Research in Biology Education: Where do we go from here?

PROCEEDINGS

April 28-29, 2011
Chicago, IL

MICHIGAN STATE UNIVERSITY | Institute for Research on Mathematics and Science Education

About the Institute for Research on Mathematics and Science Education

The Institute for Research on Mathematics and Science Education (IRMSE) at Michigan State University provides leadership in conducting research related to pressing national and international challenges in mathematics and science teaching at both the K-12 and college levels. IRMSE encourages and supports interdisciplinary research teams to study educational issues from multiple perspectives. Founded in 2010, IRMSE is a collaboration of the MSU College of Education and the College of Natural Science.

Michigan State University is one of the nation's leading research universities known internationally for excellence in the sciences and education. For seventeen consecutive years, *U.S. News and World Report* has rated the MSU College of Education's elementary and secondary education programs as number one in the United States. MSU College of Education has established a reputation for excellence and visionary thinking in its efforts to improve teaching and learning across our nation and world, particularly within the contexts of urban and global education. MSU also has a highly ranked Physics Department with a number one ranked program in nuclear physics. MSU is home to the Facility for Rare Isotope Beams (FRIB) and the Bio/computational Evolution in Action CONsortium (BEACON) Center.

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Proceedings

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April 28-29, 2011, Chicago
Sponsored by Michigan State University Institute for Research on Mathematics and Science Education,
Colleges of Education and Natural Science, and Office of the Provost

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The Institute for Research on Mathematics and Science Education at Michigan State University welcomes Joseph Krajcik as the director. He assumed leadership in September 2011 and joined the faculty in the College of Education as a professor in the Department of Teacher Education specializing in science education. A former high school chemistry and physical science teacher, he spent 21 years at the University of Michigan before coming to MSU. During his career, he has focused on working with science teachers to reform science teaching practices to promote students' engagement in and learning of science. He holds a Ph.D. from the University of Iowa.

FORWARD

The American education system is undergoing dramatic change in how science and mathematics are taught to our students. In 2010, a majority of states adopted the Common Core State Standards for mathematics. Work is progressing on developing standards for science. Science educators now have a unique opportunity to identify new research areas emerging from these changes and shape the future of science education in the 21st century.

Michigan State University invited an interdisciplinary group of researchers from the fields of biology, biology education, marketing, and social science to gather in Chicago for a two-day colloquium "*Research in Biology Education: Where do we go from here?*" The meeting, sponsored by the newly formed Institute for Research on Mathematics and Science Education, provided a forum for exploring shared research agendas and introduced the interdisciplinary goals of the Institute. Five papers presented at the colloquium are included in the proceedings. The authors are:

- Spencer A. Benson, University of Maryland
- Rodger W. Bybee, Biological Sciences Curriculum Study
- James P. Collins, Arizona State University
- Felicia Keesing, Bard College
- William Wood, University of Colorado

With support from the College of Education, College of Natural Science, and the Office of the Provost, the Institute for Research on Mathematics and Science Education provides leadership in conducting research related to pressing national and international challenges in mathematics and science teaching, learning, curriculum, and policy at both the K-12 and college levels. Beginning in September 2011, Joseph Krajcik assumed leadership of the Institute. William Schmidt, University Distinguished Professor in Statistics and Education, served as interim director during the Institute's initial year.

The new Institute creates pathways for mathematicians, biologists, chemists, and other experts in their subject matter to collaborate with educational researchers who have a deep understanding of learning, pedagogy, and assessment. These collaborations will help scientists better translate their findings to the classroom and help educators transform the curriculum related to math and science learning. Dramatic changes in STEM (science, technology, engineering, and mathematics) education will need collaboration from all involved to ensure a smooth transition to a consistent framework for teaching science and mathematics.

This year the National Research Council (NRC) issued a framework for improving science education in the United States. New calls are being made for a pared down curriculum focusing less on memorization of facts and more on developing a deep understanding of core ideas. Fundamental to this framework is teaching students how to approach and solve problems, and use the science they know to better understand the world around them.

Why should biology educators change how and what they teach? In chapter one, Benson elaborates on multiple reasons driving this desired change, including a better understanding of how students learn science, the addition of new scientific discoveries and understandings, and the impact of technology on analyzing large amounts of data. But perhaps the main factor driving change, according to Benson, is the "realization that the solution to big problems - global warming, environmental degradation, disease and pandemics, water and food security - will require an aware, informed, and science literate citizenry."

The future of biology education encompasses areas hardly imagined a decade ago including diverse fields of synthetic biology, digital organisms, and personalized medicine and genomics. New discoveries create a constantly changing field where knowledge gained today may not be relative tomorrow. Nowhere is this more evident than in the medical field where daily headlines offer new hope where none existed in years past. Recent discoveries in genomics have found mutations that could determine a person's response to malaria treatment, blood thinners, and cancer therapy. This explosion of knowledge is rewriting our understanding of how the body works and our relationship to the environment we live in.

Developments in computers and research are giving scientist the ability to collect a wealth of data. The future of biology education in the next decade is finding news ways to use this treasure trove of data. Biology students will need to be well versed in mathematics, especially statistics, to understand all of the data available. Today, students have ready access to powerful computational tools, even on their smart phones. Many educators feel that moving biology education away from the rote memorization of facts makes sense. Students can easily look up the facts, but may not know what to do with them. Biology students will need training to be able to ask the correct research questions, filter through the massive amounts of data available, and understand how the it relates.

As our world becomes more interconnected, the need for interdisciplinary research in science is growing. There has been a chasm between pure science and humanities to the determent of both areas and what society needs, according to colloquium keynote speaker Robert Pennock, co-director of MSU's BEACON Center for the Study of Evolution in Action. "There is a moral component and a challenge to bring facts and values together. We, as educators, need to inspire students to awaken their curiosity and drive them to continue to seek answers," he states. A 2005 study found that public acceptance of evolution in the US is very low, only above Turkey in a study involving thirty-four countries. This is a challenge for biology education. How can you teach science if you cannot define the subject matter? Darren Schreiber, colloquium speaker and political scientist, echoes the dilemma facing biology educators who are trying to help their students navigate the intersection of fact and belief. Schreiber finds hope in the human ability to change beliefs and values. However, he cautions educators that belief change does not happen overnight. It takes time to formulate new opinions even in the face of compelling data. With any change in beliefs, the outcome can also be unpredictable or even undesirable.

The key may be in moving beyond the notion of science as a list of facts to one where the scientific process is appreciated and taught as content. In chapter three, Collins chronicles how traditional boundaries in biology such as physiology, natural history, and anatomy have faded over time. Over the past 25 years what is considered biology or life science has broadened tremendously. "Today's frontiers are often at the disciplinary edges filling the white spaces between our traditional disciplines at the intersection of biology, computer science, engineering, geoscience, mathematics, physical science, and social science," according to Collins. Educators are faced with the challenge to train students to be open to new ideas and capable of thinking broadly.

Biology is often the gateway course to high school science, setting the foundation for higher-level learning in the sciences. In chapter one, Benson discusses the AP-Biology course launching in Fall 2012 that includes a new curriculum framework. In chapter two, Bybee discusses this framework and changes in what the high school biology curriculum should look like to foster a scientifically and technologically literate society. He calls for a new curriculum integrating approaches to science, technology, engineering, and mathematics, and based on a small number of core ideas. Student learning experiences should be designed around these ideas.

Keesing and Wood call for a change not only in what is taught in biology, but also in how it is taught at the university and college levels. In chapter four, Keesing discusses the lack of research attention paid to how biology is taught to non-science majors whose only exposure to science education beyond high school may be through one or two college level courses. With so little access to non-science majors, how can departments communicate the core ideas of science most effectively? Keesing sees the broad acceptance of the core science concepts as a rallying cry for departments to develop effective and efficient curriculums. However, developing new curriculums is only part of the solution according to Wood. In chapter five, he calls for a shift away from instructor-centered teaching to a more student-centered mode of instruction. He discusses faculty attitudes toward teaching and learning, and barriers to change.

James Taylor, noted marketer and colloquium keynote speaker, sees other barriers ahead. He feels that educators and policy makers have done a poor job explaining to the US public why change is needed to the educational system. Studies show that parents become increasingly disengaged with their student's education, especially in the middle grades. Without knowing what the issues are or how to engage in making them better, parents are being caught unaware and disenfranchised to the change coming down the road. Viewed through lenses of a marketer, Taylor cautions policy makers and educators that they have not considered students as stakeholders in their own education. This is an area needing more research and quick action. Without gaining student buy-in and parental support, efforts to make sustained change face an uphill battle.

William Schmidt, colloquium organizer and speaker, raises issues of equality as a continuing obstacle facing educators and policy makers and sees an urgent need for Common Core Standards in science. His research shows wide gaps in the number and depth of science topics taught in districts and perhaps more surprisingly, within districts. As might be expected, this variation exists between richer and poorer districts across the nation, but it also exists in neighboring districts in the same geographic area. He stresses the moral obligations of policy makers to ensure all students have equal access to rigorous course work regardless of their address. Without providing equal exposure to higher-level science learning some districts are unwittingly dooming their students to remedial work in college or being unqualified for work requiring science and math skills. Findings also point to significant variations in the science that is taught in classrooms across the hall from each other. Schmidt stresses the need for continuing professional development to ensure that teachers are skilled at teaching the intended curriculum.

Achieve Inc., a non-profit, bipartisan group composed of our nation's governors and corporate leaders, is using the NRC's framework to write new science standards. Similar efforts in 2010 led to the adoption of the Common Core State Standards in Mathematics by most states.

The new standards are expected in late 2012 with drafts made available for public comment before hand. In science these issues are made more complicated because, unlike mathematics, school science is not based on a single discipline, but many disciplines including biology, chemistry, physics, and other fields. The real challenge may be in how the science standards are implemented in our nation's classrooms. It may be several years after adoption before the standards appear in the classroom.

The development of science standards presents a unique opportunity for educational researchers to explore how these standards will be put into action and their impact on students, teachers, and achievement. New research opportunities are emerging in curriculum, teacher preparation, policy, and other areas. Teachers will need to be trained in how to teach the new and much more demanding content. Professional development will need to be designed to support teachers for years to come. Current textbooks will not align with the new standards. How can textbooks be best used in light of the misalignment? How will student knowledge be accessed in light of these new standards? Research into how principals can play an important leadership role in all of this is also important.

An interdisciplinary approach to understanding these science and schooling issues will be crucial. An institute, like the one established at Michigan State University, offers the potential for encouraging and supporting such research.

Acknowledgments: The colloquium organizers wish to express our sincere appreciation to the participants, speakers, authors, and discussants. Their extensive research experience and service to the field provide valuable insights for future research in biology education. Gratitude is also extended to the colloquium keynote speakers Robert Pennock and James Taylor. Thank you to colloquium speakers and discussants: Spencer A. Benson, Rodger W. Bybee, James P. Collins, Diane Ebert-May, Joan Ferrini-Mundy, Noah Finkelstein, John Jungck, Felicia Keesing, William Schmidt, Darren Schreiber, Susan Singer, Keith Trigwell, Paul Williams, William Wood, Hung-Hsi Wu. Thank you to Jacqueline Babcock, Sue Carpenter, Susan Pettit-Riley and Nicole Geary for their assistance with the Institute. Finally, we are grateful for the support in the founding of the Institute by Michigan State University's Provost Kim Wilcox, College of Education Dean Carole Ames, and College of Natural Science Dean James Kirkpatrick.

Research in Biology Education: Where Do We Go From Here?

