluation data indicate significant student gains in problem solving and in critical analysis and understanding of research, in addition to knowledge gains in genome biology (Shaffer et al., 2010).

For more information, visit
http://gep.wustl.edu/

IN PRACTICE

INTRODUCING RESEARCH INTO LECTURE CLASSES

Research experiences need not be limited to laboratory classes. Several recent studies indicate that students can also gain an understanding of the processes of science by a detailed analysis of research done by a specific research group. In addition to demystifying these processes, the next two approaches have the added interesting effect of breaking through the stereotypes that students often hold of scientists.

In the C.R.E.A.T.E. *(**C**onsider, **R**ead, **E**lucidate hypotheses, **A**nalyze and interpret data, **T**hink of the next **E**xperiment)* approach (Hoskins et al., 2007), students learn to think of themselves as scientists as they are carefully guided through a sequence of four papers from the same laboratory, focused on a single research topic (i.e., as cited in Hoskins et al., 2007: a module of four articles from the laboratory of Christine Holt, including Nakagawa et al., 2000; Mann et al., 2002, 2003; and Williams et al., 2003) that analyzes the role of ephrin-mediated signal transduction in axon guidance during optic nerve development. Students receive individual

sections of each paper sequentially, without receiving any knowledge of who the author is and without any information on citations in the piece. Then they use concept mapping to identify and link key issues that arise in the introduction of the paper. Next, they read the methods and results sections, diagramming and dissecting each experiment, elucidating the hypotheses tested, and analyzing the data presented before drawing conclusions. In the final step of the process, students design follow-up experiments and debate their relative merits. The process is repeated iteratively for each of the four papers.

At the end of the sequence, classes compile an email survey for authors, including questions about their career paths, lifestyles, and professional rewards and challenges, as well as a set of scientific questions related to the research. Responses to the survey have the effect of humanizing researchers to the students. Assessment data for a diverse group of students indicated that the C.R.E.A.T.E. process produced not only significant gains in critical-thinking skills, understanding of content, and self-rated ability to critically analyze articles and design experiments, but also a heightened appreciation for researchers and the research process.

In contrast to the forward trajectory of the C.R.E.A.T.E. approach, Clark et al. (2009) describe a reverse approach in which students "deconstruct" research results. The deconstruction sequence begins with a research seminar given by an invited faculty speaker. The seminar is videotaped, and over the next five weeks, students and an instructor deconstruct 5- to 10-minute segments of the presentation. Students identify the hypothesis, explore the experimental approach, and analyze the experimental data. By the end of the five-week session, students are able to intelligently discuss the experiments and apply the techniques they have discussed to hypothetical situations. The seminar speaker then returns and hosts a question-and-answer session for students.

Assessment data collected with the Classroom Undergraduate Research Experience (CURE) survey (Trosset et al., 2008) indicate significant gains in student understanding of the research process and in their ability to interpret scientific data. Interestingly, these gains are slightly higher than those demonstrated by students who conducted an independent summer research project and only slightly lower than those demonstrated by students engaged in a *Drosophila* functional genomics project.

For more information, visit

http://www1.cuny.edu/mu/forum/2007/12/17/new-teaching-method-developed-at-ccny-improves-undergraduate-students%E2%80%99-skills-attitudes-toward-science/

and

http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2796859/

IN PRACTICE

SCIENCE EDUCATION FOR NEW CIVIC ENGAGEMENTS AND RESPONSIBILITIES (SENCER)

Today's students need to understand the processes and interdisciplinary nature of science. They also need to appreciate the role of science in society and be able to communicate effectively about science with diverse audiences. These key competencies apply to science majors and nonscience majors alike; indeed, they are fundamental requirements for a scientifically literate citizenry. Although the importance of the competencies has been articulated in several different venues, implementing changes in the biology curriculum to improve them remains a challenge for many undergraduate biology educators.

At the national level, the Science Education for New Civic Engagements and Responsibilities (SENCER) program provides resources to help educators make the necessary changes. Initially funded by the National Science Foundation, SENCER is the premier program of the National Center for Science and Civic Engagement (NCSCE). The goals of the program are simple but powerful:

- Interest more students in STEM learning.
- Encourage students to connect their STEM learning to other studies.
- Strengthen students' understanding of science and their capacity for responsible work and citizenship.

SENCER helps faculty develop courses or course modules in a variety of areas that connect science learning to real-world challenges such as tuberculosis, diabetes, water quality, and natural disasters. SENCER-type courses have been implemented in a number of different academic settings, including small, primarily undergraduate institutions; large comprehensive universities; and two-year colleges. Some courses focus on human health, examining the biology of disease in concert with the socioeconomic correlates of various diseases, while others apply statistics to local issues such as environmental contamination, increasing the mathematical skills of the students.

In addition to SENCER courses, NCSCE also supports larger, multi-institutional programs designed to improve STEM education and promote civic engagement. The Great Lakes Innovative Stewardship through Education Network (GLISTEN) coordinates academic, governmental, and nongovernmental partners with the aim of preserving and protecting the Great Lakes ecosystem. Each consortium consists of at least one four-year and one two-year college or university, along with a community-based organization.

As part of the SENCER project, model courses and programs have been assessed to evaluate their effectiveness. By the end of 2006, more than 10,000 students enrolled in a SENCER course had completed a Student Assessment of Learning Gains (SALG) survey. Reviewing these surveys, independent evaluators determined that students made the following gains after completing a SENCER course (Weston et al., 2006):

- students showed gains in confidence about their science literacy skills;
- women showed greater gains in confidence than men;
- nonscience majors showed greater gains in confidence than science majors;
- students showed an increased interest in exploring careers in science; and
- students showed an increased interest in teaching science.

These findings indicate that the civic engagement emphasized in the SENCER program leads to greater student confidence in their understanding of science and, perhaps more importantly, greater *interest* in science. For the development of a scientifically literate citizenry, the latter finding may prove to be the greatest strength of these kinds of courses.

For more information, visit

http://www.sencer.net/

IN PRACTICE

COMMUNITY-BASED PARTICIPATORY RESEARCH (CBPR)

LITTLE BIG HORN COLLEGE, CROW AGENCY, MONTANA

Chartered in 1980, Little Big Horn College (LBHC) serves approximately 400 students with two-year science programs emphasizing life sciences, natural resources/environmental science, and environmental health. As a result of a Crow Reservation environmental health assessment, which identified water quality as the reservation's top environmental health concern, tribal elders and other community members recruited LBHC science faculty to work on water- and wastewater-related issues. Starting in 2006, tribal college faculty and administrators signed a memorandum of understanding to work with community leaders and with researchers at Montana State University (MSU) in Bozeman to initiate a series of community-based participatory research (CBPR) projects as part of their life sciences curriculum and undergraduate research and internship programs.

Terry Heinert, USGS, conducting integrated depth sampling on the Little Big Horn River with Brandon Good Luck (Crow Tribal Environmental Protection), Mari Eggers (Little Big Horn College), Nathaniel Tucker (LBHC intern), and Crescentia Cummins (LBHC). Photographer Joanna Thamke (USGS).

CBPR emphasizes the involvement of community members and organizations, along with students and research partners, in all aspects of the research. In this case, members of the Crow Tribal Environmental and Health Departments, the Apsaalooke Water and Wastewater Authority, the Indian Health Service Hospital, and the Elders Committee work side by side with LBHC faculty and undergraduates, Montana State University and University of New England (Maine) faculty partners, and MSU graduate students. With funding provided in part by the NIH's IDeA Networks of Biomedical Research Excellence and National Institute on Minority Health and Health Disparities programs, as well as the Environmental Protection Agency, the program has established an equitable partnership, to which all parties contribute and from which they all benefit. Such an arrangement is essential for this kind of project to work, given the history of research by Native American and other minority communities.

Besides providing hands-on learning opportunities for undergraduates and developing community-based expertise in risk assessment and testing methodologies, this approach has the added benefits of imparting information to homeowners about the quality of their well water and giving the community data that it can use to raise funds to improve its water

Little Big Horn College student research interns conduct water quality monitoring of the Little Big Horn River with research director Mari Eggers. From L to R: Richard Monroy, Jr., Leslie Plainfeather, Mari Eggers, Francesca Pine, Brandon Good Luck and Dayle Felicia. Photographer Lynn Donaldson.

and wastewater infrastructure. At the same time, community participation ensures the incorporation of local environmental knowledge, the use of culturally appropriate strategies in all phases of the research, and the creation of a supportive environment in which students can learn and work alongside university researchers and tribal environmental staff. To date, LBHC students have learned to monitor surface water quality, collect well water samples for analysis, run relevant laboratory tests, and conduct surveys. They also have sampled and tested fish populations for mercury contamination.

The resulting research has been published in Family and Community Health and was recognized by NIH's National Center for Research Resources as representing an "advance in science." Partly on the basis of the success of this project, Little Big Horn College was the first tribal college to be awarded an NIH Research Infrastructure for Minority Institutions grant. The campus also receives support from the U.S. Department of Agriculture and from the NSF Undergraduate Research Mentoring program. This additional support has allowed the LBHC life sciences program to expand community-based learning opportunities in microbiology, invasive plants, environmental health, and infectious disease.

Working with MSU researchers and graduate students has the added benefit of helping create a natural bridge of sorts for LBHC students to transfer to the four-year campus to complete a four-year degree with confidence. Some students have even pursued graduate degrees. Mari Eggers, an MSU microbiology doctoral candidate who works with the program, confirmed that when she started teaching at LBHC 15 years ago, few tribal members had undergraduate degrees in biological or environmental sciences and no local members had graduate degrees in these fields. Since then, persistence rates for research interns have been near 100%, with at least a dozen LBHC students earning four-year degrees in these disciplines. Graduates are now pursuing careers in natural resource management, environmental science, and environmental health. In addition, two former research interns have completed their master's degrees, two additional students are now in graduate school, and two others are in the process of applying. These role models help LBHC students see the contributions the life sciences can make to their community and understand that a biology education is something anyone with a strong interest can achieve.

For more information, visit

http://www.lbhc.edu/

IN PRACTICE

UNDERGRADUATES AS RESEARCH COLLABORATORS

LEARNING GENETICS THROUGH ACTIVE PARTICIPATION IN A LARGE-SCALE GENETIC SCREEN

A unique undergraduate research experience that diverges from the one-on-one research apprenticeship approach typical of many such experiences has been developed by Howard Hughes Medical Insitute Professor Utpal Banerjee at UCLA. Banerjee's undergraduate class, Life Sciences 10 Honors (LS10H), involves research on the genetics of eye development in the fruit fly *D. melanogaster* and has led to the publication of two articles, each with over a hundred undergraduate coauthors (Chen et al, 2005; Call et al., 2007). Noting that the "excitement of scientific research and discovery cannot be fully conveyed by didactic lectures alone" (Chen et al., 2005), Banerjee created an elective course that invites LS10H students to collaborate on an unsolved problem: the genetic basis of development and pattern formation.

Students learn genetics as they define developmentally important genes by examining phenotypes generated through state-of-the-art genetic manipulations. While primarily laboratory focused, the course includes 1.5 hours per week of interactive lectures that cover basic genetics, ethics, and aspects of research design. Students spend an additional 1.5 hours per week in a computer laboratory, running simulated crosses and using online genomics tools to investigate genes of interest. Students gain scientific writing skills as they prepare an NIH-styled grant proposal for their midterm exam and submit a report on their results in the format of a scientific paper for their final.

Students spend nine hours per week in the laboratory, where each maintains his or her own fly stocks, creates loss-of-function phenotypes, and examines eye morphology by means of light and scanning electron microscopy. Data accumulate rapidly, as five generations of flies are analyzed by each student during the 10-week quarter. Over the first four years of

the project, over one thousand unique genes have been defined and characterized, yielding the surprising finding that a preponderance of the genes involved in eye development are located on the X chromosome (Call et al., 2007).

The LS10H experience has been assessed in two ways. Interest in research among introductory students was examined with the use of UCLA standard course evaluations and was shown to have increased after the students finished the course (Call et al., 2007). The SURE II survey, designed to measure learning gains in categories related to research science (Lopatto, 2004), was administered to 88 students drawn from the four years the program has run. Students reported large gains in nearly every category. In comparison with SURE II findings for a group of students who participated in a 2006 UCLA summer research program (more than 500 students from multiple institutions), the gains made by LS10H students were significantly higher overall (Call et al., 2007).