AGENDA

April 28-29, 2011

Welcome and Introductions: William Schmidt, Interim Director of the Institute for Research on Mathematics and Science Education; Dean Carole Ames, College of Education, Michigan State University; Dean R. James Kirkpatrick, College of Natural Science, Michigan State University; and Provost Kim A. Wilcox, Michigan State University

Keynote speaker Robert Pennock: Where is the research field of biology education headed over the next ten years and what are the implications for biology education

Session 1: We are not hard wired to be hard wired

Presenter – Darren Schreiber

Keynote speaker James Taylor: Relevance, enthusiasm, and the choice to learn biology education

Session 2: What research tells us about what high school biology should look like

Presenters – Spencer Benson and Rodger Bybee

Session 3: The role of mathematics in teaching biology

Presenters – John Jungck and Hung-Hsi Wu

Session 4: As biology has changed, how has its role in science education changed? Is the old model of biology as the "introduction to science" relevant?

Presenter – James P. Collins

Discussants – Noah Finkelstein and Paul Williams

Session 5: What research tells us about how to prepare future biological scientists

Presenters – Felicia Keesing and Susan Singer

Session 6: What research tells us about what biology at the university level should look like

Presenter – William Wood

Discussants – Diane Ebert-May and Keith Trigwell

Presentation by Joan Ferrini-Mundy: Perspective from the national policy level

Presentation by William Schmidt: Issues of equality and the need for a Common Core in science

Concluding remarks by William Schmidt

CHAPTER 1

Changing the National Science Education Landscape: The New AP-Biology Program

Spencer A. Benson

Abstract

During the last decade there have been numerous calls for educational reform in the STEM (Science Technology Engineering and Math) disciplines from industry, government and the academe. There are many reasons for changing what we teach and how we teach in the STEM disciplines, including: an explosion of new knowledge (especially in the biological sciences); a growing realization that traditional content transmission is insufficient to prepare students for an ever changing globally connected world; a better understanding of how students learn; the game changing impacts of technology, including the Internet; the need for the US to remain economically competitive in a global world; and the realization that the solution to big problems - global warming, environmental degradation, disease and pandemics, water and food security - will require an aware, informed and science literate citizenry.

The American educational system from kindergarten through university is locally administered and to a large degree curriculums are determined at the local level. Although there are national and state standards, they serve as benchmarks rather than curriculums per se. The College Board's Advance Placement program provides a mechanism for a common vetted curriculum for many subjects including the STEM disciplines. In the 2002 National Research Council report *Improving Advance Study on Math and Science in U. S. High Schools* the AP science courses were characterized as a "mile wide and an inch deep" and teaching science as a body of facts to be learned rather than a process for the development of new knowledge. In 2006 the College Board, with funding from NSF, began redesigning AP science courses including AP-Chemistry, AP-Physics, AP-Environmental Sciences, and AP-Biology. AP-Biology is the lead course in the redesign process. The AP-Biology program annually enrolls more than 160,000 students and involves nearly 10,000 teachers from across the U.S. and elsewhere. The redesign commission was charged to develop an AP-biology program that focuses on essential knowledge, integrates inquiry and other instructional practices that are essential for developing conceptual understandings, and builds upon new research and advances in biology. In other words, the commission sought to develop a model introductory college level biology course that universities would want to emulate. The New AP-Biology course will launch in Fall 2012 and includes a new curriculum framework that outlines the essential knowledge and science practices that students should have, a new testing paradigm, new and revised laboratory exercises, and professional development to enable teachers to effectively teach the new course.

About the Author

Spencer Benson is the Director of the Center for Teaching Excellence, Associate Professor in the Department of Cell Biology and Molecular Genetics and an affiliate Associate Professor in the Department of Curriculum and Instruction at the University of Maryland. He received his B.S. degree in Zoology from the University of Vermont and his Ph.D. in Genetics from the University of Chicago. As Director of the Center for Teaching Excellence he is responsible for overseeing more than 20 programs designed to improve teaching and learning through professional development of faculty, graduate students, and undergraduates. He is past chair of the Undergraduate Education Committee of the American Society of Microbiology (ASM), past chair of ASM's Div-W (Teaching), and currently is as member of ASM's International Education Committee. He is a founding member of the International Society for the Scholarship of Teaching and Learning and the ASM sponsored Biological Scholars Program. He is a University of Maryland CTE-Lilly Teaching Fellow, a 2001 Carnegie Academy for the Advancement of Scholarship in Teaching and Learning Fellow. Dr. Benson has received numerous teaching awards including the College of Chemical and Life Science teaching award and the 2002 CASE-Carnegie Maryland Professor of the Year award.

Introduction: The Needs

In 2002, the National Research Council (NRC), with support from the National Science Foundation (NSF) and the U.S. Department of Education, published the results of a two-year study of the Advanced Placement (AP) and International Baccalaureate programs. The report, *Learning and Understanding: Improving Advanced Study of Mathematics and Science in U.S. High Schools (National Research Council, 2002)*, called for important improvements in advanced study in high school mathematics and science programs. Numerous other reports from government, business, and the academy all stress the need to rethink, reshape and deliver science education in new ways that ensure a science literate citizenry and a workforce that will enable the U.S. to remain a world leader in the STEM disciplines and to retake leadership in the new, global, knowledge economies. Reports such as *Rising above the Gathering Storm (National Academies (NAS), 2007)(National Academies (NAS), 2010)*, *An American Imperative (Buisness Higher Education Forum, 2007)*, *Bio2010 (National Research Council (NRC), 2003)* and *Vision and Change (AAAS, 2010)* all clearly outline these needs and the consequences of not meeting them. Addressing these challenges requires curriculum changes at the national, state, and local school district levels. However, in the U.S. there is no mechanism to establish a national STEM curriculum. To a very large degree what gets taught and how it is taught resides at the local or state level. In light of its growing prominence in the American secondary education landscape, the College Board AP Programs in science provide the opportunity to reformed STEM curriculums taught at thousands of schools across the United States and beyond.

The 2002 National Research Council report on AP-Science courses (National Research Council (NRC), 2002) characterized AP-Biology as a "mile wide and an inch deep" and "teaching science" as a body of facts to be learned rather than a process for the development of new knowledge. In 2006 the College Board, with funding from NSF began redesigning AP science courses including, AP-Chemistry, AP-Physics, AP-Environmental Sciences, and AP-Biology. That work followed a new paradigm for science education in which science is taught not as a collection of facts or truths to be memorized, but as a way to understand and make sense of the world around us—a paradigm in which course content becomes not the *end* but the *means* for establishing conceptual understandings. This article will highlight the pathway, progress, and challenges in redesigning the AP-Biology program that annually enrolls more than 160,000 students and involves nearly 10,000 teachers in the U.S. and abroad.

The Curriculum Framework: A Roadmap for Learning Biology

The AP-Biology redesign commission was charged to develop an AP-Biology program that focused on essential knowledge, inquiry, and other student centered instructional practices essential for developing conceptual understandings, and to integrate new research and advances in biology and student learning while building existing student knowledge. In other words, to develop a model introductory college level biology course that produced enduring understanding and which universities would want to emulate. The course would build upon prior knowledge as described in the College Board Standards for College Success (College Board, 2009). To accomplish this task a commission composed of university and high school teachers met regularly and developed a draft curriculum framework that was subsequently reviewed and vetted and refined by university and high school teachers. The curriculum framework was organized around four overarching "big ideas" in current biology (Table 1). Each idea is supported by a set of enduring understandings which in turn are built upon a set of essential underlying content, e. g. facts and concepts that the student must know in order to understand and be able to communicate his or her understanding. To measure student learning, specific learning objectives were developed. Each AP-Biology learning objective describes what students should know and be able to do if they have learned the material and in doing so become adept at applying basic science practices (Table 2). Because in biology the whole is greater than the sum of the part, the curriculum framework specifically identifies content and conceptual connections within and across the big idea and conceptual understandings.

By limiting the amount of content that is required, the framework reduced the breadth of the course while focusing on building student conceptual understandings of key aspects of modern biology. Because many concepts can be taught through a variety of content examples, teachers are provided with a list of illustrative examples that serve as a guide for which systems or examples they might use to teach a particular aspect of the framework. Of equal importance, within the framework there is the clear delineation of what is beyond the scope of the course and the exam. This does not mean that this material designation beyond the scope of the course is not important, nor that it should not be taught, rather these signposts are provided to help the instructor decide what they want to include in their course. In deciding what must be present in the course the redesign commission worked to insure that the instructional time needed to teach the curriculum framework did not exceed 85 percent of the instructional time for AP-Biology in a typical school year.

Table 1. 2012-13 AP-Biology Curriculum Framework*

Big Idea	Enduring Understandings	Essential Knowledge	Learning Objectives
1. The process of evolution drives the diversity and unity of life.	4	11	32
2. Biological systems utilize free energy and molecular building blocks to grow, to reproduce and to maintain dynamic homeostasis.	5	15	40
3. Living systems store, retrieve, transmit and respond to information essential to life processes.	5	15	50
4. Biological systems interact, and these systems and their interactions possess complex properties.	3	14	27

* see AP-Biology Curriculum Framework 2012-2013 (College Board CDAC Committee, 2011) http://advancesinap.collegeboard.org/science/biology

Table 2. Science Practices for AP-Biology*

SP-1.0	The student can use representations and models to communicate scientific phenomena and solve scientific problems.
SP-2.0	The student can use mathematics appropriately.
SP-3.0	The student can engage in scientific questioning to extend thinking or to guide investigations within the context of the AP course.
SP-4.0	Student can plan and implement data collection strategies in relation to a particular scientific question.
SP-5.0	The student can perform data analysis and evaluation of evidence.
SP-6.0	The student can work with scientific explanations and theories.
SP-7.0	The student can connect and relate knowledge across various scales, concepts, and representations in and across domains.

* see AP-Biology Curriculum Framework 2012-2013 (College Board CDAC Committee, 2011) http://advancesinap.collegeboard.org/science/biology

Science is not a collection of facts to be memorized, but a process through which we construct knowledge to better understand and know the world. To help students understand the essence of science as inquiry, analysis, explanation and communication, a set of science practices were developed for the AP-Science courses (biology, chemistry, physics, environmental science) by science educator specialists (Table 2). Each of the seven science practices shown in Table 2 are further delineated by specific practices that describe what students can do, e. g. create, describe, use, refine, justify, apply, estimate, design, evaluate, collect, articulate, etc. Readers are referred to the AP-Biology curriculum framework (College Board CDAC Committee, 2011) for the complete set of science practice statements.

Claims and Evidence: How Will We Know?

The curriculum framework outlines the content and provides the grist for what teachers need to teach and what students' need to learn in order to develop enduring understandings of biological facts, processes, and concepts in addition to developing their ability to think as scientists. In order to determine if students in the new course are obtaining knowledge and skills that are comparable to those expected of students who successfully complete a college level introductory biology course, specific learning objectives were developed. Each learning objective combines essential knowledge with a science practice and connects the big ideas to an enduring understanding, to essential knowledge, to basic content, and a science practice. For example, in Big Idea 1: "The process of evolution drives the diversity and unity of life" is supported by Enduring Understanding 1a: "Change in the genetic makeup of a population over time is evolution", which is supported by Essential Knowledge 1.A.1: "Natural selection is a major mechanism of evolution", which is linked to the a required content 1.A.1.C: "Genetic variation and mutation play roles in natural selection". This set of connections yields learning objective: LO1.2: "The student is able to evaluate evidence provided by data to qualitatively and quantitatively investigate the role of natural selection in evolution" which incorporates science practices SP-2: "the student can use mathematics appropriately" and SP-5: "the student can perform data analysis and evaluation of evidence". To determine if students have learned the concepts and have command of the necessary content for each of the big ideas, enduring understandings and essential knowledge, a set of claims (that the student will know and/or be able to do) and evidence (what student work product(s) would demonstrate that they had mastered the material) were developed. Each of the more than one hundred claims and evidence statements link specific content knowledge with one or more science practices. The claims and evidence statements provide test item writers with a blue print and specifications for what individual test items need to contain and measure.

The AP-Exam: Measuring What Students Know

More than 140,000 students annually take the AP-Biology Advance Placement exam. Individual performance on this high stakes exam determines whether they will receive advance placement credit at the university level. Each college and university sets their own criteria regarding AP credit. Successful completion of Advance Placement courses as measured by exam performance is a factor considered in admission at many institutions. Traditionally the AP-Biology exam contains two components: a selected response (multiple choice) section and an extended free response section consisting of four essay questions. The free response questions have multiple parts and are graded by readers from high school and university faculties against a common set of standards. The 180-minute exam is administered on a specific day in late spring at thousands of sites in the U.S. and abroad. The fact that all AP-students take the same standardized exam is one of the mechanisms for standardizations of the AP curriculum across thousands of high schools since all students take the same test. The second mechanism for standardization is the AP-Audit, *College Board (2010)* in which schools submit documentation showing that they are teaching an AP-Biology course that meets the expectations set forth by the College Board. In many ways the AP-Exams are the keystones for the Advance Placement programs and certainly the item that is the upmost concern for both students and teachers. The exam for the redesigned AP-Biology course will be different than previous exams in a number of ways. The format will be expanded. In addition to selected responses and extended free response questions, the new exam will include a grid in questions where student must provide a numerical answer by filling in the appropriate bubbles, students will be allowed to use a simple four-function plus square-root calculator, and a new short answer free response type questions in which the answer is confined to few sentences will be part of the exam. The number of multiple choice and extended free response questions will be reduced to offset the introduction of the grid-in questions, the short answer questions, and the necessity to provide more context in the question stems. Because many concepts within the curriculum framework can be taught with various illustrative examples, which are not required knowledge, exam questions that build upon illustrative examples must provide sufficient background information to enable all students to fairly answer the question. The most important change in the new exam is the paradigm shift to using evidence-centered design (ECD) for the construction of all test items. ECD is based on principles of evidentiary reasoning (Mislevy, R. J., Almond, R. G. and Lukas, J. F., 2003) to make valid inferences regarding what students know and can do. By embedding in the curriculum framework the learning objects and providing design parameters through claims and evidence statements for construction of the test items used to elicit evidence of student understanding, the new AP-Exam is designed to directly measure content knowledge, conceptual understandings, and application of science practices based on student work, e.g. their answers on the exam. This is in contrast to previous exam development where student knowledge and understanding of content within broad areas of biology, e.g. molecular, genetics, cellular, organ systems, organisms, populations, ecology etc, served as the basis for test item development. To ensure scientific accuracy, alignment with the curriculum framework, and equal representation of the four big ideas, all test items are reviewed by the curriculum development and assessment committee (CDAC) composed of high school and university teachers who are experts on the curriculum framework. In addition, because of the new nature of the exam extensive pilot testing of individual items, as well as for student reading times, are being done.

The Labs: Learning Through Inquiry

The new AP-Biology course is anchored in the concept that through inquiry student learning of content and science practices are facilitated. While there is a strong expectation that inquiry be embedded in all aspects of the course, lecture, discussion, projects, etc, the laboratory component is the area most amenable for easy integration of student inquiry. The new AP-Biology course has a requirement that at least 25 percent of instructional time is devoted to laboratory activities, which will be monitored via the AP-Biology course audit (College Board, 2010). The current AP-Biology course has an associated set of laboratory exercises, however many are typical "cookbook" type labs that are more teacher directed than student directed. A new AP-Biology Laboratory Manual is under development with a January 2012 expected release date. The AP Biology labs align with the recommendations of America's Lab Report (National Research Council (NRC), 2005) and require students to be actively involved in the process of scientific inquiry and develop an understanding of the way in which scientific knowledge is acquired. Each of the four big ideas will be supported by several new or revised laboratory exercises. Importantly all of the new and revised labs, field experiences and investigations will be accessible to all— this means that they will require no new major equipment purchases. The laboratories like the curriculum framework and exam items are being vetted, piloted, and refined based on student and teacher feedback. The laboratories provide a robust range of teacher directed to fully student directed inquiry activities that align with the science practices (Table 2). A number of the science practices are especially amenable to laboratory exercises these include, SP-2.0 "students can use mathematics appropriately", SP-3.0 "students can engage in scientific questioning to extend thinking or to guide investigations within the context of the AP course", SP-4.0 "student can plan and implement data collection strategies in relation to a particular scientific question", and SP-5.0 "students can perform data analysis and evaluation of evidence" (Table 2). In addition to providing instructional guidance for the laboratory exercises the laboratory manual contains introductory an chapter on the goals for lab including investigations, learning objectives, exemplars and guidance to help teachers create activities; a chapter on managing the investigative experience, safety considerations, preparing students for introducing inquiry, and accommodating students with special needs; a chapter on written and oral communication from reports to presentations; a chapter on quantitative skills including statistical tests, standard errors, measuring, modeling, predictions and calculations; and a chapter describing how to transitioning from teacher directed to student directed lab investigations and modify existing labs to make them more student directed and inquiry based.

Professional Development: Building Capacity

AP-Biology is taught by nearly ten thousand teachers across the US and elsewhere. As a group AP teachers tend to be skilled motivated teachers who are deeply committed to biology and student learning. Their classroom experience range from a few years to many decades thus the challenge of providing appropriate professional development to this diverse population is large, especially in light of the short window of time available. The new AP-biology course will launch in fall of 2012. In additional to the in-place AP-Biology workshop and summer institutes a number of new approaches for delivery and dissemination of resources will be used. These are likely to include increased use of on-line formats to deliver content, examples and information, increased use of existing and new social network tools to build communities and the use of peer-to-peer mentoring. A full description of the on-going professional development initiatives, processes and approaches is beyond the scope of this article.

Summary and Conclusions

The science for the 21st century is indeed biology. Technological advances now allow us to probe into biological systems and problems in ways, which just a few years ago were simply not possible. These include high through put DNA sequencing, proteomics, metabolomics, f-MRI, satellite imaging of the environment, etc. Increasingly biology is becoming an integrated science that requires collaborations and connections to chemistry, physics, geology, engineering, computational sciences and math. In addition, the last decade has seen a virtual explosion in new data and information regarding biological systems and the rate on new information acquisition continues to accelerate. Training student to understand and be successful biologists requires new approaches to teaching biology and a shift from teaching biology as a set of facts to be covered to teaching biology as a set of interconnected concepts through which students acquire the content needed to understand concepts and build connections across the STEM disciplines, develop the ability to think like biologist/scientist and ultimately be able to understand and address complex problems. The new AP-Biology program represents a large-scale experiment in teaching biology content through concepts and inquiry. By organizing biology into four big ideas and then using them to scaffold enduring understanding and essential knowledge the goal is to provide students with a robust network of biology understandings that will allow they to easily build in new information, make informed judgments regarding how biology impacts societal issues and problems and be equipped to be successful in upper level biology courses. A number of components define and differentiate the new curriculum from the old; i) a focus on enduring conceptual understandings, ii) increased attention to the quantitative aspects of biology, iii) a focus on student inquiry throughout the courses, iv) a high stakes exam based on evidence of student work products that measure what students can do, and v) new resources that support professional development of teacher and student learning.

Because AP-Biology uses a common curriculum platform and exam that impacts many thousands of teachers and students annually it is has the potential to change the landscape of biology teaching at both the high school and university levels. In developing the curriculum framework the goal was not to replicate the best university practices but to use them to develop and test a new framework, which the universities would want to emulate. The basic ideas and tenets of the AP-Curriculum show a high degree of alignment with the core concepts outlined in Vision and Change (*AAAS, 2010)*, a document produced after the curriculum framework. This alignment along with previous reports strongly indicates that changes in biology education are imperative and doable if we are to remain at the cutting edge of research and retain our leadership in this realm.

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CHAPTER 2

The Next Generation of Science Standards: Implications for High School Biology

Rodger W. Bybee

Abstract

Release of the new science education standards will engage the question – What should high school biology look like? Based on the new standards, the life science curriculum will incorporate a small number of core ideas that have a long history in biology and biology education and clear scientific and educational support. High school biology should include learning experiences for the following core ideas:

- Organisms have structures and functions that maintain their life processes and facilitate growth, development, and reproduction.
- Organisms obtain necessary resources from their environment.
- Organisms have mechanisms and processes for passing traits and variations of traits from the present to the next generation.
- Biological evolution explains the unity and diversity of species.

High school biology also will address more than core ideas for life processes, ecology, heredity, and evolution. In addition to content, the design and implementation of the life science curriculum will be based on:

- research on student learning,
- information and communications technologies,
- twenty-first century skills and abilities,
- contexts for twenty-first century biology, and
- integrated approaches to science, technology, engineering, and mathematics.

The new generation of standards and high school biology programs should contribute to:

- a scientifically and technologically literate society,
- a deep technical workforce, and
- a diverse and advanced scientific and technological workforce.

About the Author

Rodger Bybee is Chair of the Science Forum and Science Expert Group, and Questionnaire Panel Consultant for PISA 2006. Until 2007, Dr. Bybee was Executive Director of the Biological Sciences Curriculum Study (BSCS), a non-profit organization in Colorado Springs, Colorado that develops curriculum materials, provides professional development for the science education community, and conducts research and evaluation on curriculum reform. Prior to joining BSCS, he was Executive Director of the National Research Council's Center for Science, Mathematics, and Engineering Education (CSMEE), in Washington, D.C. Between 1985 and 1995, he participated in the development of the National Science Education Standards, and in 1992-1995 he chaired the content working group of that National Research Council project. Dr. Bybee has received numerous awards, including the National Science Teachers Association (NSTA) Distinguished Service to Science Education Award (1998); The American Institute of Biological Sciences (AIBS) first AIBS Education Award (2001); and in 2007, he received the Robert H. Carleton Award, NSTA's highest honor, for national leadership in science education.

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Introduction

Many reasons can be cited for reforming high school biology. Among the more prominent, one would have to include: poor student achievement on national and international assessments, progress in our understanding of how students learn, pressing biology-related issues such as health, food, resources, and environment, and advances in our understanding of living systems from molecular to biosphere levels. While these and other reasons carry weight, the most significant force for reform of high school biology likely will be the next generation of standards for science education.

This essay first discusses biological content and several innovative features of the next generation of science standards. Next, there is a brief review of evidence-based and policy-based innovations that should be considered for new high school biology curricula. Finally, design issues for high school biology are discussed.

Biological Content and Science Practices

The Content of High School Biology

One of the first questions many ask centers on the concepts that students should learn. The question often is asked with an anxiety that there may be great changes in the major domains of biology. The concern is ill spent. The major domains of study for high school biology will parallel those initially stated 50 years ago in the 1960 edition of the *Biology Teacher's Handbook*, periodically updated (BSCS, 1993, 2001, 2009) and restated in the national standards (AAAS, 1993; NRC, 1996).

Although the National Research Council (NRC) framework for national standards has not been released, the next generation of biological content very well may be similar to the framework released for public review in late 2010 (see Table 1) and the recently completed standards for Advanced Placement biology (Wood, 2009; College Board, 2009). See Table 2.

Table 1. Major Biological Concepts (NRC 2010 Framework).

- Organisms: Processes and Structures
- Organisms: Transfer and Flow of Matter and Energy
- Heredity: Inheritance and Variation of Traits
- Ecosystems; Interactions, Energy, and Dynamics
- Biological Evolution: Unity and Diversity

Table 2. Major Biological Concepts (AP Biology).

- Evolution as the basis for both the diversity and the unity of life
- Biological systems and their properties, including energy use, molecular components, growth, reproduction, and homeostasis
- Information: how organisms store it, retrieve and use it, transmit and respond to it
- Interaction of systems components and the emergent properties of the resulting entities, from DNA molecules to cells to organisms to ecosystems

In addition to concepts that define the basic structure of biology, the next generation of science standards will include cross-cutting scientific concepts. Table 3 displays those concepts as presented in the 2010 NRC framework.