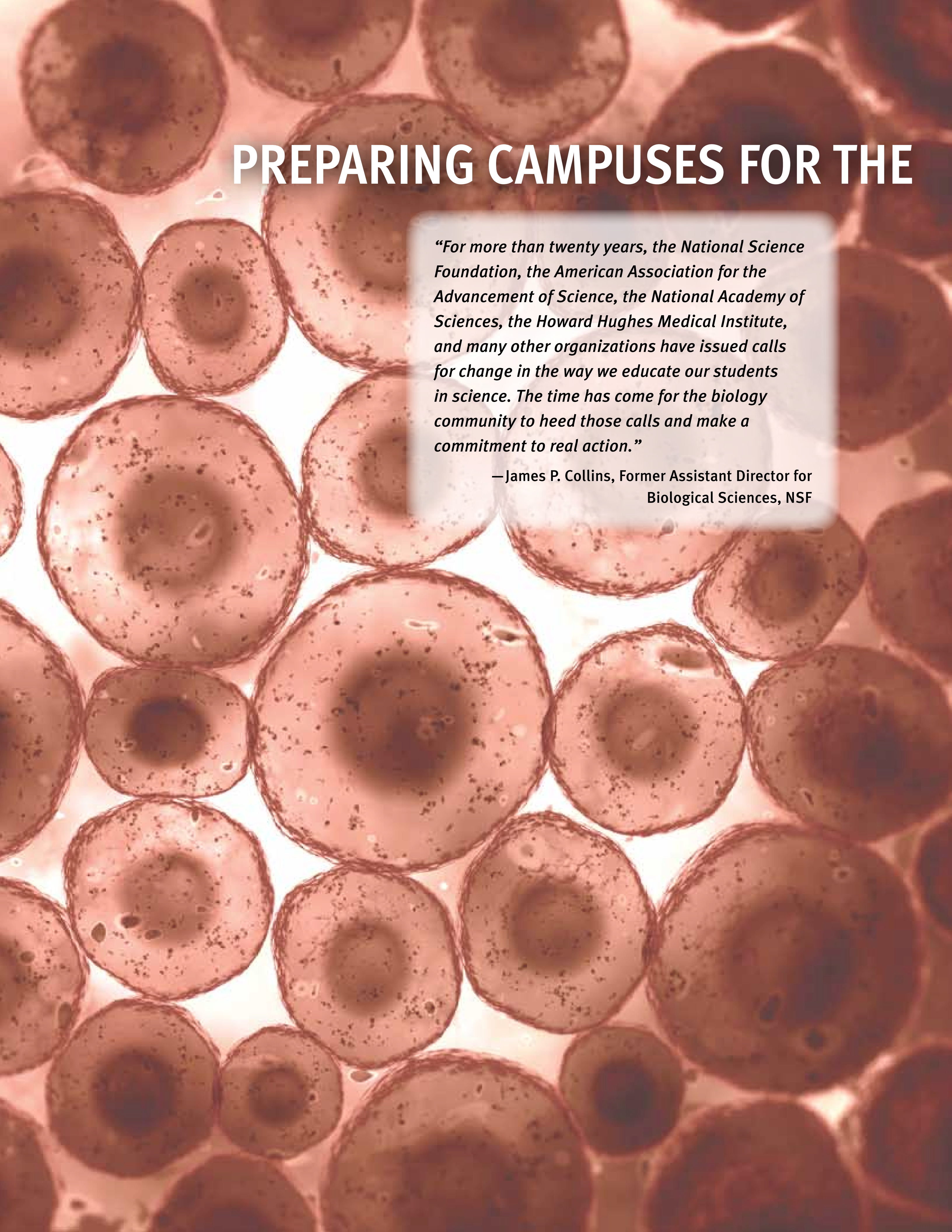
Students interviewed about the course have noted with pride that it was a genuine, open-ended project (HHMI, 2005). In addition, the principal investigator suggests that student learning in the course was substantially increased by the "sense of ownership" that students developed for their research.

For more information, see

Chen, J., and more than 100 authors. 2005. Discovery-Based Science Education: Functional Genomic Dissection in *Drosophila* by Undergraduate Researchers. *PloS Biol.* 3(2):e59.

Call, G., and more than 100 authors. 2007. Genomewide Clonal Analysis of Lethal Mutations in the *Drosophila melanogaster* Eye: Comparison of the X Chromosome and Autosomes. *Genetics* 177:689–697.

The Eye of the Fly: HHMI Professor and 138 Undergraduates Identify Essential Genes that Function in Eye Formation. *HHMI Research News,* February 15, 2005.



PREPARING CAMPUSES FOR THE

"For more than twenty years, the National Science Foundation, the American Association for the Advancement of Science, the National Academy of Sciences, the Howard Hughes Medical Institute, and many other organizations have issued calls for change in the way we educate our students in science. The time has come for the biology community to heed those calls and make a commitment to real action."

—James P. Collins, Former Assistant Director for Biological Sciences, NSF

CHAPTER 4

CHALLENGES AHEAD

To ensure that undergraduates are better prepared for the challenges of the 21st century, life sciences departments and biology faculty need to be better prepared to teach them. Professional development for biology faculty who teach undergraduates, combined with a coherent undergraduate curriculum, can help all biology faculty become more effective teachers and ensure that all students—even those who take only one or two introductory biology courses—develop the ability to think critically, to evaluate evidence, and to graduate, at a minimum, with a basic understanding of core biological principles. Enhancing their teaching skills can also help biology faculty develop courses that engage all students, as well as help counter the serious "leaks" of science majors to other disciplines that the nation currently experiences at all levels of the academic science pipeline (Seymour and Hewitt, 1997; Hue, 2010).

Professional Development for All Biology Faculty

Biology faculty now have many opportunities to develop their teaching skills and make our life science courses more student centered and appealing to diverse student populations. Many college and university campuses offer faculty development workshops designed to improve teaching, as well as support research into how students learn. For example, since 2004, the Science Education Partnership and Assessment Laboratory (SEPAL) at San Francisco State University has integrated science education efforts into the university's Department of Biology and College of Science and Engineering, resulting in a vibrant community of scientists with an interest in teaching and learning. SEPAL investigates how science is learned, offers undergraduate and graduate courses, and provides multiple opportunities for students and faculty to collaborate with precollege and college educators (Smith and Tanner, 2010).

Professional societies also make important contributions. As part of the conversations leading up to the Vision and Change conference, major biology-related professional societies exchanged information on their current programs in support of undergraduate education. (See http://visionandchange.org/files/2010/03/VC-Prelimary-Reports-from-Conversations1.pdf for a report of the conversations.) For example, the American Society for Cell Biology (ASCB), the American Society of Plant Biology (ASPB), many groups within the Federation of American Societies for Experimental Biology (FASEB), and the Ecological Society of America (ESA) all organize educational programs within their national annual meetings. The programs include symposia and workshops on teaching and learning, plenary sessions on educational topics of interest within the discipline, and highlights of innovative teaching methods. Starting in the late 1980s ESA began offering sessions on what is important in the teaching of ecology as well as on evidence-based strategies to connect teaching with learning. Since the 1990s ESA has sponsored professional development workshops for two days prior to its annual meeting, with special attention paid to educational opportunities for graduate students and postdoctoral fellows. Participants at the Vision and Change conference urged all life science professional societies to follow these examples.

Often, departmental changes have come about when biology departments have dedicated a position to a PhD-level biologist with research interests in biology education (Bush et al., 2008). Hiring a biologist with an education specialty enriches a department in many ways. These professionals can collaborate with other faculty, both scientists and nonscientists, using their combined expertise to address curricular and assessment issues. They can also help garner grant funds and other resources to integrate biology education activities into the fabric of the department. Although physics and chemistry departments have been hiring science faculty with education specialties for decades, this approach is only now beginning to emerge as a more common practice in college and university biology departments.

Many national programs have been developed to help biology and other science faculty improve their undergraduate teaching and develop the skills needed to become agents of change at the departmental, university, and national levels. The week-long Project Kaleidoscope (PKAL) Summer Leadership Institute, for example, uses case studies, collaborative problem solving, experiential learning, and mentoring to develop the skills that early-career faculty need to become effective advocates of teaching and learning on their campuses.

Participants at the National Academies Summer Institute for Undergraduate Education in Biology, supported by HHMI, develop innovative instructional materials for an introductory biology course, learning how to help their students understand overarching concepts and ideas in the sciences. To date, more than 300 participants have completed the course and are reaching a combined estimate of 100,000 students annually. In addition, participants have created a national dialogue around standard practices for improving biology education (Pfund et al., 2009).

Developing Future Faculty

Comparable opportunities are beginning to emerge for graduate students and postdoctoral fellows—the nation's future faculty—to address the responsibility they have to enrich their teaching skills. For example, NIH, through its National Institute of General Medical Sciences Minority Opportunities in Research Division, now offers the Institutional Research and Academic Career Development Awards program (IRACDA). Established in 1999 at two campuses, this "teaching postdoctoral" program has grown to include 18 grantee institutions. The program provides traditional mentored postdoctoral training at a research-intensive institution, combined with an opportunity to develop the full range of skills, including teaching skills, needed for an academic career. The program accomplishes this through workshops and through mentored teaching assignments of the postdoctoral fellows at a minority-serving institution. An initial concern was that the added teaching obligation might make IRACDA postdoctoral fellows less competitive than their non-IRACDA counterparts. However, progress reports to date do not show any diminished competitiveness, and in many cases the IRACDA fellows have higher peer-reviewed research publication rates, outperforming their counterparts at the same research-intensive institutions.

Recognizing that graduate students in science, technology, engineering, and mathematics (STEM) fields must be able to communicate science and research to a variety of audiences, NSF launched the Graduate STEM Fellows in K–12 Education program (GK–12). The program provides prestigious fellowships to graduate students so that they can bring their cutting-edge research and practice into the K–12 classroom. As they collaborate with teachers and their students, GK–12 fellows gain skills that enable them to explain science to people of all ages. Since its inception in 1999, the program has funded 299 projects in more than 181 different universities throughout the United States. As of 2010, more than 10,400 graduate students had been awarded GK-12 fellowships, with approximately 1800 in the biological sciences.

Graduate student participants in GK–12 programs often report that they have become better scientists *through* becoming better teachers. For example, fellows reported that, by having to articulate complex ideas to students, they were forced to reflect deeply on fundamental science concepts and the relationships among them in ways they never had before (Mitchell et al., 2003; Stamp and O'Brien, 2005; Trautmann and Krasny, 2006; McBride et al., in press). Many have reported that this experience directly improved their ability to frame and approach their own research questions and hypotheses.

The HHMI Teaching Fellows Program at the University of Wisconsin offers a different approach (Miller et al., 2008). In this academic-year program, graduate students and postdoctoral fellows learn how to use a "scientific teaching" approach to produce "teachable units" for undergraduate biology courses. The fellows present the units in practice teaching sessions, during which colleagues and instructors evaluate the units' potential to engage and inform a diverse set of students, their scientific accuracy, and their appropriateness for the intended course. After integrating the feedback, fellows teach their units in introductory courses at the University of Wisconsin and exchange information about student-learning outcomes at the end of the semester. This program has now been replicated at the Center for Scientific Teaching at Yale University. It and the Science Education Initiative (SEI) program at the University of Colorado at Boulder, using postdoctoral fellows to serve departments and faculty, have the potential to demonstrate how early career faculty can become agents for change on a campus.

Today, all major federal and private organizations that fund biological research (e.g., NSF, HHMI, and NIH) offer a significant number of grants for enhancing faculty involvement with undergraduate education. The NSF Transforming Undergraduate Education in STEM (TUES) program (formerly called the Course, Curriculum, and Laboratory Improvement Program, or CCLI) supports projects that "develop faculty expertise, implement educational innovations, assess learning and evaluate innovations, prepare K–12 teachers, or conduct research on STEM teaching and learning." TUES also supports evaluation planning webinars, conferences, and a project information portal. In the last four years, this program has funded 35 projects (an investment of more than $10 million) that deal exclusively or principally with enhancement of the educational skills of both current and future faculty. Recently, as a direct result of the Vision and Change discussions, many of the awards within the TUES and the RCN-UBE programs (see Chapter 5) have been reviewed and jointly funded by the Directorate for Biological Sciences and the Division of Undergraduate Education within the Directorate for Education and Human Resources.

A PRESSING NEED FOR CHANGE

The statistics that follow are of interest to those of us whose work affects the environmental, social, and economic future of the country. The collective message is that the United States appears to be falling behind many developing countries in scientific innovation (DeHann and Venkat Narayan, 2007; Branscomb, 2008). The message serves to underline the Vision and Change call for a solid approach to undergraduate biology education, the development of more effective teaching strategies, and a diverse and well-prepared life sciences faculty.