Table 3. Cross-cutting Science Concepts (NRC, 2010)

- Patterns, similarity, and diversity
- Cause and effect: mechanism and prediction
- Scale, proportion, and quantity
- Systems and system models
- Energy and matter: flows, cycles, and conservation
- Stability and change

Science Practices and Inquiry

Since the late 1950s, the biology curriculum has included both the concepts and processes of biology. Beginning with the inclusion of inquiry in the framework developed for the Biological Sciences Curriculum Study (BSCS), inquiry (i.e., processes of science) has been a component of BSCS programs and the life science curriculum (Rudolph, 2002, 2008). The 2010 NRC framework released for review included a new variation on traditional inquiry; namely, science practices presented in Table 4. The science practices are reflective of those described in the AP Standards *Science College Board Standards for College Success* (College Board, 2009) and the National Research Council reports *Taking Science to School* (Duschl et al., 2007) and *Ready Set Science* (Michaels et al., 2008).

Table 4. Science Practices and Inquiry (College Board, 2009; NRC, 2007, 2008).

- Asking Questions and Defining Problems
- Developing and Using Models
- Planning and Carrying Out Investigations
- Analyzing and Interpreting Data
- Using Math and Computational Thinking
- Constructing Explanations and Designing Solutions
- Engaging in Argument from Evidence
- Obtaining, Evaluating, and Communicating Information

Scientific Proficiency

The 2007 NRC publication *Taking Science to School* has directly influenced the new science standards, especially in the description of content and processes. The report answered the question – What does it mean to be proficient in science? The answer rests on a foundation of both knowledge and processes that refine, extend, and revise knowledge. The framework of scientific proficiencies answers either/or questions about science content or processes. The answer is that scientific proficiencies include both. Table 5 displays the scientific proficiencies.

Table 5. Scientific Proficiencies (Duschl et al., 2007).

• Knowing, using, and interpreting scientific explanations of the natural world
• Generating and evaluating scientific evidence and explanations
• Understanding the nature and development of scientific knowledge
• Participating productively in scientific practices and discourse

These proficiencies describe broad learning outcomes of science education and thus elements in a framework for the biology curriculum. One should note the fact that the proficiencies include all science disciplines and that the knowledge and reasoning skills of scientific inquiry are included. One also should note that the scientific proficiencies do not include components of technological knowledge or engineering design, both aspects of the new science standards.

Innovations and the Design of High School Biology

The prior section addressed the question – What should high school students learn about biology? This section addresses questions about contemporary research on learning that should be basic to the design of instructional materials.

How Students Learn Science

Many contemporary discussions center on state assessments, teacher accountability, and student achievement. At their base, these discussions must be about student learning and the assumption that curriculum and instruction will result in high levels of student achievement. Enhancing student achievement will rely on implementing research that has advanced our understanding of how students learn science. The National Research Council reports, *How People Learn: Brain, Mind, Experience, and School* (Bransford, Brown, & Cocking, 2000), *How People Learn: Bridging Research and Practice* (Donovan, Bransford & Pellegrino, 2000), and the more recent *How Students Learn: Science in the Classroom* (Donovan & Bransford, 2005) present a major synthesis of research on human learning. Three findings from these NRC reports have both a solid research base and clear implications for the high school biology curriculum. The following findings are from *How People Learn: Bridging Research and Practice*.

> *Students come to the classroom with preconceptions about how the world works. If their initial understanding is not engaged, they may fail to grasp the new concepts and information that are taught, or they may learn them for purposes of a test but revert to their preconceptions outside the classroom.* (p. 10)

The curricular implications of the first finding relates to the structure of experiences that draw out students' current understandings, bring about some sense of the inadequacy of the ideas, and provide opportunities and time to reconstruct ideas so they are consistent with basic scientific concepts.

A second finding refers to the conceptual foundation of a biology curriculum.

> *To develop competence in an area of inquiry, students must: (a) have a deep foundation of factual knowledge, (b) understand facts and ideas in the context of a conceptual framework, and (c) organize knowledge in ways that facilitate retrieval and application.* (p 12)

The high school biology curriculum should incorporate fundamental knowledge and be based on, and contribute to, the students' development of a strong conceptual framework. Research comparing performance of novices and experts, as well as research on learning and transfer, shows that experts draw upon a richly structured information base. Although factual information is necessary, it is not sufficient. Essential to expertise is the mastery of concepts that allows for deep understanding and a framework that organizes facts and information.

Finally, there is a finding related to students' ability to think about their thinking.

> *Students can be taught strategies that help them monitor their progress in problem solving*. (p. 13)

Research on the performance of experts suggests that they reflect on and monitor their understanding of a scientific investigation. They note any requirement for additional information, the alignment of new information with what is known, and the use of analogies that may provide insights and advance their understanding. For experts, there are often internal conversations grounded in the processes of scientific inquiry. Students can learn the latter if taught in the context of biology concepts and scientific investigations.

In summary, the high school biology curriculum should acknowledge the fact that students already have ideas about objects, organisms, and biological phenomena. And, many of these ideas do not align with contemporary scientific knowledge. The challenge for curriculum developers and biology teachers is not so much the fact that students have these misconceptions, but how to change the current concepts so they align with accepted biological knowledge and understandings. In contrast to many contemporary programs, research on learning indicates that curriculum and instruction should include a clear conceptual framework as well as facts and information. Finally, students can enhance their own learning through self-reflection and monitoring.

Learning Progressions

One innovation in the new science standards will be the description of learning progressions across the grades. Learning progressions are defined as "descriptions of the successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time: e.g., 6 to 8 years (Duschl et al., 2007, p. 219).

Learning progressions do not exist for all biological concepts across all grades. To be clear, they should be stated as proposed progressions that describe the pathways students are likely to follow to the mastery of core concepts. They are based on research about how students' learning actually progresses and not on a logical analysis of current disciplinary knowledge and personal experiences of teaching science (Corcoran, Mosher, & Rogat, 2009). Two examples important for biology are modern genetics (Duncan et al., 2009) and biological evolution (Lehrer et al., 2004).

Contexts for 21st Century Biology

One aspect that is not addressed in the next generation of science standards centers on the context in which high school biology might be taught. While several reports and articles have introduced contextual themes (Kress & Barrett, 2001; NRC, 2009; Bybee, 2002), Table 6 presents the general areas of food, environments, energy, and health as four contexts critical to the understanding and application of biology in the 21st century.

Table 6. Contexts for High School Biology (NRC, 2009).

- Generate food plants to adapt and grow sustainably in changing environments
- Understand and sustain ecosystem function and biodiversity in the face of rapid change
- Expand sustainable alternatives to fossil fuels
- Understand individual health

The contexts in Table 6 are from *The New Biology for the 21st Century* (NRC, 2009). Contexts such as these have been the basis for research in science education (see Special Issue: Scientific Literacy and Contexts in PISA [Bybee et al., 2009]) and could certainly be important for the biology curriculum.

What High School Biology Should Look Like

The Curriculum Structure

Coherence for the structure of biology concepts must be paramount in the curriculum. The biology content should be (1) consistent with the new generation of standards, and (2) well-thought-out, coordinated, conceptually procedural, and organized with a clear focus. The role of biology concepts, science practices, inquiry, personal and social contexts, and the history and nature of science should be clear and explicit.

The biology curriculum should have a varied emphasis. As an artist decides what will be in the foreground and what will be in the background by varying emphasis, so should curriculum materials. Varying emphasis, for example, from everyday applications of biology in society, can better accommodate the interests, strengths, and demands of science content.

Finally, high school biology should provide an array of opportunities to develop knowledge, understanding, and abilities associated with different dimensions of biological literacy (BSCS, 1993). Opportunities include laboratory experiences, projects, technological simulations and games, as well as reading, videos, and explanations by the teacher.

The Instructional Approach

The high school program should incorporate an organized and systematic approach to instruction. The NRC publication *America's Lab Report: Investigations in High School Science* (NRC, 2006) termed this the use of an integrated instructional unit. I prefer an instructional model.

I will return to a prior report on student learning to set the stage for this discussion of an instructional model. *How People Learn* made the following point:

> *An alternative to simply progressing through a series of exercises that derive from a scope and sequence chart is to expose students to the major features of a subject domain as they arise naturally in problem situations. Activities can be structured so that students are able to explore, explain, extend, and evaluate their progress. Ideas are best introduced when students see a need or a reason for their use—this helps them see relevant uses of knowledge to make sense of what they are learning.* (Bransford, Brown, & Cocking, 1999, p. 127)

Incorporation of an instructional model (1) provides for different forms of interaction among students and between the teachers and students, (2) allows for a variety of teaching strategies, such as inquiry-oriented investigations, cooperative groups, use of technology, and (3) allows adequate time and opportunities for students to formulate knowledge, skills, and attitudes.

Research supports an instructional sequence very similar to the BSCS 5E model. Table 7 displays the 5E model. I have discussed the origin and use of the 5E model elsewhere (Bybee, 1997). Here, I acknowledge that other instructional models exist and are effective. For reasons that should be obvious, I recommend the 5E model (Bybee et. al, 2006).

Table 7. BSCS 5E Instructional Model (BSCS, 2001).

BSCS 5E Instructional Model	
Engage	The instructor accesses the learners' prior knowledge and helps them become engaged in a new concept by reading a vignette, posing questions, presenting a discrepant event, showing a video clip, or conducting some other short activity that promotes curiosity and elicits prior knowledge.
Explore	Learners work in collaborative teams to complete lab activities that help them use prior knowledge to generate ideas, explore questions and possibilities, and design and conduct a preliminary inquiry.
Explain	To explain their understanding of the concept, learners may make presentations, share ideas with one another, review current scientific explanations and compare these to their own understanding, and/or listen to an explanation from the teacher that guides the learners toward a more in-depth understanding.
Elaborate	Learners elaborate their understanding of the concept by conducting additional lab activities. They may revisit an earlier lab and build on it or conduct an activity that requires an application of the concept.
Evaluate	The evaluation phase helps both learners and instructors assess how well the learners understand the concept and whether or not they have met the learning outcomes.

Conclusion

In this essay, I have introduced several features of the next generation of science standards and research that apply to various components of a high school biology curriculum.

I will conclude with an observation based on prior work on national standards. The next generation of science standards is the first, easiest, and least expensive step in the reform of biology education. Development of new instructional materials, changing assessments, and professional development of biology teachers present the more significant challenges.

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CHAPTER 3
Changes in Biology and Biology's Evolving Role in Science Education

James P. Collins

Abstract

In the late 19th and early 20th centuries several areas of study including physiology, natural history, and anatomy coalesced to form the discipline of biology. In today's parlance, early 20th century biology arose as an "interdisciplinary" or even a "transdisciplinary" activity. It is a simplification of a complex history, but as biology emerged some practitioners of this new science took an interest in studies focused on a strongly theory-based approach to understanding life in the sense of "What is life?" or "How did life emerge?" Others took a more pragmatic, engineering approach and asked "How can life be manipulated and the results applied?" Throughout the 20th century these two visions of the science wove together and came apart. By the middle of the 20th century four conceptual and theoretical frameworks centered on cell biology, genetics, ecology, and evolutionary biology emerged to define the discipline of biology alongside practical advances in areas such as medicine, public health, and agriculture.

Late 20th and early 21st century discoveries in biology are driving advances within the life sciences and at their interface with many other areas of scholarship. Biology research and education today differ from how they were done 10 or even 5 years ago. Today's frontiers are often at disciplinary edges filling the white spaces between our traditional disciplines at the intersection of biology and computer and information sciences, engineering, geosciences, mathematics, physical sciences, and social sciences. What gets called "biology" or "the life sciences" has broadened immensely in the last 25 years. These intellectual advances bring the challenge of training students to be open to new ideas and capable of thinking broadly, while developing the depth of knowledge we expect of our best thinkers. The challenge will be training students not to be limited by traditional disciplines if we are to inspire a new generation of scientists and educators whose imagination, skills, and creativity will result in the transformative research and education needed for understanding life on Earth and adapting to a changing world.

I will explore the thesis that early in the 21st century biology is a gateway science to learning to think about complex systems, increasingly through interdisciplinary research—and education must follow. It is a science that helps us understand our place in the biosphere while informing how we can live in harmony with it. As a result, there is an increasingly broad interface between biology and society. Biology's rapid evolution as an area of study is highlighting what gets included in "the life sciences" and the importance of approaches to learning that emphasize the process of discovery itself.

About the Author

James P. Collins received his B.S. from Manhattan College in 1969 and his Ph.D. from The University of Michigan in 1975. He then moved to Arizona State University where he is currently the Virginia M. Ullman Professor of Natural History and the Environment in the School of Life Sciences. From 1989 to 2002 he was Chairman of the Zoology, then Biology Department. At the National Science Foundation (NSF) Dr. Collins was Director of the Population Biology and Physiological Ecology program from 1985 to 1986. He joined NSF's senior management in 2005 serving as Assistant Director for Biological Sciences from 2005 to 2009. Dr. Collins's research is centered on the evolutionary ecology of emerging infectious diseases and the biology of extinction. He is a Fellow of the American Association for the Advancement of Science, a Fellow of the Association for Women in Science, and President of the American Institute of Biological Sciences (AIBS). Dr. Collins has served on the editorial board of *Ecology* and *Ecological Monographs* as well as *Evolution*. He is the author of over 100 peer reviewed papers and book chapters, co-editor of three special journal issues, and co-author with Dr. Martha Crump of *Extinction in Our Times. Global Amphibian Decline* (Oxford University Press, 2009).

Introduction

In the late 19th and early 20th centuries the discipline of biology coalesced from several areas of research and education including physiology, embryology, evolution, ecology, and morphology (Laubichler 2007). By the 1920s in America "generalized areas designated as physiology and morphology" gave way to the disciplinary boundaries of biology and zoology with subspecialties that included comparative anatomy and comparative physiology, ecology, genetics, botany, invertebrate and vertebrate zoology, embryology, and cytology (Benson 1991). By the middle of the 20th century conceptual and theoretical frameworks centered in cell biology, genetics, ecology, and evolutionary biology constituted the core of the biological sciences.

In her analysis of the emergence of biology in America, Maienschein (1991: 3) argued that "historians have widely agreed that biology in 1910 looked very different from biology in 1880: the sorts of papers produced, the organisms used, the questions asked and the problems attacked, the methods and approaches adopted—all changed in at least some important ways." These changes often emerged as investigators studying living systems drew upon multiple areas of study. For example, in the late 19th and early 20th centuries researchers studying the biology of cells did so by taking "the cell" as the interesting object of study: What are cells? How do cells work? How are cells regulated? And importantly, how do cells interact? The object of study—the cell—was central, and in an effort to understand its biology researchers borrowed methods, concepts, and theories from morphology, physics, chemistry, and biochemistry. Scientific advances were complemented by, and in some cases driven by, the technology and mathematics needed for describing and analyzing living systems, often shifting the center and margins of biological research as a result.

If we fast forward one hundred years, there is a parallel set of developments surrounding what is now the discipline of biology. Many aspects of research in biology today differ greatly from how they were done 5, 10, or especially 20 years ago. Biology in 2011 differs in important ways from biology in 1990: the kinds of papers written as well as how they are produced and published, questions asked, and problems seen as important. Other disciplines engaged by biologists and methods used, especially analytical and computational methods, have changed significantly in the last 20 years. Today's leading research questions often lack a single traditional disciplinary home. In a fashion analogous to choosing the cell as an object of study, today's researchers may choose a topic to study, for example, synthesizing life, biofuels, or sustainability of ecosystems, and advances depend on drawing from multiple areas of scholarship.

In this essay I address two questions related to how these evolving changes in the content and practice of biology should influence education today.

First, as biology has changed, how has its role in science education changed? Early in the 21st century biology is ideally suited to serve as a gateway science for learning to think about complex systems. Interdisciplinary approaches to research and education offer ways to understand and teach this complexity. We are also witnessing an explosion of biological knowledge that is broadening what gets included in the discipline of biology. The two forces together—biology as a gateway to complex systems coupled to a broadening of what counts as biology—highlight the importance of methods of learning that emphasize the practices of scientific inquiry, quantitative and computational reasoning, and critical thinking as opposed to memorizing content as primary learning outcomes of education in the biological sciences. The content of especially introductory courses must reflect how biological research is actually done by scientists, and this includes using quantitative methods and interdisciplinary instruction. It is critical to ensure that the way students are introduced to biology is not driven only by memorizing facts, but is also focused on understanding the complexity of living systems and the changing nature of biology as a science.

Second, is the old model of biology as the "introduction to science" relevant? Biology remains inherently interesting to many students who are drawn to the subject through issues such as human health and physiology, the environment, natural history, and biotechnology. The curiosity that students bring to biology lends itself to engaging them in learning to think about the practice and content of science, how disciplines change, and even what gets to count as a discipline at a time when the biological sciences are evolving in so many lively and exciting ways. Biology is also a science that helps us to understand our place in the biosphere and our responsibility as stewards of planet Earth for generations yet to come. As a result, there is an increasingly broad interface between biology and society as the value we place on science changes depending upon the context of the problem. We need more research to understand how students learn about biology and how information acquired in courses transfers to biological areas that students will encounter throughout their lives.

As Biology has Changed, How Has Its Role in Science Education Changed?

In an echo of changes a century ago, biology in the last 20 years has broadened immensely by intersecting with other research areas including engineering, physics, chemistry, and biochemistry. There are also broad contacts with the geosciences and mathematics, joined by many new alliances with computer and information sciences as well as the social sciences. The following example illustrates these trends.

Synthetic biology is not new as efforts to synthesize life date to early in the 20th century (Morange 2010). In practice, however, contemporary synthetic biology emerges from a confluence of disciplines as an "interdisciplinary" or even a "transdisciplinary" activity (Collins 2002). Designing, fabricating, and testing new gene sequences, chromosomes, and even cells can require computational modeling, synthetic chemistry, material science, physics, genomics, engineering, evolution, plus molecular biology. Attention to the ethical, legal, and social implications of the research is also an essential feature of the work resting at the interface of biology and society.

Scientists working in synthetic biology, and the related area of systems biology, "share the conviction that organisms are made of partially independent functional modules that are organized in networks" (Morange 2009:1). He goes on to distinguish the areas by noting that "systems biology aims to describe this modular organization, and synthetic biology is geared towards more practical developments" (Morange 2009:1). A National Research Council report (2009:61) described systems biology more broadly as a research area that "seeks a deep quantitative understanding of complex biological processes through dynamic interaction of components that may include multiple molecular, cellular, organismal, population, community, and ecosystem functions."

Current research in synthetic biology and systems biology illustrates how the biological sciences keep changing and begs the question: How should biology education accommodate such multifaceted research areas? Educators will need to appreciate that problems in these areas are complicated, may generate large amounts of data, and solutions increasingly involve computational and quantitative methods. Biologists have tackled complicated problems, generated data, and relied on computational and quantitative methods since the late 1800s. Recently, however, we have seen an interest in biological problems as not just complicated, but complex. There is an increase by orders of magnitude in the data available along with the scope of computational and quantitative methods. These elements—complexity, data intensive problems, modern computational and quantitative methods—must be reflected in biology curricula.

First, consider complexity. Biological systems are often complicated with many parts working together. These same systems usually turn out to be complex because the components themselves are complicated. Imagine a diversity of cells with intricate parts forming a population of organisms that is one of many species in an ecosystem. It is this complexity along with their innate historical contingencies that makes biological systems interesting but difficult to study and often resistant to simple generalizations or predictions. Many of today's challenges, such as developing renewable energy systems and sustainable ecosystems, are difficult to solve because these systems are so complex. Biology affords students a gateway to confronting such problems and beginning to imagine solutions. The challenges are multifaceted and will not be solved by drawing on one or perhaps a few disciplines. Thinking about these problems stimulates students to move beyond the limits of a single area of study to acquire information from diverse disciplines as needed.

Second, by the 2000s biologists began experiencing a challenge called the data deluge or information overload (Nature 2009) that was already familiar to astronomers and particle physicists. Gathering at least some kinds of biological data was becoming a quick and easy task: terabytes of genetic sequence data gave rise to genomics, 40 years of research in bioinformatics leveraged the availability of supercomputers and computer networks (Hagen 2000), and diverse ever more efficient sensors gathered environmental information all day, every day of the year. These and other areas of biology are now data intensive sciences (Hey et al. 2009), highlighting a need for biology education to incorporate more computational (Pevzner & Shamir 2009) and mathematical (Robeva & Laubenbacher 2009) skills into curricula.

Finally, added to this mix is the fact that over the last two decades solving complex problems and using data intensive methods became embedded in a larger movement toward "computational thinking"—the use of computers as computational devices, but also intellectual amplifiers (Wing 2006).

Taken together these three late 20th and early 21st century conceptual and methodological advances should cause us to think about how and what students are learning. These changes also raise the question: At what point should one or more courses centered on a current interdisciplinary topic be offered? It is not simple to decide when a course or courses in synthetic biology, for example, should replace courses in cell biology, genetics, etc. But it is reasonable to ask what problems and questions we are trying to solve and then decide if a course is needed to teach those issues. In the decades surrounding the turn of the 20th century questions related to how cells work gave rise to cell biology textbooks and courses (Maienschein 1991). If a century later the science is centered on questions that do not fit readily into traditional biological subdisciplines such as cell biology or genetics, then the curriculum should be revised with courses that include the new ideas. Restricting newer areas to a prolonged status as add-ons to existing disciplines tends to limit their potential impact on scholarship and separate the science from related ethical, legal, and social issues. For example, topics in an area such as synthetic biology could include the use of cloning, questions related to when life begins, and the origin and use of stem cells. If they find their way at all into a curriculum, these topics are often covered separately in a course on bioethics rather than integrated in productive ways as students learn about the science itself. It is important for students to see and appreciate issues at the interface of biology and society as integral features of the basic science.

As was true in the late 19th and early 20th centuries, biologists today continue to study complex topics from cells to ecosystems, often drawing upon other disciplines. Research biologists are also experiencing a major increase in the capacity to collect and store data, calling for new methods of analysis for solving problems. An ever widening circle of interdisciplinary studies is expanding our vision of what counts as the biological sciences while adding new dimensions to the role that biology should play in science education, especially as a gateway science for learning to think about complex systems, data intensive science, and computational and quantitative thinking.

Is the Old Model of Biology as the "Introduction to Science" Relevant?

For many students a biology course is their first formal exposure to "science" and what it means to "think as a scientist." Thinking about what science is and how it is done is a starting point for challenging standard textbook representations of scientific practice. The practice of science regularly changes with new modes of research and new ways of thinking about how science can and should be done. In the biological sciences in America the pace of this change accelerated from the 1920s to 1950 (Rainger 1991), again after the launch of Sputnik in 1957, and has increased even more in the last 20 years driven in part by significant increases in the research budgets of the U.S. National Institutes of Health and the U.S. National Science Foundation. One outcome of the heightened pace of change and accompanying discoveries is the fact that thinking as a biologist in 2011 means mastering ever more sophisticated quantitative and computational skills. How should these changes, taken together with the fact that researchers in biology are often quick to embrace concepts, theories, and methods from other disciplines, influence biology's contemporary role as an introduction to science? In short, the content in biology courses must be more aligned with how biological research is actually done, and from this, new methods of instruction should follow that are based on how biological phenomena are explored and understood.

At the heart of innovation is the process of discovery, which begins when one or a few individuals develop and test an original idea typically using deductive or inductive reasoning. Innovation, therefore, emerges from a process that links one, or a few, to many individuals. As networks of computers unite investigators in solving problems this process increasingly incorporates larger and larger groups that may or may not be in one place. At its best, this social-computational environment should facilitate what we might call open source innovation, in which advances have a sociotechnical component (Collins 2010).

Students are also learning in new ways. Twitter, Facebook, texting, and e-mail provide young people, who are often early adopters of new information technology, with an understanding of a social network driven way of learning. Early in the 21st century, educators stand astride rapidly changing sets of practices associated with both the formal process of scientific inquiry as well as informal learning in social networks. Here is an illustration of how these two sets of practices and their cultures can be integrated.