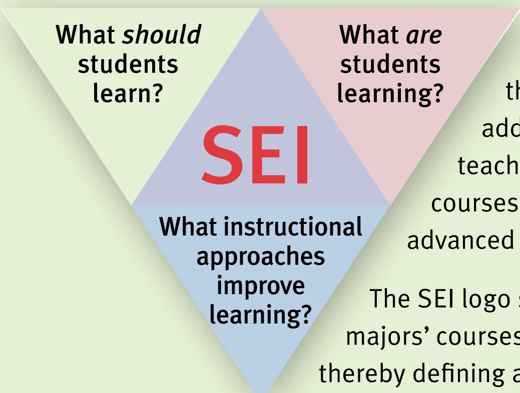
- The United States ranks 27th among developed nations in the proportion of college students receiving undergraduate degrees in science or engineering (NAS, 2010).
- According to a 2005 survey, half of all students who begin in the biological sciences will drop out of these fields by their senior year (Committee on Science and Technology, 2010).
- Most postdoctoral fellows trained in the United States today are from other nations (Olefsky, 2007).
- The nation faces shortages of qualified precollege science educators (King, 2006).
- The number of science publications increased from 1992 to 2006 by 40% worldwide, but those written by Americans decreased (Olefsky, 2007).
- Underrepresented minority groups made up 28.5 percent of the U.S. population in 2006, but only 9.1 percent of college-educated Americans in (academic and nonacademic) science and engineering occupations (NAS, 2010c).
- In 2006, women earned the majority of bachelor's degrees in biology and about one-half of doctorates, yet they represented less than one-quarter of tenured faculty and only 34% of tenure-track faculty (Hill et al., 2010).
- One-half of male faculty members at doctoral institutions are full professors—*five times* the representation of women at this professional level (Trower and Chait, 2002).

IN PRACTICE

IMPROVING TEACHING AND LEARNING CAMPUSWIDE

THE SCIENCE EDUCATION INITIATIVE AT THE UNIVERSITY OF COLORADO, BOULDER (CU), AND THE UNIVERSITY OF BRITISH COLUMBIA, VANCOUVER (UBC)

The CU Science Education Initiative (SEI) began in 2006 with university funding to catalyze changes in the teaching culture of several science departments through the introduction of promising research-based practices in teaching. Funds were awarded competitively, with five research-intensive departments—Chemistry; Earth Science; Integrative Physiology; Molecular, Cell, and Developmental Biology; and Physics—making commitments to transform the core courses in their respective undergraduate majors over five years. A similar program was subsequently initiated at UBC (Wieman et al., 2010).



SEI funding has been used primarily to recruit and support science teaching fellows: postdoctoral fellows with recent PhD degrees in their disciplines and with a strong interest in education. The fellows take additional pedagogical training, study the literature on undergraduate teaching, and work with faculty in each department to redesign their major's courses, starting at the introductory level in the first year and then moving to more advanced courses.

The SEI logo symbolizes the process of transformation that has been followed in all majors' courses. Specific learning objectives are first agreed to by the faculty as a whole, thereby defining as departmental policy what students in the major should be learning. To find out what students are learning, fellows work with faculty in each course to design and validate pre- and postconcept assessments that can be used to obtain normalized learning gains as a measure of student progress toward the learning objectives. Finally, the fellows assist with the design of homework and classroom activities that supplement or replace traditional lectures, are aligned with the learning objectives, and are based on promising practices established by educational research (Wood, 2009b). These activities include organizing students to work in groups, providing immediate feedback, and requiring students to recall, think about, verbalize, and apply important concepts. On the basis of identified learning gains, activities are modified to optimize student learning.

Evaluation of the SEI program is still progressing, but indications of its success include high levels of fellow–faculty interaction in participating departments, self-reported changes in teaching approach from the majority of participating faculty, impacts on more than 50 courses serving about 10,000 students per year, increased faculty discussion of pedagogical issues between peers and at faculty meetings, and over a dozen peer-reviewed educational publications, coauthored by fellows and faculty, that document increases in student learning. Because this kind of institutional change is notoriously difficult to achieve, it is worth noting three SEI features that appear to be contributing to its success:

1. Change is department based, not dictated by the school's administration, and funding is competitive, requiring an up-front departmental commitment to participate.
2. Changes are accomplished incrementally, one course and instructor at a time, but within the framework of departmentally established learning goals.
3. Postdoctoral fellows work with each other and foster interdisciplinary interaction and innovation. As PhDs in their respective disciplines with additional pedagogical training, they have enough subject-matter knowledge to help faculty design effective instructional materials (they do very little actual teaching) and they are not threatening to faculty (as outsiders with education degrees might be, for example). To effect change in faculty, they rely on their "people skills," their enthusiasm for teaching and learning, their knowledge of the pedagogical literature, and their willingness to do the labor-intensive work of creating classroom activities and assessments that research-active faculty may not have time to develop.

For more information, visit

www.colorado.edu/sei/

www.cwsei.ubc.ca/

Institutional Change

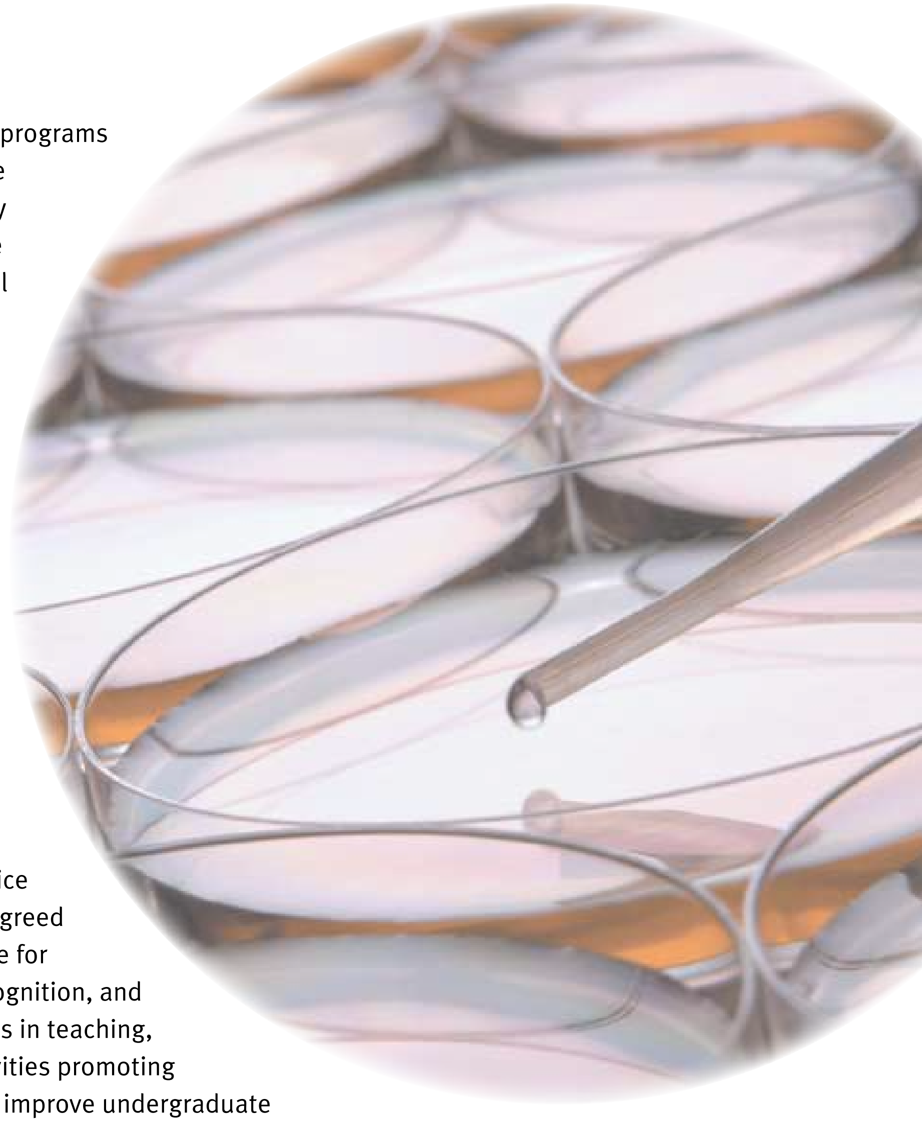
The success of the nation's biology faculty and their undergraduate students depends on broad institutional support. Therefore, the kinds of initiatives discussed here need to be fully integrated within the existing culture of the academy. For example, Centers for Teaching and Learning (CTLs) are present on many campuses, with a primary mission of advancing teaching excellence. And yet, because many faculty lack institutional support for updating their teaching skills, these centers tend to be underutilized.

CTLs offer faculty a wide array of programs, events, and services that foster innovation in teaching and promote the translation of educational research and learning theory into practice. In particular, CTLs offer biology faculty opportunities to learn how to assess student learning and can facilitate conversations about expected learning outcomes. Productive partnerships between CTLs and biology departments also can help overcome obstacles to connecting teaching with student learning, through the following approaches:

- Outlining strategies for leveraging resources and expertise at existing CTLs in order to enhance undergraduate biology education. This approach would involve identifying goals, expected outcomes, strategies, and activities for the CTL and biology departments.
- Identifying appropriate programs, support, and resources from CTLs for biology faculty to maintain a lifelong commitment to their development as educators.
- Identifying ways of utilizing faculty insight into student learning issues in order to inform the planning of professional development programs.
- Preparing recommendations for how administrators might support and recognize educational innovation and professional development through partnerships with CTLs.

As participants in the Vision and Change national conference emphasized, current and future biology faculty need opportunities to continue to develop their expertise as educators as well as researchers. And colleges and universities need to do a better job of acknowledging the importance of undergraduate teaching, as well as supporting programs such as the Centers for Teaching and Learning, where current and future biology faculty can develop and sharpen their teaching skills.

NEXT STEPS



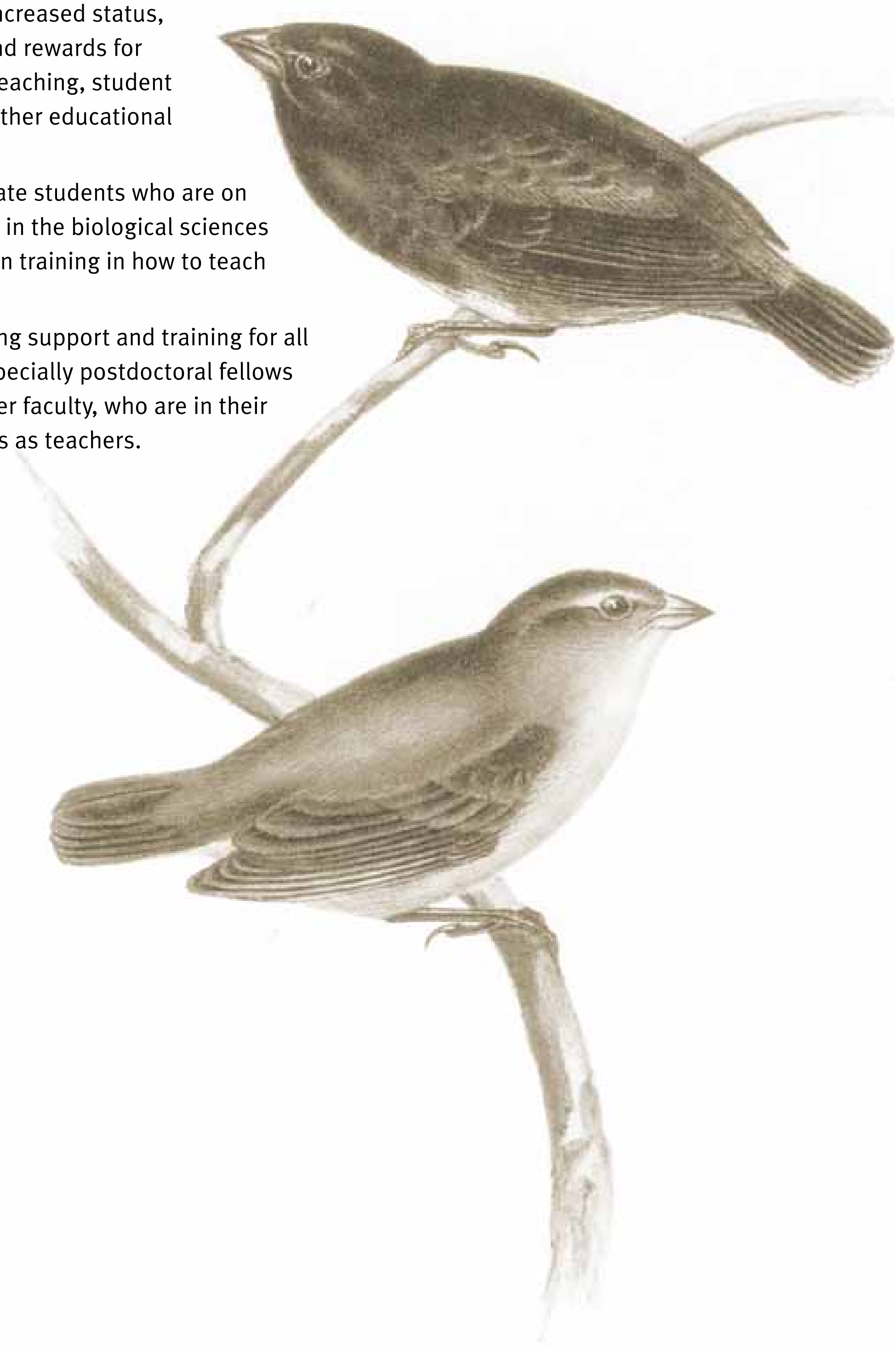
Local and national professional development programs and funding opportunities are becoming more widely available for current and future biology faculty. However, as was discussed during the Vision and Change conversations and national conference, many biology faculty continue to be skeptical about investing the time needed to improve the teaching and learning in their undergraduate classes. Their involvement has been impeded in part by the *perceived lesser value* placed on education activities by campus department chairs, deans, and even colleagues, many of whom serve on tenure review committees (Fairweather, 2006; Savkar and Lakere, 2010). Clearly, if the nation's colleges and universities want faculty to dedicate more time to improving their teaching, campuses must increase the recognition of, support for, and rewards to faculty who add serious engagement in educational efforts to their research and service efforts. Vision and Change participants also agreed that campus decision makers should advocate for increased department and faculty status, recognition, and rewards for introducing successful innovations in teaching, for improving student outcomes, and for activities promoting the scholarship of teaching. Faculty efforts to improve undergraduate biology education can be encouraged by establishing on-campus programs that explicitly recognize and support such activities through teaching awards, access to the resources and release time needed to engage in educational endeavors, and recognition of those endeavors in promotion and tenure decisions.