Predicting the structure of a protein is a biologically important, but computationally difficult problem. Researchers in this area reasoned that they might make faster progress by creating and using an online game called "Foldit." They engaged a group called the "Foldit players," some with little or no knowledge of molecular biology, in solving protein folding problems and it worked (Cooper et al. 2010). The authors described their approach as one that integrated human visual problem-solving and strategy development capabilities with computational algorithms via an interactive multiplayer game. They further argued that having the Foldit players solve a problem as challenging as predicting protein structure demonstrated "the considerable potential of a hybrid human–computer optimization framework in the form of a massively multiplayer game....Our results indicate that scientific advancement is possible if even a small fraction of the energy that goes into playing computer games can be channeled into scientific discovery."

The protein folding result, and other cases of using networks of contributors to solve scientific problems, exemplifies "distributed thinking" (Hand 2010). In a remark indicative of innovation driven by a sociotechnical component, Hand (2010) went on to quote one observer as saying "We're at the dawn of a new era, in which computation between humans and machines is being mixed." In addition to using games to solve scientific problems, they are also envisioned as a way to learn about how science is done (Krotoski 2010). In particular, it is argued that games hold the potential "to help students develop logic skills, design effective experiments, and discuss scientific reasoning in the classroom or lab" (Strom & Barolo 2011:1).

We can extend these ideas further by returning to the example of synthetic biology. A prediction market is an exchange that tries to forecast events based on the virtual money wagered on a particular outcome. Moving beyond corporate applications, there is increasing interest in tapping into the knowledge of larger "communities of practice" that might be found in the sciences, arts, or other professional fields. David Rajeski and colleagues at the Woodrow Wilson International Center for Scholars used synthetic biology as a case study to explore the possibility that prediction markets might be a way of employing social networks to identify the most productive research questions to ask and how they might be answered (http://www.synbioproject.org/about/). Some possible questions are (courtesy of D. Rajeski): How many genes/proteins will be included in the first self-replicating synthetic organism? What kind of structure will the first self-replicating synthetic organism feature? Will the first self-replicating synthetic organism be achieved using a top-down, bottom-up, or hybrid approach? When might the above happen?

It is important to emphasize that networks and collaboration have historically been part of the process of inquiry in the life sciences (for example, Maienschein 1991), so networking per se is not the novelty that emerges late in the 20^{th} and early 21^{st} centuries. But information technology driven social networking combined with computational thinking are together changing the breadth and depth of what it means to have a network of people collaborating and thinking about a problem—from units or tens of individuals to hundreds of people who can now be drawn quickly into the process of problem solving. These practices are at the creative edge of how research is being done, but they also afford ways to teach students to convert their informal understanding of how to learn using social networking into formal scientific reasoning. The methods are ways to engage students using media with which they are familiar under conditions that give them an active stake in learning.

Recently, a working group at the Wissenschaftskolleg zu Berlin/Institute for Advanced Study suggested 11 principles of curricular reform that are useful guidelines for framing a conversation about revising undergraduate curricula (Elkana et al. 2010). The group proposed the guidelines out of a conviction that in today's colleges and universities "Curricula are mostly separated from research, and subjects are taught in disciplinary isolation. Knowledge is conflated with information and is too often presented as static rather than dynamic." Here are adaptations of 5 of the 11 principles that should be part of designing a biology course as an introduction to science (see www.curriculumreform.org for all 11 principles):

- Teach introductory courses with parallel seminars for interdisciplinary problems that create an awareness of the great problems humanity faces;
- Highlight challenges, open questions, and uncertainties; the world is complex and messy;
- Treat knowledge historically—do not treat knowledge as static within a fixed canon;
- Emphasize evolutionary thinking;
- Think through the role of modern communication and information technologies for education.

Integrating changes in how science is practiced and how students learn is an opportunity to revise the pedagogical model from one where there is "the sage on the stage" filling the minds of students with facts into a process of inquiry that is an interactive, vibrant experience. Students and instructor engaging in a mutually creative process of learning is something to which both can and should aspire. To understand, study, and solve such complex challenges will require that students have several skills for asking and answering modern science questions; in particular, thinking beyond disciplinary borders in a quest for answers, adapting quickly to new methods, networking globally, understanding the strengths and weaknesses of computational thinking, and embracing disruptive ways of learning. Biology remains an ideal introduction to science because it offers these opportunities across a range of subjects that include examples such as origin and synthesis of life, early events in photosynthesis and biofuels, or biodiversity and ecosystem services.

Pulling the Pieces Together

Today's frontiers in biology often fill the white spaces at intersections with computer and information sciences, engineering, geosciences, humanities, mathematics, physical sciences, and social sciences. What gets called "the biological sciences" has broadened in the last 20 years, highlighting biology's important role in science education. Biology is a gateway science for learning about complex systems that embraces problem solving across multiple disciplines powered by quantitative and computational methods. Biology is also a conceptually and theoretically rich science (National Research Council 2008). But is this the biology that we are teaching now? In most cases probably not; rather, biology is too often taught and learned as the dense science of facts and memorization. This is changing in some places (Wood 2009), but we have to increase the pace of change and there are hopes that this will happen (Labov et al. 2010, Brewer & Smith 2011).

Scientists and engineers are taking inspiration from living systems to produce new knowledge, develop practical applications, reshape our scientific concepts, and change the definition of what is possible. The intellectual advances of the last 20 years together with changes in the practices of the biological sciences bring the task of training students to be open to new ideas and capable of thinking broadly, while developing the depth of knowledge we expect of our best problem solvers. The challenge going forward is training students to look beyond traditional disciplines if we are to inspire a new generation of scientists and educators whose imagination, skills, and creativity will result in the transformative research and education needed for understanding life on Earth and adapting to a changing world (Collins 2011). Such a fluid intellectual environment adds great value to approaches to learning that focus on basic theories, concepts, and the process of inquiry itself. Problem solving within social networks—an increasingly important feature of research and learning—is a way to use distributed thinking to solve problems and engage students. The centrality of the life sciences for solving complex, contemporary problems in public health, agriculture, energy, and the environment (National Research Council 2009), while embracing modern scientific practices, makes the case that more than ever this vision of 21st century biology is an excellent "introduction to science."

Biology's growth and diversification as an area of study has also increased the range of issues at the interface of biology and society. Advances in the sciences must be placed in a larger societal context by drawing on the law, humanities, arts, and ethics (see for example, Minteer & Collins 2008). Lessons can still to be learned from Aldous Huxley's *Brave New World* and George Orwell's *1984*. In his vision of 21st century biology Carl Woese (2004) offers a particularly sobering view: "A society that permits biology to become an engineering discipline, that allows that science to slip into the role of changing the living world without trying to understand it, is a danger to itself. Modern society knows that it desperately needs to learn how to live in harmony with the biosphere. Today more than ever we are in need of a science of biology that helps us to do this, shows the way. An engineering biology might still show us how to get there; it just doesn't know where there is."

In today's world there is an increasing disaggregation of facts and ideas. Although many futurists foresee a bright road ahead in information technology, we are only at the beginning of our capacity to link related but disjointed information into knowledge. Our students are coming to us from this world, and educators will have to teach aggregation, which is critical if an educated person is to have a context for action based on understanding how facts and ideas relate to one another. "We are drowning in information while starving for wisdom," wrote E.O. Wilson. "The world henceforth will be run by synthesizers, people able to put together the right information at the right time, think critically about it, and make important choices wisely" (Wilson 1998:v).

Students need a context for understanding, especially at a time when so much of the society around us seems to be moving with a quicker metabolism. The context is provided by other areas of scholarship such as history, philosophy, and literature accompanied by a deep appreciation of the role concepts and theories play in asking and answering questions. Biology should not be studied alone, but as part of a diverse fabric of other areas of learning. In this sense then, education in the sciences should adhere to the goals of higher education in the U.S. and draw upon what we know about student learning in the context of a liberal education that stresses a breadth of understanding.

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CHAPTER 4
What Biology Education Should Look Like at Colleges and Universities

Felicia Keesing

Abstract

Biology professors at colleges and universities should have two major goals in their classrooms – to prepare future biologists for the challenges of 21st century biology, and to foster lifelong scientific literacy in students who will not become scientists. Over the years, much more thought has been applied to building an effective curriculum for biology majors than for non-majors. It is clear that future scientists will need to learn concepts and skills from biology, but also from chemistry, physics, mathematics and computer science. Students will need an efficient curriculum that provides time to practice and learn these skills. There are many lists of core concepts and competencies in biology with similarly basic content that are now widely agreed upon by large groups of biologists. This presents an encouraging opportunity for colleges and universities to build both an effective and efficient biology curriculum for future scientists. However, students who are non-science majors may only take one or two science courses during their undergraduate studies. How can departments restructure the curriculum to teach basic science literacy and what is the most effective way to help this student build these skills? While the goals of teaching science to non-science majors and science majors appear to be quite distinct, current evidence suggests that the methods for achieving them are strikingly similar. This paper outlines these methods and describes an important frontier for achieving their widespread adoption.

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Introduction

Biology professors at colleges and universities should have two major goals in their classrooms – to prepare future biologists for the challenges of 21st century biology, and to foster lifelong scientific literacy in students who will not become scientists. Though these goals appear to be quite distinct, current evidence suggests that the methods for achieving them are strikingly similar. In this paper, I will outline these methods, and I will describe an important frontier for achieving their widespread adoption.

Focus on Core Concepts

The biology challenges of this century will require scientists who are broadly trained in multiple fields of science and who have sophisticated quantitative and computational skills (NRC 2009). Those future scientists must learn concepts and skills from biology, of course, but also from chemistry, physics, mathematics, and computer science. Because students will need time to learn and practice concepts from these other fields, they will need an efficient biology curriculum. This efficiency can best be achieved by distilling the biology they need to learn into its most essential concepts. Many lists of core concepts in biology now exist. For example, the Vision and Change report (AAAS 2010) lists five key concepts (Table 1), while the new Advanced Placement exam includes four (College Board 2011). Though the details of each list differ, the basic content is the same. The fact that large groups of biologists from lots of different institutions can agree on core principles is encouraging. It suggests that there is reason to expect that individual biology departments can choose one of these lists and build their curriculum around it. Another inference from these relatively similar lists is that we do not need to achieve complete uniformity in our framing of the core concepts across the discipline because the lists will be fairly similar, even if they differ in their precise formulation.

Table 1. Core concepts and competencies as defined by the *Vision and Change* report on undergraduate biology education (AAAS 2011).

CORE CONCEPTS
The diversity of life evolved over time by processes of mutation, selection, and genetic change
Basic units of structure define the function of all living things.
The growth and behavior of organisms are activated through the expression of genetic information in context.
Biological systems grow and change by processes based upon chemical transformation pathways and are governed by the laws of thermodynamics.
Living systems are interconnected and interacting.
CORE COMPETENCIES
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.

But what do core concepts have to do with educating *non*-scientists? At best, most non-scientists take a few science courses during their undergraduate years, and many take just one. For the majority, that is the end of their formal schooling in science. If the science literacy they gain from these courses is to last a lifetime, the courses should emphasize those aspects of science literacy that will best sustain them over the long term. One approach to doing this would be to focus on core concepts – the foundations of biology. Teaching five or six core ideas from biology in a single course might be possible, whereas surveying hundreds of important developments in the field is not.

Unfortunately, there has been much less progress identifying the core concepts that non-scientists should learn in college, and how those concepts from biology integrate with core scientific concepts from other disciplines. The new National Science Education Standards, developed through the National Academy of Sciences, provide an interesting model from K-12 education. In the NSES report, there are five content standards that transcend individual scientific disciplines (NSES 2011). The unifying concepts and processes are:

- Systems, order, and organization.
- Evidence, models, and explanation.
- Change, constancy, and measurement.
- Evolution and equilibrium.
- Form and function.