Many administrators have moved in this direction, making clear through decision making and, sometimes, policy documents that funds granted for education projects are of equal status to those brought in for research projects. With the emergence of several highly regarded biology education research journals (e.g., *CBE-Life Sciences Education, Advances in Physiology Education*) and even flagship journals of professional societies (e.g., AAAS's *Science,* ESA's *Frontiers in Ecology and the Environment,* and the Society for the Study of Evolution's *Evolution*), some tenure-and-promotion committees, department chairs, and deans have started to judge peer-reviewed publications on discipline-related educational practice and research on a par with those reporting on disciplinary research, judging each on the basis of merit and scholarly impact.

This kind of transformative leadership cannot just come from the top, however: *All* members of the biology academic community should be committed to creating, using, assessing, and disseminating effective practices in teaching and learning and in building a true community of scholars. This kind of campuswide scholarship requires both a renewed commitment to teaching and learning throughout the discipline and the recognition of teaching as a professional activity.

ACTION ITEMS

- Mobilize all stakeholders, from students to administrators, to commit to improving the quality of undergraduate biology education.
- Support the development of a true community of scholars dedicated to advancing the life sciences and the science of teaching.
- Advocate for increased status, recognition, and rewards for innovation in teaching, student success, and other educational outcomes.
- Require graduate students who are on training grants in the biological sciences to participate in training in how to teach biology.
- Provide teaching support and training for all faculty, but especially postdoctoral fellows and early-career faculty, who are in their formative years as teachers.



UNDERGRADUATE STUDENT VOICES

DISCUSSION QUESTION

In what ways can biology education be improved?

STUDENT RESPONSES

Thinking about teaching on our campus

- Increase the expectation of excellence in teaching: All professors should be familiar with educational theory and there should be more professional development for faculty to enhance their teaching skills. Maybe pair new faculty with more experienced faculty who have demonstrated good teaching skills.
- More value on teaching the intro courses. Offer some incentives for teaching these courses.
- More avenues for student feedback: Professors need to be attuned to what students want out of the class, what they feel they are missing, and students need to feel that they have a voice.
- There should be more "face-time" with faculty (office hours or small discussion groups).
- Sites like *ratemyprofessor* are popular with students, but not always embraced by campuses and are often a venue for student complaints; maybe a more organized effort could be made to get all students to give and share feedback on courses so students can make more informed decisions and so faculty can see that student opinions are important and hold weight.

More opportunities to develop quantitative skills

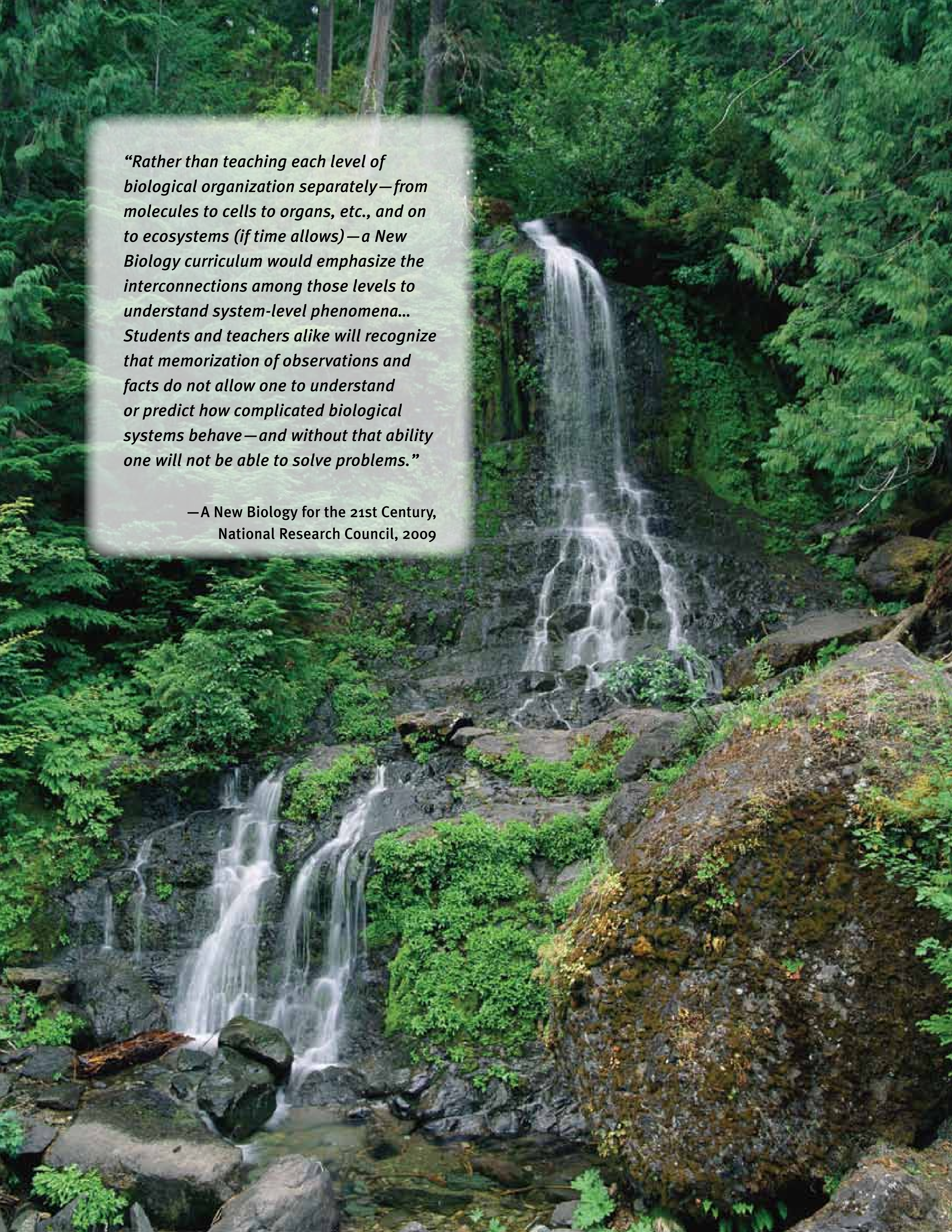
- Offer more courses on quantitative abilities, including statistics, programming/computer science, technology, etc., tailored for biology students.

More opportunities to develop communication skills

- More writing assignments in class and/or seminar courses on writing.
- More student presentations with chances for feedback.

Less emphasis on competition

- Students feel that there is too much pressure to get "good grades" to get into graduate and professional programs. They are discouraged from trying new and different courses for fear of harming their GPA. Allow for "stretching your mind" courses—where at the end of the course you can opt out of having your course grade reported.



"Rather than teaching each level of biological organization separately—from molecules to cells to organs, etc., and on to ecosystems (if time allows)—a New Biology curriculum would emphasize the interconnections among those levels to understand system-level phenomena... Students and teachers alike will recognize that memorization of observations and facts do not allow one to understand or predict how complicated biological systems behave—and without that ability one will not be able to solve problems."

—A New Biology for the 21st Century,
National Research Council, 2009

CHAPTER 5

UNITY OF PURPOSE

Those involved in the various Vision and Change discussions agreed that the time has come for the life sciences community to make a serious commitment to improving undergraduate biology education nationwide. Transforming undergraduate biology education requires a concerted and sustained effort by *all* stakeholders in the life sciences, unified by a common vision of first-rate, student-centered learning and, as with any scientific endeavor, subjected to rigorous and ongoing evaluation. To realize this vision and implement these changes, faculty need a variety of resources, including ready access to ongoing professional development opportunities; better instruments to help gather data on factual, conceptual, and skills-based student learning; and curriculum resources anchored in evidence-based practice and design principles of teaching and learning. In addition to improved resources, more support is needed at the institutional level, particularly in the form of changes in the faculty reward and support systems (Anderson et al., 2011).

Success also is predicated on an inclusive model whereby undergraduates have input into their education. Education should not be something we do *to* our students: It must be something we do *in collaboration with* our students. For example, undergraduates participated in focus groups at the Vision and Change conversations and, at the national conference, joined biologists from around the country to discuss the future of undergraduate biology education. At the conference, students participated in breakout sessions and presented their recommendations to the group as a whole. As one student noted, “Feeling like we had a voice in this change was really great because we’ve had ideas but [we’ve never been able to articulate them or] truly brainstorm solutions.”

NEXT STEPS

Today, more than ever before, biology faculty, campus leaders, and funding agencies need to rise to the occasion and respond decisively to the call to improve undergraduate biology education. All stakeholders should take a serious look at how undergraduates are introduced to biology in order to ensure that all students develop the skills they need to participate fully in today’s society. As Vision and Change participants noted, all students need to graduate with a basic understanding of science and scientific principles so that they can better address the complex challenges facing the nation today and those the nation will no doubt face in the future.

Curricula and Teaching Materials

Biology faculty and educational researchers are beginning to develop evidence-based teaching materials that have been shown to be effective in achieving specific learning outcomes. Websites featuring science education innovations (e.g., BEN, HHMI Cool Science) are becoming available, but it is still important that quality biology education strategies be collected in an ongoing and coordinated fashion and made easily accessible. Shared curricula, problem sets, interactive animations and simulations, laboratory experiences of all kinds, case studies, assessment tools, and faculty development tools are all needed. In addition, more examples of how faculty and departments have successfully integrated research experiences into their courses and curricula will help others introduce such activities into the undergraduate curriculum.

Clearly, more is needed than simply updating and modernizing the content and approach of textbooks. Textbooks conveniently package background information on biology content in one place, but they also can have a negative impact if used as the sole source of information in a course. Faculty need a variety of printed and vetted online tools and resources that are organized and easily accessible to more actively engage undergraduates in learning biology.

Models of "Interdisciplinarity"

Workshops, meetings, and online resources to support biology education would benefit from connecting with educational efforts in other disciplines. To ensure that all students graduate with a basic level of scientific literacy and meet the challenges raised in *Bio 2010: Transforming Undergraduate Education for Future Research Biologists* (2003a)*, Scientific Foundations for Future Physicians: Report of the AAMC-HHMI Committee* (2009), *A New Biology for the 21st Century (*2009), and similar reports, biologists, physicists, chemists, and mathematicians need to look thoughtfully at ways they can introduce interdisciplinary approaches into their gateway courses. For example, the National Research Council's *Evidence on Promising Practices in Undergraduate Science, Technology, Engineering, and Mathematics (STEM) Education* (Fairweather, 2008) discusses an evidence-based interdisciplinary approach to undergraduate biology education. Case study approaches, such as the workshop/web resource model of the National Center for Case Study Teaching, provide another method for integrating social, environmental, and ethical considerations into the teaching of biology. Service learning projects provide yet another.

Assessment Tools

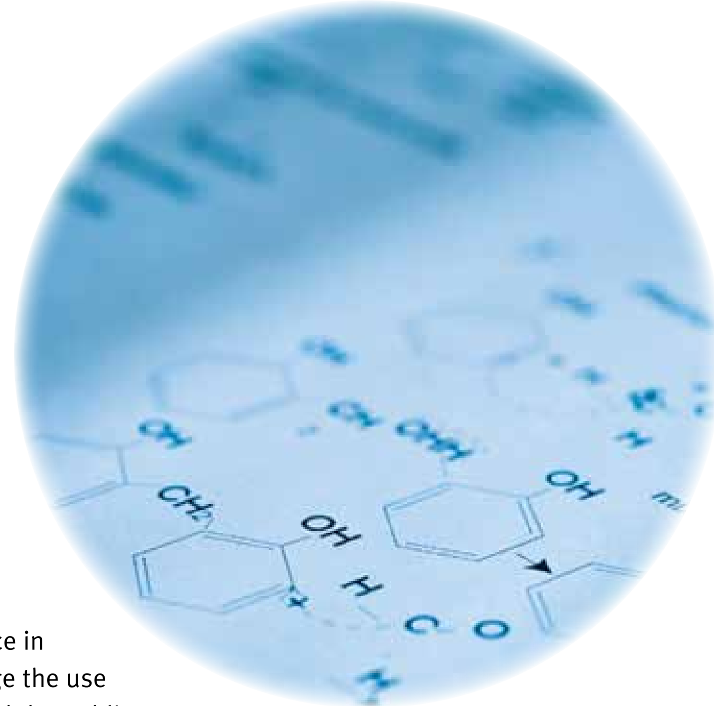
Assessment can help transform undergraduate biology education, particularly if social scientists and biology educators work together to develop a comprehensive set of tools. As biology faculty become more informed through their research on learning, the assessment of student learning also will be improved.

Chapter 3 mentioned two tools that are available to assess student learning: SURE (Lopatto, 2008) and SALG (Westen et al., 2006). A third tool, the Tuning USA project, funded by the Lumina Foundation for Education, supports educators in biology and other disciplines with the goal of collectively developing a set of learning outcomes for science majors. However, a much more comprehensive set of assessment instruments is needed. A nationwide consensus on learning outcomes may be neither possible nor desirable, but an agreed-upon collection of common outcomes for undergraduates can drive the development of a core set of vetted assessment tools for adaptation and use in undergraduate biology classrooms.

Faculty Development

The breadth of biology subdisciplines and the diversity of institutions of higher education create both barriers and opportunities for transforming biology education. More national opportunities like the Vision and Change conference are needed in which biologists representing the full spectrum of life science specialties, from molecules and cells to organisms and ecosystems, can work together on a unified approach to improving undergraduate education. Creating opportunities for faculty at community colleges, liberal arts baccalaureate colleges, and comprehensive and research-intensive universities to meet and collectively shape 21st-century biology education is imperative.

Biology faculty can also benefit from the lessons learned in other education sectors. For example, one of the lessons learned from the K–12 professional development community is that single workshops without some follow-up do not necessarily bring about sustained changes in teaching practices. Establishing a follow-up process to help workshop participants maintain contact with the workshop leadership and fellow participants may be much more successful in informing and supporting changes in teaching practices in biology departments. Ongoing models of these approaches include the HHMI/National Academies Summer Institute, conducted for some years at the University of Wisconsin and now centered at Yale University; the American Society of Microbiology's Biology Scholars Program; the SEI program at the University of Colorado at Boulder; and the Minnesota State Colleges and Universities program.



The Reward System

The current faculty reward system discourages innovative educators from investing time in their teaching. Attention to this issue is needed both at individual institutions of higher education and at the national level. Ultimately, the institution needs to recognize and reward outstanding teaching. Both Project Kaleidoscope's work on institutional transformation and the numerous examples presented in O'Meara and Rice's (2005) *Faculty Priorities Reconsidered* offer models to inspire a range of institutions to transform undergraduate education.

Models that celebrate effective teaching are growing, but more are needed to encourage transformative teaching. For example, the AAAS Science Prize for Online Resources in Education (SPORE) recognizes innovation and excellence in online educational materials, thereby helping to encourage the use of high-quality online resources by students, teachers, and the public. In addition, the "Education Forum" feature in the journal *Science* highlights transformative education efforts. In another effort, an increasing number of professional societies are offering education and teaching awards in recognition of members who have made outstanding contributions to education. These high-profile programs and awards recognize the nation's best educators, but professional societies and state and national organizations are just beginning to capitalize on this recognition in order to promote undergraduate teaching.

Professional Societies in the Life Sciences

A growing number of life science professional societies are starting to stress the importance of education issues in both their publications and their annual meetings. Many of the recommendations in this document were foreshadowed by, for example, *Professional Societies and the Faculty Scholar: Promoting Scholarship and Learning in the Life Sciences* (Coalition for Education in the Life Sciences [CELS], 1998). Not only do professional societies provide much-needed recognition for members engaged in education, but many offer workshops for new faculty, as well as ongoing faculty development for all members of the society. Efforts to professionalize teaching are also seen in the number of society-supported publication venues for educational research, including the 2002 launch of *Cell Biology Education: Life Sciences Education.* Even more significant as a sign of professional societies' recognition of the importance of educational efforts is the inclusion of appropriate education-related articles directly in the societies' main professional journals. Continual attention to, and support for, these efforts and the introduction of new ones are needed if these changes are to have a truly national impact.

A VIRTUAL COMMUNITY OF BIOLOGISTS

A growing number of biology faculty and departments have developed student-centered curricula, assessment strategies and tools, professional development programs, and other teaching and learning resources available for others to adapt to better meet the needs of their undergraduate students and campus environments. Colleges and universities around the country also have invested in programs that integrate curricular innovation and change efforts campuswide. The National Science Foundation, in a joint effort of its Directorate for Biological Sciences and the Directorate for Education and Human Resources, has established a Research Coordination Networks in Undergraduate Biology Education (RCN-UBE) program to bring together people who are working on similar projects and could benefit by coordinating their efforts. These kinds of programs need to be more widely disseminated to the undergraduate teaching community.

Participants at the Vision and Change conversations and the national conference expressed strong support for creating an online national clearinghouse for life sciences teaching materials and strategies (i.e., an "educational tool kit" for biology faculty). As envisioned, this clearinghouse would include a registry of "best practices" and "best materials," as well as links to data sets for teaching quantitative skills and links to summaries of research on teaching and learning. A key element of such a registry would be the review and vetting of these materials by the faculty who use them.

Building a community of biology educators who integrate evidence-based practice into their teaching would be greatly facilitated by such an online community, as demonstrated by several examples already in existence. The Higher Education Academy in the United Kingdom has created an online resource called EvidenceNet that cuts across disciplinary boundaries and provides resources, information about events, and opportunities for faculty to share resources and materials or develop a case study. MERLOT offers a collection of resources that not only provides a way to share instructional materials, but also makes it possible for educators to identify others who use similar instructional resources. Biology educators also have access to both the AAAS-supported BioSciEdNet, known as BEN, part of the National Science Digital Library, and the suite of resources available on the iBioSeminar website developed by ASCB. Examples from ecology, including both data sets and curricular models, are available in the online journal *Teaching Issues and Experiments in Ecology*. The HHMI Cool Science for Educators website is a rich source of materials designed for both college faculty and K–12 teachers. "On the Cutting Edge," a website offering professional development for geoscience faculty, grows through workshops and web resource development projects focused on evidence-based teaching. This hybrid virtual and real-time development effort, which received a 2009 AAAS SPORE award, could serve as a model for the biology undergraduate education community. Finally, a number of programs offer a range of tools for undergraduate biology teaching, with varying degrees of assessment to support their efficacy. (See http://visionandchange.org/for more information.)

Both the HHMI Cool Science and BEN resources exemplify useful sites for educators, but an overall focus on faculty development to support improved teaching of undergraduate biology is still needed. Ultimately, undergraduate biology educators need to bring together all of the preceding recommendations under one umbrella to encourage the development and dissemination of tools that support inquiry and collaboration, provide a current and relevant context, and foster authentic research experiences, including findings on learning outcomes. This resource would utilize the strengths of Web 2.0, creating a new, high-quality interface for undergraduate biology educators. Such a site would search like Google, recommend like Amazon, vet like *Consumer Reports*, and annotate like Wikipedia. Done well, this interface would provide a core of information, tools, and networks for undergraduate biology educators.

A CALL TO ACTION

As life scientists, we stand at the forefront of a new movement to convey the excitement and potential of the fresh direction the discipline is taking, a direction that promises to improve undergraduate biology education and to ensure that all undergraduates develop the level of biological literacy they need to understand, contribute to, and make informed decisions about the complex problems facing the world. Our community faces new challenges to our assumptions about the study, practice, and teaching of biology—but also new opportunities to revisit those assumptions. First and foremost, participants at the NSF/AAAS Vision and Change national conference expressed an overwhelming commitment to unifying our two major vocations: teaching and research. The conference's clear message of valuing the integration of teaching and research, made without dissent, may signal the end of the historical rift between biology faculty as science researchers and biology faculty as science educators.

The growing areas of "scientific teaching" and "classroom research" provide the entry for biology and education researchers to work together to make teaching more evidence based and classrooms more student centered. By setting an agenda of integration at the conference, participants sent what may prove to be the first of many messages designed to create a bridge between these two complementary, but frequently isolated, communities, which are often unaware of the synergistic potential between them.

Finally, the theme of unity may be applied to the conference participants themselves, who left the meeting determined to become a force for reform. For it is up to all of us within the academic life sciences community to ensure that all undergraduates—biology majors and those majoring in other subjects—have opportunities to develop the analytical skills and knowledge they will need to become informed members of society. As noted in the conversations and at the conference, if we are to realize this vision, science education will need to change in several important ways:

- Life sciences education must become a much more active process than is currently the case for too many students. The *National Science Education Standards* (NRC, 1996) emphasized that science education for Grades K–12 must be something that students *do,* not something that is done for them. Should we expect anything less for undergraduates wanting to learn biology?
- Undergraduate biology education must become more concept oriented and concentrate more on integrating factual knowledge within those concepts. Given the rapid rate of new information produced each year, much of what undergraduates learn in a first-year biology course may change by the time they graduate from college. It is, therefore, important not to consider factual content as the sole basis for undergraduate biology, especially at the introductory level. Instead, we must teach students how to integrate facts into a larger conceptual context so that the students become more engaged with the science, more curious, and better able to pursue questions on their own. Facts divorced from concepts and context are not effective in helping students learn and understand science.
- Similarly, we must reexamine the notion that the content and processes of science are separate, independent goals for student learning. Given the accelerating pace and complexity of modern science, students who are steeped in specific content without understanding how that knowledge is generated and how (or even whether) it should be used and applied will be at a considerable disadvantage in dealing with the scientific issues that arise in their lives, compared with students who understand and have had authentic experiences with the processes, nature, and limits of science.

- The cognitive and learning sciences have provided critical insights into how people learn and, thus, how teaching can be made more effective. For example, students of all ages and levels of education may encounter difficulties transferring knowledge from one domain to another, so faculty have to help them learn how to do this. In addition, students who, from the beginning, appreciate the relevance and importance of the subject matter they are learning will absorb and be able to apply more information than those who are merely presented with a corpus of facts. Too few faculty and graduate students are aware of the literature on learning, let alone its implications for their classrooms and teaching laboratories. Thus, in designing their courses, faculty should have access to, and take advantage of, the teaching and learning research referenced throughout this report.
- The patterns of active engagement and discovery learning described here should begin with first-year biology courses and be available to *all* students. Introductory life science courses often give undergraduates their first and, for many students, their last formal experience with science. For the vast majority of undergraduates, these introductory courses are actually terminal courses, the last chance they have to learn about the natural world in a formal educational setting. Thus, for the educated lay public, introductory courses may be the only means to acquire a basic level of scientific literacy. These courses greatly influence whether or not many students, especially those from populations that are underrepresented in science, technology, engineering, and mathematics, will continue to pursue science in college. Impressions developed in introductory courses in biology and other sciences are especially important for undergraduates who become K–12 teachers. Their experiences will influence the scientific knowledge and the attitudes toward science of the next generation of students.

The preceding recommendations lead to the most important recommendation of all:

- As biology faculty, we need to put the "depth versus breadth" debate behind us. It is true today, and will be even more so in the future, that faculty cannot pack everything known in the life sciences into one or two survey courses. The advances and breakthroughs in the understanding of living systems cannot be covered in a classroom or a textbook. They cannot even be covered in the curriculum of life sciences majors. A more tenable approach is to recast the focus of biology courses and curricula on the conceptual framework on which the science itself is built and from which discoveries emerge. Such a focus is increasingly interdisciplinary, demands quantitative competency, and requires the instructor to use facts judiciously as a means of illustrating concepts rather than as items to be memorized in isolation.