The list was developed for use in K-12 education, of course, but it provides a compelling model that could be adapted for colleges and universities. These themes – or others like them – could be taught in a course focused on virtually any particular topic within biology, but which could, in principle, provide students with an over-arching understanding of scientific concepts.

A potential advantage of teaching non-scientists a set of core concepts is that it could give them time to work on "transfer" – the application of ideas learned in one domain to a new domain. For example, if students in a course learned in detail about DNA as a way to encode genetic information, they might need to transfer this concept on their own to understanding the biology of, for example, genetic diseases. Transfer is critical for educating scientifically literate citizens because they will be required to transfer the concepts they learn in class to new domains – domains they did not learn about in their courses or entirely new domains created by scientific advances.

One key aspect of transfer that emerges from the education literature is that transfer itself is a skill and that it needs to be practiced (NSF 2002). If students need to acquire this skill – a fundamental one for establishing scientific literacy – they need to have time during their classes to practice it. This is yet another reason to distill the concepts they need to learn.

Teach Core Competencies

Most biology faculty would agree that biology majors should acquire a suite of competencies during their undergraduate years, in addition to a suite of concepts. Most faculty would also agree on some number of these competencies, including, perhaps, the ability to use specific laboratory and field skills, to read the primary literature and design simple experiments, and to create graphs and analyze data. Of course, most faculty would also agree that an essential competency is the ability to apply core concepts in new contexts.

An example of a list of competencies, and their associated learning goals, can be found in the 2009 report on *Scientific Foundations for Future Physicians*, prepared by the Howard Hughes Medical Institute and the American Association of Medical Colleges (AAMC-HHMI 2009). While the list of competencies in the report was compiled with future physicians in mind, the list includes general competencies that would be applicable to any biology major (e.g. "*Apply quantitative reasoning and appropriate mathematics to describe or explain phenomena in the natural world"; "Demonstrate understanding of the process of scientific inquiry, and explain how scientific knowledge is discovered and validated.")*. The *Vision and Change* report (AAAS 2011) also included a list of core competencies with many similarities to the AAMC-HHMI list (Table 1).

An advantage of defining the competencies we want students to have is that then we can determine whether they have acquired them. This kind of assessment is critical for evaluating the success of our programs and the preparation of our students. However, conducting high-quality assessment is not simple and faculty are typically not trained to do it. Partnerships with social scientists can be helpful, and many teaching workshops for faculty now include instruction in basic assessment.

If we assume that we have a basic set of competencies that future scientists should acquire, which of these are competencies that non-majors should also have, especially if they only take one or two courses? Given the limits to the time that non-majors spend in science courses, one promising approach is to focus attention on the nature of scientific studies themselves. That is the purpose of a new general education course, required of all students, at Bard College in upstate New York. Students in this course learn the strengths and weaknesses of three main approaches to answering scientific questions – experiments, comparisons, and models. They pursue this understanding within a particular domain of science, and then practice transferring this competency to new domains. The goal is to have them prepared to interpret the basis for scientific claims in many domains after they graduate.

Make Learning Student-Centered

Most college science faculty were taught in the traditional manner. We sat in lectures and learned the material as the instructor presented it, supplemented by readings from the book. Because we have never been presented with an alternative model of how to teach, nor have we been *taught* how to teach, we replicate the lecture-based approach in our classes. However, one clear result of recent research is that we can improve the quality of the education future biologists and future citizens receive by teaching them in new ways using modern pedagogical practices.

Based on hundreds of studies, it is now clear that engaging students as active participants in acquiring knowledge is more effective than having them be passive recipients, as they are in most lectures. Indeed, a recent meta-analysis of over 800 studies showed that a variety of student-centered learning activities – including collaborative activities, conceptually-oriented tasks, and inquiry-based projects – all had a positive effect on learning outcomes (Ruiz-Primo et al. 2011). Another meta-analysis reported the effects of problem-based learning on student knowledge and skills (Dochy et al. 2003). In problem-based learning, students are presented with a problem that they do not have enough information to solve. With the guidance of an instructor, they educate themselves and each other about new concepts in order to solve the problem. Dochy et al. (2003) analyzed 43 studies of problem-based learning. Students who participated in problem-based learning activities gained slightly less knowledge but retained it longer than students in more traditional approaches. Effects of problem-based learning on student skills were consistently positive (Dochy et al. 2003).

Given the clarity of these results, and the fact that the purpose of a college education is for students to acquire knowledge and the ability to apply it, it is unconscionable for institutions not to encourage and motivate the adoption of student-centered learning practices. The barriers to widespread implementation are not as high as they once were, but there are still significant challenges. Efforts to overcome these barriers are addressed in other papers in this volume (Wood).

For the Future: Think Like an Epidemiologist

Meta-analyses of student-centered learning highlight the value of quality evidence. The publication of such analyses in *Science* magazine -- as in the meta-study of student-centered learning research described above (Ruiz-Primo et al. 2011) -- shows that strong evidence about education can gather the attention of a broad audience and can potentially have a huge effect on educational practices. However, according to the authors, only 3% of the studies examined in the *Science* study were sufficiently rigorous to be included in their statistical analyses; 97% lacked the necessary data to be evaluated (Ruiz-Primo et al. 2011). Even within the studies they were able to include, there was wide variation in the quality of the evidence. For example, the investigators compared results from studies in which students had been randomly assigned to experimental and treatment groups to studies that were "pseudo-experiments" in which students assorted themselves into control and experimental treatments. When students assigned themselves to treatment groups, the effect sizes were twice as large, suggesting that pseudo-experiments are a poor choice for generating widely applicable evidence because they inflate the magnitude of the actual effect. If we are going to emphasize the quality of the evidence for adopting modern educational practices, we need to be sure that the evidence can withstand the scrutiny.

Collecting high-quality evidence about the effectiveness of educational practices is challenging. Because educational interventions are often implemented in individual classes, three problems perennially arise. One challenge is having a sufficiently large sample of students with which to detect an effect; another is developing a rigorous experimental design, including an appropriate control group. A third challenge is an ethical one. In the interests of rigor, most educational studies today are expected to include a control group. But is it ethical to create a control group for a study if we already have evidence that the intervention is better than the control?

I suggest that we could do a better job if we thought more like epidemiologists. Epidemiologists, of course, deal with issues of sample size and ethics all the time. And they constantly confront the difficulty of finding an appropriate control group. How, for example, can you ethically determine the effects of exposure to a rare toxin on a person's risk of developing cancer? Or characterize risk factors for a rare disease? Experiments (at least on humans) are out of the question. Because they constantly answer questions like these, epidemiologists have developed a suite of approaches to confront these challenges rigorously. We should learn from them.

Epidemiologists value experiments highly, just as all scientists do. Experiments are the best way to isolate cause and effect. When the predicted effect is small (<20%), they are often the only effective way to detect a pattern

(Aschengrau & Seage 2008). In some cases, however, experiments are not ethical. For example, human-based experiments are never used to examine the causes of human diseases because that would require experimentally causing the disease, or at least trying to.

If the predicted effect is large (>20%), or if an experiment would be unethical or infeasible, epidemiologists use sophisticated comparative methods. One of the most common comparative methods is a cohort study. In a cohort study, the characteristics of groups (cohorts) of individuals are compared through time. Typically, one cohort has been "exposed" to something -- such as a toxin – by circumstance and the other has not. The frequency with which the cohorts develop conditions over time is then compared. Cohort studies require large numbers of participants, but they are a powerful way to detect patterns.

A second comparative method used by epidemiologists is the case-control study. In this approach, individuals with a condition (cases) are compared to individuals without the condition (controls). "Cases" acquire their condition without experimental intervention. Outcomes can be compared over time between the groups, and causes can be characterized retrospectively.

Of course, cohort and case-control studies are used in educational research already. I am arguing that they are not used widely enough. They present a valuable alternative to small-scale classroom-level manipulations.

We know enough about student-centered learning to predict that most interventions that incorporate this type of learning will be more effective than more conventional alternatives. Do we know enough now so that we do not need to experimentally test every implementation? I would argue that we do. Instead, we should focus our efforts on getting effective teaching practices *implemented* (rather than experimentally evaluated).

Of course, there is still much that we do not know. We should identify a small set of critical questions about undergraduate biology education and address them the way epidemiologists do – with large-scale comparative studies. One recent study of student involvement in summer research illustrates the value of this kind of approach. Over 2000 students from more than 60 institutions completed on-line questionnaires in which they characterized their experiences in summer research programs (Lopatto 2007). Asked about the effect of the experience, more than 75% of students reported that the experience had made them more active learners, more independent thinkers, and more self-motivated students. Students from under-represented minorities reported significantly greater learning gains than other students in, for example, their ability to integrate theory and practice, their understanding of science, and their ability to read primary literature. Imagine the potential of other studies of this magnitude.

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CHAPTER 5
The Challenge of Changing the Way We Teach

William B. Wood

Abstract

Current policymakers agree that our national interests require training more students in the fields of science, technology, engineering, and mathematics (STEM), as well as raising the scientific literacy of all college graduates. Recent educational research has identified several promising practices for undergraduate instruction that can help accomplish these goals by substantially increasing student learning in STEM courses and retaining students in STEM majors. However, adoption of these practices requires moving from traditional instructor-centered teaching to more student-centered modes of instruction. Resistance to such change has proven particularly strong at large research universities, which produce the majority of our STEM graduates. Barriers to change range from student and faculty attitudes toward teaching and learning, to structural features of the current system. This paper summarizes the most important research-based promising instructional practices, discusses the major barriers, and describes two programs that have demonstrated some success in changing the culture of teaching and learning in university science departments.

About the Author

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Introduction: Why We Must Change

Concerns about maintaining the nation's competitiveness and raising the science literacy of all Americans have led to calls from many quarters for improvements in science education (e.g. NAS, 2004, 2010). We need to improve the science teaching of undergraduates, as well as K-12 students. At our research universities, on which we depend for the majority of our science degree graduates, the large introductory science courses overemphasize the accumulation of factual knowledge and rote problem-solving strategies at the expense of meaningful conceptual understanding and critical thinking. Partly as a result of this emphasis, many talented students drop out of science majors, disillusioned by the lack of intellectual challenge and apparent relevance to their lives (Seymour & Hewitt, 1997; McWilliam, Poronnik, & Taylor, 2008). Non-majors who take these courses, which may be their only experience of science at the college level, quickly forget the factual information they are asked to memorize and fail to gain appreciation for the nature, the power, and the beauty of science, as a way of understanding their world and aiding their future decision making in our technically complex society.

How We Must Change

A large part of the problem is the way these courses have traditionally been taught. From a large body of research in education and the cognitive sciences over the past few decades, we have gained valuable general understanding of how people learn and the conditions that promote meaningful learning (reviewed in NRC, 1999; Zull, 2002). These understandings which support a *constructivist* view of learning (Dewey, 1916; Ausubel, 1963, 2000) can be summarized as follows.

- We learn by building on our previous knowledge structures. Effective instruction must begin with pre-existing knowledge, which may include misconceptions.
- We are all different, in inherent characteristics as well as past social and educational experience. Effective instruction must be inclusive of all individuals in the learner community.
- Frequent feedback helps us learn, by continually testing our understanding through non-judgmental questioning as we acquire new knowledge. Educators call this feedback *formative assessment*, in contrast to the *summative assessment* used to judge learning performance in order to assign a grade at the end of a course or determine our readiness to enter a post-graduate program.
- To learn effectively, we must be aware of our own learning process, to know what activities help us to learn and how well we understand new knowledge. Educators call this awareness *metacognition*.
- Participation in a community of learners enhances learning, through diversity of prior experience and the social interactions among members of a group with shared values in the learning process.
- The neuronal changes in our brains that occur during learning are triggered by active intellectual and emotional engagement with the concepts we are trying to learn, much more than by passive listening to an explanation of these concepts. Maintenance of such neuronal changes requires repeated practice with the cognitive processes we are trying to develop.