The time has come for *all* biology faculty, but particularly those of us who teach undergraduates, to change the way we think about teaching and begin to develop a coordinated and sustainable plan for implementing sound principles of teaching and learning. The stakes are too high for all biologists *not* to get involved.

IN PRACTICE

IMPLEMENTING CHANGE ON COLLEGE CAMPUSES STATEWIDE

THE MINNESOTA PARTNERSHIPS

Statewide transformation of science education in Minnesota began in 2008 with a collaboration between Project Kaleidoscope (PKAL) and the Minnesota State Colleges and Universities (MnSCU) to integrate active learning into the classroom and into campus culture, with a focus on the STEM disciplines. Workshops introduced faculty and administrators to a range of pedagogies that engage students, and faculty developed and shared peer-reviewed teaching activities on a thoughtfully developed website. It was not unusual for faculty from community colleges and comprehensive universities to drive hundreds of miles to participate in workshops held throughout the state.

As a result of the success of the PKAL and MnSCU partnership, Minnesota faculty led a pilot project designed to define what students must know, understand, and be able to demonstrate after completing a degree in biology as part of the Lumina-funded Tuning USA project. MnSCU faculty joined faculty from the University of Minnesota system and from private undergraduate colleges for the Tuning effort. Representing a range of institutional types with very different student populations, the Minnesota faculty identified much common ground for student learning and effective teaching.

The MnSCU schools are now working together to create discrete, reusable educational materials for their biology students and faculty with the support of Minnesota's Strategic Alliance for Bioscience Research and Education (SABRE), which provided grants to stimulate the development of learning tools. In addition, the Tuning Biology Team found its interinstitutional meetings to be so productive that the team launched the Minnesota Consortium for Undergraduate Biology Education (MnCUBE), which hosts annual statewide conferences modeled after the AAAS Transforming Undergraduate Education in Biology conference.

For more information, visit

http://serc.carleton.edu/sp/pkal/mnscu/index.html

IN PRACTICE

PROFESSIONAL SOCIETIES TAKING THE LEAD

THE ASM CONFERENCE FOR UNDERGRADUATE EDUCATORS

In 1994, the American Society for Microbiology (ASM) established the annual ASM Conference for Undergraduate Educators (ASMCUE) to augment the education sessions at the ASM conference. Conference organizers often schedule the meeting prior to, and in the same city as, the general ASM meeting, usually at a local college campus. These critical strategies help members limit expenses by traveling once to participate in two different meetings. Over the years, ASMCUE has evolved from a meeting that disseminates specific teaching strategies, such as variations on a student laboratory exercise, to one that advances more generally the scholarship of teaching and learning in biology.

In 2004, the Society emailed surveys to 759 past participants. Their responses afford an insight into the outcomes of ASM's efforts in support of undergraduate biology education reform:

- Eighty-two percent of respondents changed their courses or programs on the basis of information gained at the conference. The respondents shared information with colleagues (61%), revamped entire courses (30%), conducted more extensive research about ASM curriculum guidelines (48%), added new course materials from the ASM-sponsored digital library (49%), or introduced more group learning and writing assignments (51%). About one-third introduced case-based assignments (35%) and investigative experiences (32%).
- Thirty percent changed their assessment tools to evaluate critical thinking and revamped their entire microbiology course. In a comparison of faculty behavior before and after attending ASMCUE, 66% of the respondents had never made changes in their teaching approaches prior to ASMCUE, but 82% made changes after attending the conference.
- More than half of the respondents (57%) attended to safety issues more regularly, and about one-third introduced new laboratory exercises to develop new skills, aligned current laboratory exercises with the guidelines, and introduced inquiry-based learning more extensively.
- Participants networked in several ways. Fifty-two percent solicited advice from or provided advice to others, and 41% contacted or visited another participant after the conference. Fourteen percent established collaborations, and 10% invited someone to their campus to speak. About 5% described new leadership positions involving the establishment of new programs, such as regional networks for sharing ideas and regional teaching conferences and campus-based faculty development programs for colleagues, postdoctoral scholars, and graduate students.

Conference organizers also distributed postconference surveys, with an average return rate of 70%. From the data collected by these surveys and from registration data, the following is known about more recent (i.e., 2007–2008) attendees:

- ASMCUE serves more than 300 biologists annually. Thirty-two percent represent community colleges, 35% come from primarily undergraduate institutions, and 33% come from institutions that grant master's or doctoral degrees.
- Forty-five percent of participants teach STEM majors, 45% teach microbiology for nursing and health sciences majors, and 10% teach microbiology majors. In general, nearly 70% teach introductory or general biology, 55% teach general microbiology, 45% teach upper-division biology, and 15% teach human anatomy and physiology.
- About 50% were attending the conference for the first time, suggesting that they are early-career faculty. On the basis of the large number of participants in introductory sessions on active learning and assessment, it appears that many attend to learn practical classroom teaching tips and to interact with a supportive community.

ASMCUE has become an important resource for biologists who are involved in undergraduate biology education. Attendees have improved or revamped their courses, introduced new laboratory experiences or new approaches to teaching, developed new courses, and been recognized for their efforts by obtaining faculty improvement awards and grants. Ninety-five percent of respondents indicated that ASMCUE improved their thinking and approach to teaching, and 85% indicated that it improved the quality and scope of the content in their courses and programs.

Although these data suggest a successful conference, faculty attendees continue to drive the conference goals to more scholarly heights. In the previous six years, a growing number of biologists have called for more scholarly approaches toward their teaching. Under the leadership of several Carnegie Scholars in biology and chemistry, and in response to biologists' needs, ASM, with the support of the NSF, established the Biology Scholars Program in 2005. This program develops biologists' knowledge about the scholarship of teaching and learning and encourages them to publish their teaching-related research in biology education journals, such as ASM's *Journal of Microbiology & Biology Education*.

Another important ASMCUE innovation is inviting those attendees who have collected assessment data demonstrating gains in student learning based on a specific teaching approach to present a poster at the conference. In 2010, ASM began publishing ASMCUE poster abstracts in the *Journal of Microbiology & Biology Education,* providing authors with citations of their work and those who did not attend the conference with access to the work presented. It is expected that ASMCUE participants will contribute new knowledge and understanding in biology education as they develop professionally and that they will be recognized and rewarded for these efforts, leading to genuine reform in undergraduate biology education.

For more information, visit

http://www.asmcue.org/

www.biologyscholars.org

http://jmbe.asm.org

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AUTHOR BIOGRAPHIES

EDITORS

Carol A. Brewer, PhD, is Professor Emeritus of Biology at the University of Montana and founder of the Prairie Ecotone Research Group, LLC, a firm that provides consulting, assessment, and research services for scientists and educators in the life sciences. As a professor, she conducted research and mentored graduate students in both physiological plant ecology and ecological education. Her major areas of research and collaboration have included studying the functional morphology of plants, from the northern Rockies in the United States to the southern Andes of Patagonian Argentina; exploring how film and television programs influence science literacy; cofounding a citizen science campaign, called Project BudBurst, to monitor plant phenology; and training teachers to use their schoolyards to lead ecological investigations. Over the past 25 years, Dr. Brewer has led dozens of workshops on teaching, assessment, and mentoring. She has served on the editorial boards of the journals *Conservation Biology* and *Frontiers in Ecology and the Environment,* and was a vice president of the Ecological Society of America. Currently, she serves the Long Term Ecological Research Network as the chair of their National Advisory Board. She also serves on the boards of the American Institute of Biological Sciences, Earth and Sky Radio, and the National Ecological Observatory Network (NEON). She was part of the founding team and is current NEON secretary of the board. In 2007, she received both the Eugene P. Odum Award for Ecological Education from the Ecological Society of America and the AIBS Education Award from the American Institute of Biological Sciences.

Diane Smith is a historian of science and an independent scholar who specializes in writing about science, mathematics, and engineering. Since the mid-1980s, she has authored more than twenty reports on improving undergraduate science education and teacher preparation, led National Science Foundation (NSF)–supported writing retreats for science and mathematics faculty and graduate students, and helped establish an NSF Engineering Research Center in environmental biotechnology at Montana State University, where she served as an Associate Director for Research Development.

COAUTHORS

Charles W. Anderson, PhD, is a professor of teacher education at Michigan State University. His research centers on classroom teaching and the learning of science. He studies how students' prior knowledge, language, and social relationships affect their engagement in science learning and their development of scientific literacy. His current work focuses on learning progressions leading to the development of environmental science literacy. Dr. Anderson received his PhD from the University of Texas–Austin in 1979. He has served as president of the National Association for Research in Science Teaching, as well as on many National Research Council panels and committees.

Cynthia Bauerle, PhD, is a Senior Program Officer in Precollege and Undergraduate Science Education at the Howard Hughes Medical Institute, where she manages the HHMI Professors program. Prior to her position at HHMI, she spent twenty years on the faculty at primarily undergraduate-serving institutions, where she focused on the development of undergraduate research infrastructure and curricular reform in science and general studies. Her research interest is cellular homeostasis and enzyme assembly, and she has published in scientific and science educational journals. From 1992 to 2005, Dr. Bauerle served on the Liberal Arts College faculty at Hamline University, where she held a joint appointment in biology and women's studies. In 1999–2000, she was a Fulbright Senior Scholar at the University of Dar es Salaam in Tanzania, where she consulted on the development of a national biotechnology training program. More recently, she was professor and chair of biology at Spelman College, where she also directed the college's HHMI Undergraduate Science Education program. Dr. Bauerle earned her B.A. in biology from the University of Virginia and her PhD in molecular biology from the University of Wisconsin–Madison.

Anthony DePass, PhD, is the Assistant Vice President for Research Development and an Associate Professor of Biology at Long Island University (LIU). He has led several efforts at the institutional, regional, and national levels that target student learning and advancement through inquiry-based pedagogic approaches that have been central to professional development activities for faculty and to research training and development for students. Dr. DePass' leadership in this area began in 1996, as Principal Investigator and Codirector of the National Science Foundation–funded Multimedia and Interactive Learning (MIL) project, which provided training for STEM faculty from six institutions in the New York Metropolitan area in the development of instructional multimedia and pioneered pedagogic approaches designed to enhance active learning. He has since provided leadership at the national level in coordinating programs that address the underrepresentation of minorities in the scientific workforce. As a member and chair of the Minorities Affairs Committees for the American Society for Cell Biology, Dr. DePass was the Principal Investigator of its National Institutes of Health–funded T36 grant, focusing on education and professional development through activities that have directly affected individuals from over 140 institutions. As chair/cochair for recent national conferences on Understanding Interventions that Broaden Participation in Research Careers, Dr. DePass has also provided leadership in bringing together communities of scholarship and practice in an effort to incorporate scholarship more actively into student training. Currently the Principal Investigator and Director of the Minority Biomedical Research Support program at LIU, Dr. DePass runs an active research program and serves as reviewer, advisory board member, and evaluator for programs that focus on training the next generation of scientists.

Sam Donovan, PhD, is a Research Associate Professor in the Department of Biological Sciences at the University of Pittsburgh and the Director of Undergraduate Programs for the BioQUEST Curriculum Consortium. He received his B.S. in biology at Virginia Tech and M.S. in ecology and evolution at the University of Oregon. Teaching and curriculum development opportunities led him to two related conclusions: He really enjoyed teaching, and it would be valuable to know more about education theory and research. The next stop was a PhD in science education from the Department of Curriculum and Instruction at the University of Wisconsin–Madison. While completing his doctorate, Dr. Donovan also held a visiting faculty position in the Biology Department at Beloit College. His scholarship involves research on student learning, curriculum design, and faculty development projects. His learning research focuses on how students reason about evolutionary events and interpret phylogenetic diagrams. Dr. Donovan has had a series of National Science Foundation–supported curriculum and faculty development projects that focus on evolution education, integrating bioinformatics across the biology curriculum, and using networked communications and computing resources to engage students in doing science. Much of this work has been done in collaboration with the BioQUEST Curriculum Consortium, a 25-year national reform effort in biology education. Dr. Donovan is currently involved as a director, advisory board member, or consultant in over a dozen science education projects.

Shawn Drew, PhD, is a program director at the National Institute of General Medical Sciences at the National Institutes of Health (NIH), where she manages research and research training programs aimed at increasing the number of historically underrepresented populations for leadership positions in science. Dr. Drew also manages the biostatistics T32 training grants and the R01 research grants from the Biostatistical Methods and Research Design (BMRD) study section and is chair of the Committee to Maximize Representation for the Institute's T32 training program. Before serving in her current position, Dr. Drew was the director of the NIH Academy, an intramural postbaccalaureate research training program. She earned her B.S. degree in chemistry from Spelman College and her PhD in biology from Howard University, where she conducted both her PhD dissertation research and postdoctoral work at the National Institute of Diabetes and Digestion and Kidney Diseases, NIH.

Diane Ebert-May, PhD, is a professor in the Department of Plant Biology at Michigan State University. She provides national leadership for promoting professional development, assessment and improvement of faculty, postdoctoral scholars, and graduate students who actively participate in creative research on teaching and learning in the context of their discipline. Dr. Ebert-May's research group developed and tested a model for professional development workshops on teaching and learning. The group is investigating the impact of students' design and use of models to build conceptual connections across scales in biology and is following student progress through a sequence of introductory courses. Dr. Ebert-May is Principal Investigator of FIRST III (Faculty Institutes for Reforming Science Teaching), a National Science Foundation–funded project which is creating an assessment database that stores and retrieves assessment items and associated student data. She also leads FIRST IV, an NSF-funded professional development program to help postdoctoral scholars create and teach their first introductory biology course in preparation for their future academic positions. Her recent book with Jan Hodder, *Pathways to Scientific Teaching,* is about active learning, inquiry-based instructional strategies, and assessment and research. She teaches plant biology, introductory biology to majors, large-enrollment environmental science courses open to all students, and a graduate seminar on scientific teaching. Her plant ecology research continues on Niwot Ridge, Colorado, where she has conducted long-term ecological research on alpine tundra plant communities since 1971. She received a B.S. in botany from the University of Wisconsin and an M.A. and PhD in ecology and evolutionary biology from the University of Colorado.

Louis J. Gross, PhD, is James R. Cox and Alvin and Sally Beaman Professor of Ecology and Evolutionary Biology and Mathematics, and director of The Institute for Environmental Modeling at the University of Tennessee, Knoxville (UTK). He is also director of the National Institute for Mathematical and Biological Synthesis, a National Science Foundation–funded center to foster research and education at the interface between mathematics and biology. He completed a B.S. degree in mathematics at Drexel University and a PhD in applied mathematics at Cornell University and has been at UTK since 1979. His research focuses on applications of mathematics and computational methods in many areas of ecology, including disease ecology, landscape ecology, spatial control for natural resource management, photosynthetic dynamics, and quantitative education for life science undergraduates. He has led the effort at UTK to develop a modeling framework across trophic levels to assess the biotic impacts of alternative water planning for restoration of the Everglades of Florida. He has served as program chair of the Ecological Society of America, as president of the Society for Mathematical Biology, as president of the UTK Faculty Senate, and as chair of the National Research Council Committee on Education in Biocomplexity Research. He is the 2006 Distinguished Scientist awardee of the American Institute of Biological Sciences (AIBS) and is a Fellow of the American Association for the Advancement of Science. He currently serves on the National Research Council Board on Life Sciences and is treasurer and on the board of directors of AIBS.

Sally G. Hoskins, PhD, is a professor of biology at the City College of the City University of New York and a developmental biologist with particular interest in the embryonic nervous system. With collaborator Dr. Leslie M. Stevens (University of Texas–Austin), she developed C.R.E.A.T.E., a process that uses intensive analysis of sequentially published journal articles to demystify science research and provide insights about the scientists who do the research. Support from the National Science Foundation (NSF) allowed the development and piloting of C.R.E.A.T.E. at the City College of New York and the project's subsequent expansion to student cohorts at additional colleges and universities in the New York area. The success of this method in the hands of a variety of teachers studying diverse topics in biology has spurred ongoing expansion of the project and a NSF-supported plan to train a nationally distributed cohort of biology faculty.

A three-time City College Academy for Professional Preparation (CCAPP) Teacher of the Year at City College, Hoskins feels that close reading and critical analysis of primary literature, coupled with email surveys of authors of papers, can help students gain transferable analytical skills while at the same time emphasizing the creativity of scientific thinking and clarifying "who does science, and why?"

Jay Labov, PhD, is Senior Advisor for Education and Communication for the National Academy of Sciences and the National Research Council. He has directed the production of eleven National Academies reports focusing on teacher education, advanced study for high school students, K–8 education, and undergraduate education. He has served as director of committees on K–12 and undergraduate science education and the National Academies' Teacher Advisory Council, and was deputy director for the Academy's Center for Education. He also directed a committee of the National Academy of Sciences (NAS) and the Institute of Medicine that authored *Science, Evolution, and Creationism* (2008), and he oversees NAS's efforts to confront challenges to teaching evolution in the nation's public schools. In addition, he oversees an effort at the Academy to work with professional societies and with state academies of science on education issues. Dr. Labov is an organismal biologist by training. Prior to taking his position at the Academy in 1997, he spent 20 years on the faculty in the Department of Biology at Colby College in Maine. He was awarded a Kellogg National Fellowship (1988), elected as a Fellow in Education of the American Association for the Advancement of Science (2005) and as Member-at-Large for the Education Section of AAAS (2009), and appointed as a Woodrow Wilson Visiting Fellow (2009).

David Lopatto, PhD, is a professor of psychology and the Samuel R. and Marie-Louise Rosenthal Professor of Natural Sciences and Mathematics at Grinnell College. His work on the SURE (Summer Undergraduate Research Experiences) and CURE (Classroom Undergraduate Research Experiences) programs assesses the learning and attitude outcomes of student involvement with undergraduate research in the sciences. His recent work includes *Science in Solution: The Impact of Undergraduate Research on Student Learning,* published in 2009 by the Council on Undergraduate Research and the Research Corporation for Science Advancement.

David Lynn, PhD, is well known for his contributions in the general areas of molecular recognition, synthetic biology and chemical evolution, and the development of chemical and physical methods for the analysis of supramolecular self-assemblies; signal transduction in cellular development and pathogenesis; molecular skeletons for storing and reading information; and the evolution of biological order. After a fellowship at Columbia University and teaching briefly at the University of Virginia and Cornell University, he served as a professor of chemistry at the University of Chicago. He moved to accept the Asa Griggs Candler Professorship in Chemistry and Biology at Emory University in 2000. In 2002 Lynn was awarded one of 20 inaugural Howard Hughes Medical Institute professorships, and in 2006 he was appointed chair of the Department of Chemistry.

Will McClatchey, RPh, PhD, is Vice President and Director of Research, Botanical Research Institute of Texas, Fort Worth, Texas. He grew up on the White Mountain Reservation in Arizona before his family moved to Oregon, where he completed high school and then college at Oregon State University, earning B..S. degrees in anthropology and pharmacy. He worked as a community and consultant pharmacist for ten years, during which time he earned an M.S. in ethnobotany from Brigham Young University and a PhD in botany (with an emphasis on evolutionary biology) from the University of Florida. His research, which addresses hypotheses about the evolution of patterns of human interactions with plants and artificial ecosystems, has largely been conducted in the southern and western Pacific and focuses on questions combining plant systematics, biogeography, and ethnobiology. Currently, his research group is working in southeast Asia, Europe, and the Pacific Islands, studying (1) relationships between distribution patterns of human knowledge of biodiversity and actual biodiversity, (2) the development and distribution of anthropogenic ecosystems, and (3) the production of traditional alcoholic beverages. Dr. McClatchey is active in the Open Science Network Research Cooperative Network, developing science curricula for courses and field schools in ethnobiology and conservation biology.

Clare O'Connor, PhD, is an associate professor in the Biology Department at Boston College. She received her B.S. and PhD degrees from Purdue University. Following postdoctoral fellowships at the California Institute of Technology and the University of California at Los Angeles, she joined the faculty of the Worcester Foundation for Experimental Biology in Shrewsbury, Massachusetts. Dr. O'Connor became a faculty member in the Biology Department at Boston College in 1995. From 2002 to 2003, she served as a program director in the Molecular Cellular Biosciences Division at the National Science Foundation (NSF). Her research focuses on enzymes involved in repairing proteins that have been damaged during aging and during oxidative stress. Her laboratory has developed genetic models of yeast and *Drosophila* for studying the protein repair process. Dr. O'Connor has taught courses in genetics, cell biology, and biochemistry at both the undergraduate and graduate level. She also teaches laboratory courses in biochemistry and cell biology that are designed to engage students in functional genomics research. The laboratory classes are part of a curriculum project that receives support from the NSF. Dr. O'Connor has received several awards from Boston College for her innovative use of technology in undergraduate teaching. She also serves as an editor for Scitable, an online resource for undergraduate education sponsored by Nature Education.

Nancy Pelaez, PhD, is an associate professor of biological sciences at Purdue University. Using image acquisition systems to track fluorescent pH and calcium labels as blood vessels contract and relax, the Pelaez laboratory investigates smooth muscle function, including the contractile response to hypoxia in blood vessels of animals that live where oxygen availability varies. Pelaez completed a rotation as program director at the National Science Foundation in 2007. As a former biology and chemistry teacher with ten years' science teaching experience in Bogota, Colombia, she developed and directed the scope and sequence for K–12 science education at Colegio Los Nogales in Bogotá from 1989 to 1992, before teaching high school biology and chemistry in the Indianapolis public school system. Dr. Pelaez is active in the Teaching Section of the American Physiological Society (APS) and was a founding member of the MERLOT Teacher Education Editorial Board. She received a B.S. in biology, summa cum laude, from Newcomb College of Tulane University; a K–12 California single-subject teaching credential in both life sciences and physical science from Mills College; and a PhD in physiology and biophysics, with a research focus on vascular muscle physiology, from the Indiana University School of Medicine. Her PhD research was supported by a Howard Hughes Medical Institute fellowship. A Leadership Award was given to Pelaez in 2010 after she established Purdue's doctoral program for science education research in the Department of Biological Sciences. In the program, doctoral students examine the difficulties students encounter when they apply quantitative and scientific reasoning to biological experiments.

Muriel Poston, PhD, is Dean of the Faculty and a professor in the Biology Department at Skidmore College. Since coming to Skidmore in 2005, she has worked with colleagues to reenvision the science program, supported efforts to broaden the participation of underrepresented students and faculty in STEM disciplines, and sought to enhance the capacity and infrastructure of the STEM facilities. Her primary research interests are in plant systematics, especially the evolutionary relationships of the neotropical family Loasaceae. Prior to her appointment at Skidmore, Dr. Poston spent over twenty years as a professor in the Department of Biology/Botany at Howard University, where she focused on undergraduate education, served as curator of the university herbarium, and worked to develop the school's environmental science program. She also served as a program director and deputy division director in the Biological Sciences Directorate at the National Science Foundation (NSF), where she was responsible for programs aimed at enhancing infrastructure for biological research collections, research instrumentation, and field station facilities. She currently serves on the NSF Committee on Equal Opportunity in Science and Engineering, as well as on the NSF Advisory Committee for the Biological Sciences Directorate. Dr. Poston earned a B.A. degree from Stanford University, M.A. and PhD degrees from the University of California at Los Angeles, and a JD degree from the University of Maryland.

Susan Rundell Singer, PhD, Laurence McKinley Gould Professor of Natural Sciences, joined the Department of Biology at Carleton in 1986 and has pursued a career that integrates science and education. Her PhD is from Rensselaer Polytechnic Institute, and she completed a teacher certification program in New York State. Dr. Singer directed Carleton's Perlman Center for Learning and Teaching and worked at the National Science Foundation (NSF) as a program officer in developmental mechanisms. She studies the development and evolution of flowering in legumes and does research on learning in genomics. She is a coauthor of an introductory biology text and is actively engaged in efforts to improve undergraduate science education. She received the Excellence in Teaching award from the American Society of Plant Biology and is a AAAS fellow. Dr. Singer serves on the Advisory Committee for Education and Human Resources at NSF, the Center for Excellence in Education's board of directors, the iPlant board of directors and iPlant's Education, Outreach and Training advisory committee, the American Society of Plant Biology Education Foundation board, and the National Academy of Science's Board on Science Education. Her National Academy committee service has included contributions to committees that authored *America's Lab Report* (chair), *Taking Science to School* (science consultant), *Transforming Agricultural Education* (committee member), and *Challenges and Opportunities for Education About Dual Use Issues in the Life Sciences* (committee member), as well as to the committee on Promising Practices in STEM Undergraduate Education (chair) and the committee on Discipline Based Education Research (chair).

Kimberly Tanner, PhD, is an associate professor of biology at San Francisco State University (SFSU). Hired in January 2004 as a biologist educator, she trained as a sensory neurobiologist prior to pursuing a career in science education through a National Science Foundation (NSF) postdoctoral fellowship in science education (PFSMETE) and senior staff positions at the UCSF Science and Health Education Partnership (SEP). Since joining the SFSU faculty, Dr. Tanner has established *SEPAL: The Science Education Partnership and Assessment Laboratory,* which offers formal courses, partnership programs, and research opportunities to undergraduate students, graduate students, faculty, and local K–12 teachers who are interested in improving science education from kindergarten through college. Her SEPAL Research Group addresses three main lines of inquiry: understanding the novice-to-expert transition among undergraduate biology majors; developing novel assessment approaches to revealing student conceptions in biology and other science disciplines; and evaluating the effectiveness of approaches to promoting gender equity in science. In addition, she collaborates with research colleagues on conceptualizing and investigating Science Faculty with Education Specialties (SFES) in the United States. She is Principal Investigator on NSF-funded GK–12, CCLI, and CAREER grant awards, as well as on a National Institutes of Health (NIH) Science Education Partnership Award. Dr. Tanner is a founding member of the editorial board for *CBE: A Journal of Life Sciences Education* and has served on committees and review panels for the NSF, the National Research Council, the Society for Neuroscience, the American Society for Cell Biology, and the NIH.

Pratibha Varma-Nelson, PhD, is a professor of chemistry and the executive director of the Center for Teaching and Learning (CTL) at Indiana University–Purdue University Indianapolis (IUPUI). She received a B.Sc. in Chemistry from the University of Pune, India, in 1970 and a PhD in organic chemistry from the University of Illinois, Chicago, in 1978. In 1979, she joined the faculty of Saint Xavier University, Chicago, where she was promoted to professor in 1992 and served as department cochair from 1992 to 1995. She moved to Northeastern Illinois University in 2002 as a professor of chemistry and served as chair of the Department of Chemistry, Earth Science and Physics. From August 2006 to 2008, she was a program director at the National Science Foundation (NSF) in the Division of Undergraduate Education. Dr. Varma-Nelson's research is in the development, implementation, and dissemination of the Peer-Led Team Learning (PLTL) model. She was Co-Principal Investigator of two NSF-funded National Dissemination Grants and a senior partner of the Multi-Initiative Dissemination (MID) project. She was founding Co- Principal Investigator of the Center for Authentic Science Practice in Education, (CASPiE). She is currently working on the development and evaluation of cyber-

PLTL (cPLTL) for science courses. As the executive director of the CTL at IUPUI, she is developing discipline-based professional development programs for faculty. Dr. Varma-Nelson is coauthor of several publications about PLTL and CASPiE and has made numerous presentations in national and international venues. She was the corecipient of the 2008 James Flack Norris award for her role in developing the PLTL Workshop model for teaching chemistry courses.

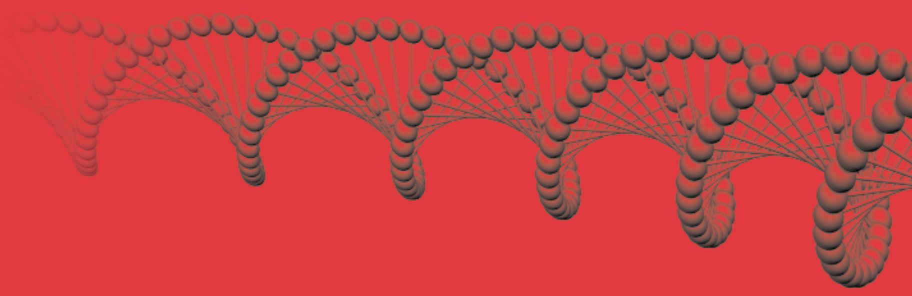
David Wessner, PhD, is an associate professor of biology at Davidson College, where he teaches introductory biology and courses on genetics, microbiology, and HIV/AIDS. His research interests include reovirus pathogenesis and uses of new media in the classroom. He is a member of the Charlotte Teachers Institute's University Advisory Council and the American Society for Microbiology's Committee for K–12 Education. Prior to joining the faculty at Davidson, Dr. Wessner conducted research at the Navy Medical Center and National Zoo in Washington, DC. He earned his PhD in microbiology and molecular genetics from Harvard University and his B.A. in biology from Franklin and Marshall College.

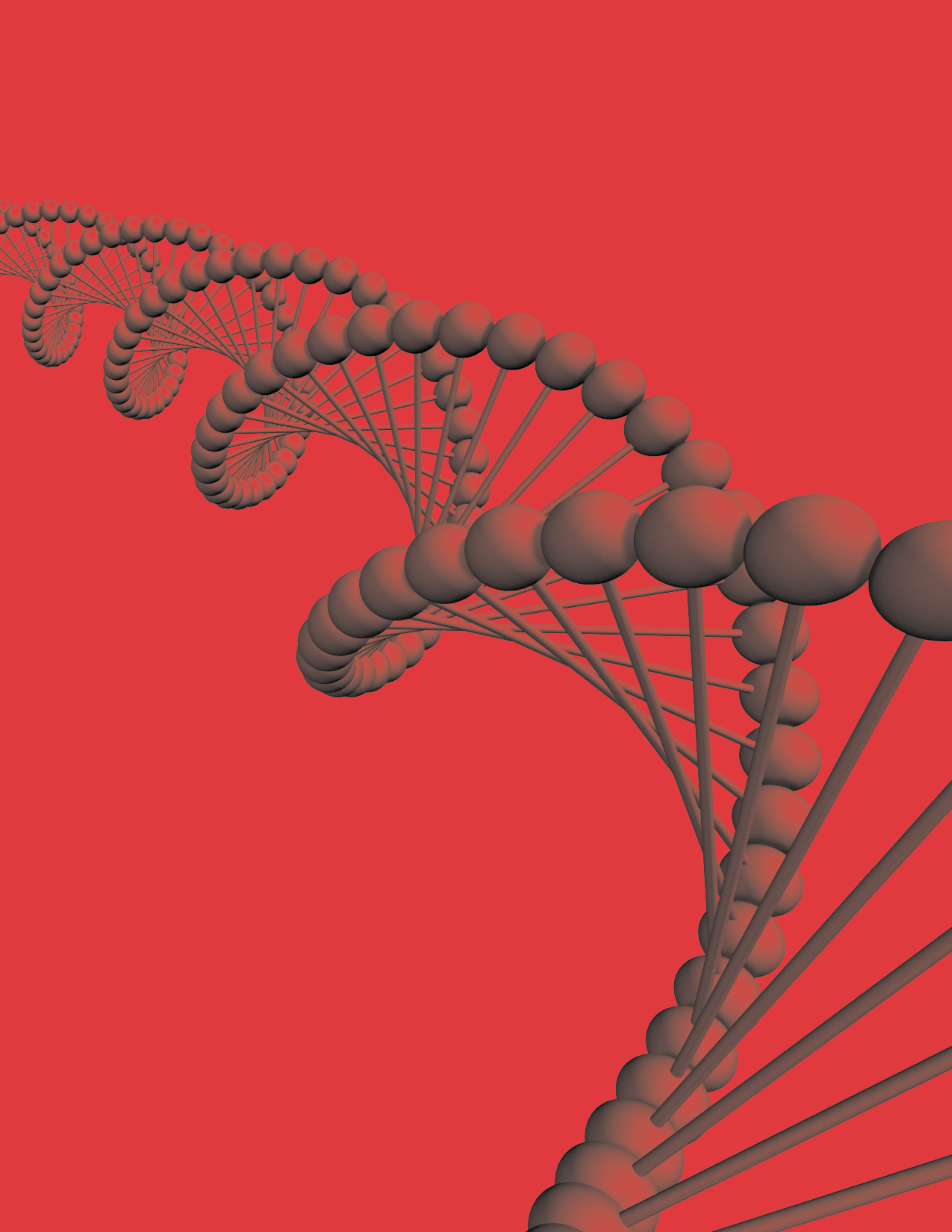
Harold White, III, PhD, was born in New England and raised in central Pennsylvania, where he graduated from the Pennsylvania State University with a B.S. in biochemistry. He joined the Department of Chemistry and Biochemistry at the University of Delaware in 1971 after a postdoctoral research fellowship in chemistry at Harvard University, a PhD in biochemistry from Brandeis University, and a summer at the Marine Biological Laboratory. Between 1977 and 1981, he was the recipient of a National Institutes of Health Research Career Development Award. His research interests have been in the structure, function, and evolution of vitamin-binding proteins, particularly riboflavin-binding protein from chicken eggs, but he also has strong interests in intermediary metabolism, biochemical evolution, and entomology. He was one of the investigators who realized earlier than most that RNA could act as an enzyme. Since the mid-1990s, his interests have focused on undergraduate education. Between 1994 and 1998, he served as Principal Investigator on the first National Science Foundation/Division of Undergraduate Education grant on problem-based learning (PBL) to the University of Delaware. As a member of the Education and Professional Development Committee of the American Society for Biochemistry and Molecular Biology, he conducted numerous PBL workshops. Currently, he is a section editor for *Biochemistry and Molecular Biology Education,* for which he writes commentaries on active learning. Dr. White received the College of Arts and Sciences Outstanding Teaching Award in 2005 and its Outstanding Service Award in 2007. He is a professor of biochemistry and has been the director of the Howard Hughes Medical Institute's Undergraduate Science Education Program at the University of Delaware since 1998.

Michelle Withers, PhD, is an assistant professor of biology at West Virginia University. Her research focuses on improving undergraduate science education, particularly evaluating the efficacy of different teaching methods in enhancing student learning. Another major focus is training faculty and future faculty in scientific teaching. She runs the National Science Foundation–funded West Virginia Summer Institute (WVUSI) on Undergraduate Science and Math Education, a regional offshoot of the National Academies Summer Institute (NASI) on Undergraduate Biology Education. She also runs workshops on assessment, active learning, and scientific teaching for NASI; the Scientific Teaching Assessment and Resources (STAR) mini-institute at Louisiana State University; and the Faculty Institutes for Reforming Science Teaching's Institute for Transforming Undergraduate Biology Education through Postdoctoral Scholars (FIRST IV). She serves on the steering committee for the National Academies Summer Institute and on the executive board of the Biology Director's Consortium (BDC) and is a founding member of the Society for the Advancement of Biology Education Research (SABER). She received her PhD in neuroscience from the University of Arizona, Tucson.

William Wood, PhD, has been a faculty member at the California Institute of Technology and at the University of Colorado, Boulder, where he is now Distinguished Professor of Molecular, Cellular and Developmental Biology, Emeritus. He holds an A.B. degree from Harvard College and a PhD in biochemistry from Stanford University, and he is a member of the National Academy of Sciences and the American Academy of Arts and Sciences. His research interests are the genetic control and molecular biology of axis formation and patterning in embryos of *C. elegans,* as well as biology education. In the 1970s and 1980s, he was lead author of the textbook *Biochemistry: A Problems Approach,* which helped introduce problem-based learning to biochemistry. Dr. Wood was a member of the National Research Council (NRC) committee that produced the 2002 report *Learning and Understanding: Improving Advanced Study of Mathematics and Science in U.S. High Schools* and was editor of the Biology Panel Report from that study. He has served as a consultant to the College Board on revision of the Biology Advanced Placement course for high schools. Currently he is a codirector of the National Academies Summer Institute on Undergraduate Education in Biology, and until recently he was Editor-in-Chief of the biology education journal *CBE—Life Sciences Education*. He is also a member of the NRC Board on Science Education (BOSE) and the Education Advisory Board of the Howard Hughes Medical Institute. In 2004, he received the Bruce Alberts Award of the American Society for Cell Biology for distinguished contributions to science education.

Daniel Wubah, PhD, is the Vice President and Dean for Undergraduate Education and a professor of biological sciences at Virginia Polytechnic Institute and State University. He served as Associate Provost for Undergraduate Academic Affairs and was a professor of zoology at the University of Florida. Prior to that, he was a professor and special assistant to the president at James Madison University. Dr. Wubah has taught several courses in microbiology, microbial ecology, and mycology. He has published extensively on his research, which involves the characterization of obligate anaerobic zoosporic fungi, the microbial dehalogenation of polychlorinated biphenyls, and fiber degradation in the wood-eating catfish, *Panaque*. Since 1995, he has continuously led several research-training programs funded by the National Science Foundation (NSF) and National Institutes of Health. Currently, he directs both the Scieneering Program at Virginia Tech, which is supported by the Howard Hughes Medical Institute, and an NSF-funded program in Ghana that offers international research experiences for undergraduates and focuses on ecology, ethnobotany, conservation, and environmental biology. Dr. Wubah is a member of three NSF advisory committees: the Biology Directorate, the Committee for Environmental Research and Education, and the Office of International Science and Engineering. He has been a member of the Board of Governors of the National Aquarium in Baltimore for the past eight years. He earned a B.S. with honors and a B.Ed. from the University of Cape Coast, Ghana, an M.S. from the University of Akron, and a PhD from the University of Georgia. He was a postdoctoral fellow at the US EPA Research lab in Athens, Georgia, before starting his career at Towson University as an assistant professor.





For more information on the AAAS Vision and Change in Undergraduate Biology Education Initiative, see *http://www.visionandchange.org/.*

This report is on the website at http://visionandchange.org/finalreport.

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