Discipline-based educational research (DBER) into learning of the various science disciplines at the undergraduate level has provided strong additional evidence, grounded in the general principles above, that a small set of *promising practices* for undergraduate science courses can substantially enhance student learning when compared to traditional instruction (Froyd, 2008; Wood, 2009; Dirks, 2011). Most large introductory courses, for example in the life sciences, are taught in the following traditional manner. The students receive a syllabus at the start of the course, listing the topics that each class or unit will cover. In class, the instructor lectures, often with visual aids from a slide presentation, during most or all of the class period. The students listen and take notes on the subject matter for future study. They do not communicate with each other or with the instructor except perhaps in response to a question, and then generally only a few students take part. It is difficult for the instructor to know how many of the students are engaged with the material or how well they are understanding it. If, as in many introductory biology courses, there is no homework or other formative assessment, the instructor does not find out what students are learning until they are tested on the first exam. Exams are summative, designed to rank students for grading, and students are in competition with each other, encouraging individual rather than cooperative studying and learning.

Obviously, this course design violates most of the learning principles discussed above. In contrast, these principles are the basis for the promising instructional practices that are now overwhelmingly supported by the results of education research in general and DBER in particular. Courses that incorporate them, referred to here as "transformed" courses, have the following characteristics:

- In place of a syllabus, the instructor formulates a set of intended learning outcomes, specifying in some detail what students should be able to *do* after completing the course, and explicitly shares these outcomes with the students.
- Prior to each class, students do assigned reading, work through problems or other formative assessment activities, and post their answers on the course website, attempting to master on their own the basic information the class will deal with. By sampling the results of this homework, the instructor can see where students are having difficulty and tailor the upcoming class session to help them. This approach has been called Just-in-Time Teaching (JiTT) by the physicists who first popularized it (G. Novak, Gavrin, Christian, & Patterson, 1999).
- During class, the instructor transmits very little new information by lecturing. Instead, she guides the students through various learning exercises that involve answering questions or solving problems, such as responding to challenging multiple-choice questions using an audience response system ("clickers:" Wood, 2004; Wieman & al., 2008), analyzing a case-study problem (e.g. NSF, 2010), or concept-mapping a set of complex functional relationships (J. D. Novak, 2003). These exercises also, of course, provide formative assessment of student understanding.
- Students work on these exercises primarily in small groups. Although the instructor may award some course credit for participation, she does not grade the responses, in order to encourage free and open discussion. Feedback comes from student peers as well as from the instructor, who is continually aware of the students' level of understanding and where they may be having difficulties.
- Following the principle of *backward design* (Wiggins & McTighe, 2000), the instructor aligns all instruction and formative assessment with the initially formulated intended learning outcomes, and designs the summative assessments to determine how successfully students have attained these outcomes.
- Ideally, in addition to a final summative exam, the instructor administers a validated, reliable *concept inventory* (CI) to assess general conceptual understanding of the subject matter dealt with, once as a pre-test at the start of the course and again at the end (perhaps embedded in the final exam), in order to measure a learning gain for each student.[1] Use of the first such CI on Newtonian mechanics (Hestenes, Wells, & Swackhamer, 1992) helped to revolutionize physics instruction starting in the 1990's, and a variety of these assessments have since been developed and published for various areas of the life sciences (Smith, Wood, & Knight, 2008; Shi et al., 2010). Results from CIs and similar concept assessments show unequivocally that on average, students achieve substantially higher learning gains in transformed courses than in those taught traditionally (Hake, 1998; Knight & Wood, 2005; Deslauriers, Schelew, & Wieman, 2011). CIs are designed to measure achievement of specific intended learning outcomes. To the extent that these outcomes align with those of the course, the instructor can use student learning gains determined by a CI to assay the effectiveness of new instructional approaches from year to year as the course evolves (Wieman, 2007; Smith, et al., 2008).

Why is Widespread Course Transformation Not Occurring?

Despite the strong evidence for efficacy of the promising practices described above for enhancing student learning, most large introductory courses are still taught in the traditional manner. Lecturing is the usual mode of instruction, and summative exams provide the only feedback on student learning. What is preventing the shift to research-based teaching approaches?

Table 1. Seven barriers to changing the teaching of large courses in research universities

1. Lack of awareness that there is a better way
2. Lack of suitable classrooms
3. Coverage anxiety
4. Student resistance
5. Faculty resistance
6. The current faculty reward system and lack of reliable measures of teaching effectiveness
7. Time constraints on research-active faculty

[1] Generally expressed as a normalized gain, <g> = (post-test score – pretest score) / (100 – pre-test score) (Hake, 1998), to allow comparison of gains between students with different levels of incoming knowledge.

Clearly, there are substantial barriers to change (Dancy & Henderson, 2008). Table 1 lists seven of them in order of increasing difficulty to overcome, based on the research literature as well as the author's experience. Each of these barriers, and suggested strategies for surmounting them, are discussed briefly in the following paragraphs. The final sections of the paper describe two model programs that are successfully facilitating both change in the teaching culture of biology departments and the adoption of research-based, promising instructional practices.

1. *Lack of awareness that there is a better way*. A decade ago, few of the research-active faculty who taught large introductory courses at research universities were aware of the growing body of education research on how people learn and its implications for instructional practice. In the last few years, this situation has been changing, as the calls for improvements in science education have become more urgent, and mainstream publications read by scientists, such as *Science* and *Nature*, have begun publishing articles on educational issues. Assuming these trends continue, the awareness problem may slowly take care of itself.

2. *Lack of suitable classrooms*. The typical lecture auditorium, in which most large science courses are held, is designed to promote traditional instruction. The raised podium at the front of the hall invites the instructor to hold forth from that secure spot rather than moving among the students. Long rows of fixed seats, often with only one or two aisles at the sides, focus students' attention on the podium and make it difficult for groups of students to collaborate. Although a dynamic, imaginative instructor can teach a transformed course in such a setting, the architecture greatly hampers interactions between students as well as between the instructor and collaborating students. In contrast, the SCALE-UP physics classrooms introduced by Beichner at North Carolina State University (Beichner, 2008) are designed to discourage lecturing and encourage student interaction and group work (Figure 1). The classroom resembles a banquet hall, with groups of nine students seated in movable chairs around 7-foot-diameter round tables, each equipped with three computers, which subgroups of three students can use for group problem solving. The instructor, who can control the computers as appropriate from a central station, can easily move between the tables, interacting with different groups of students as the class progresses. Such classrooms have now been built at many institutions and are steadily becoming more widely accepted for instruction in all fields (http://scaleup.ncsu.edu).

3. *Coverage anxiety*. When contemplating the move toward transformed courses, in which there is obviously less class time for the instructor to transmit information than in a traditional lecture, instructors as well as students are often concerned about "covering" all the course material. Examined more closely, the notion of coverage is largely a myth, perpetrated by mutually reinforcing student and faculty misconceptions about teaching and learning. It is a "transmissionist" fallacy, in contrast to the constructivist model of education described above. Many students seem to believe that they cannot learn information not transmitted to them by an instructor, and that examining them on information they haven't been taught in class is somehow unfair. Many faculty seem to believe that students cannot or will not learn on their own anything the instructor hasn't explained to them, but that students *will* learn whatever is transmitted (covered) in class. This belief can lead faculty to conclude that the more they cover, the more students will learn – clearly an untenable proposition beyond a certain point! In fact, learning from books, articles, and online resources and critically evaluating the information encountered are skills that students urgently need to master in our society, and they are quite capable of doing so if given the incentive. The JiTT approach described among the promising practices above neatly solves the coverage problem, while at the same time helping students develop these valuable skills. Students learn much of the necessary vocabulary and factual content through reading and homework outside of classes, which can then be used primarily for problem solving and other collaborative activities that enhance understanding and retention.

4. *Student and faculty resistance to new approaches*. In a course built around JiTT and active learning in class, students must play a more active role than they may be accustomed to, and naturally at first, they resist. In their recent book *Academically Adrift*, Arum and Roksa (2011) describe an unwritten pact that seems to have developed between faculty and students in some institutions: faculty will not make rigorous demands on students and will keep average grade point averages (GPAs) up; students will pay their tuition and eventually receive their degrees with a minimum of effort. As the result of this arrangement, average GPAs during the past decade have been increasing, while average time spent studying outside of class has been decreasing. The process of course transformation changes the rules for students, who must now take responsibility for much of their own learning or suffer the consequences. They may complain that the new

demands are unreasonable, and that the instructor is no longer "teaching" them, but rather asking them to learn on their own. (What is she being paid for, anyway?!) Based on personal experience and a sparse literature on this topic (e.g. Silverthorn, 2006), instructors can help students cope with the new approaches in two ways. First, be explicit about the reasons for changes in course expectations and how these changes will benefit the students. At the start of the course, introduce students to the concept of learning at different levels of understanding (e.g. Bloom's Taxonomy, Figure 2), and point out (frequently) that the students' future academic and professional success will primarily require higher-level skills such as application of conceptual knowledge to new situations and creative problem solving, rather than the lower-level skills (factual recall, explanation) emphasized in most introductory biology courses (Zheng, 2008). Second, be understanding, sympathetic, and supportive. For students accustomed only to traditional instruction, the change is indeed not an easy one. However, as Silverthorn (2006) reports, when students' apprehensions are supportively accepted and dealt with, and they realize the satisfaction of mastering higher level skills that seem relevant to their future careers, they will generally accept the new demands and put forth the effort required to meet them.

5. *Faculty resistance*. Faculty also may object to the idea of course transformation, for several reasons. They may maintain that their teaching is fine as is, so there is no need to change. ("I'm an excellent lecturer. My course gets very good student evaluations. My best students do very well in their future careers.") These statements may be true, but they don't tell us whether students are achieving substantial learning gains in this instructor's course. In recent surveys (reported by Savkar & Lokare, 2010) a majority of scientists view science teaching at universities in general as mediocre or poor, yet rate their own teaching as above average in terms of their impact on students and how much students learn. It seems likely that many science faculty overestimate their effectiveness as instructors. Faculty may also point out that they and all their colleagues were educated primarily in traditionally taught courses as college and beginning graduate students, suggesting that traditional instruction must work well. This conclusion seems surprising, particularly among biologists, who should realize that their success is the result of a selection process, not an optimal instructional strategy for all students. How can universities help faculty adopt new instructional practices that are proven to be more effective than traditional lecture courses? Awareness of the research evidence is likely to be only marginally effective (Dancy & Henderson, 2008). The following sections discuss two of the more formidable barriers to faculty change and some possible ways to overcome them.

6. *The current faculty reward system and lack of reliable measures for teaching effectiveness*. In research universities, most research-active faculty view their primary mission to be maintaining the quality and quantity of their research. Teaching needs to be done, and may be viewed as important, but research prowess is generally the major consideration in departmental hiring, promotion, and salary decisions (Sakvar & Lokare, 2010). Extra efforts devoted to teaching, including the substantial work involved in transforming a traditionally taught course, are much less likely to be rewarded. Given the many demands on research-active faculty, work on teaching naturally takes a back seat to research efforts and required service activities. To promote widespread course transformation, the current reward system must change. This will be difficult for two reasons. First, even if there is a desire to reward effective teaching, there is currently no reliable way to measure it. Student evaluations and faculty peer review based on attending one or two of a colleague's classes give little indication of how much students are learning. Student learning gains, however, based on pre-/post-testing with a validated CI as described above, do provide this information. As these assessment instruments become more widely used in biology, as they have in physics, measurement of student learning gains has the potential to become a meaningful component of teaching evaluation. Second, the will to change the current reward system must be widely shared in the university community. Changing the system cannot be left to deans and provosts as a top-down administrative decision. Faculties themselves must move toward putting a higher value on effective instruction and help convince their institutions to reward it appropriately.

7. *Workload pressures on research-active faculty at research universities*. Even if higher rewards are offered for improving instruction, most research-active faculty members, who often run sizable research groups and must maintain one or more substantial grants to fund them, will simply not have the time to undertake the demanding work of transforming a traditional course. This problem may be less acute for beginning faculty, because creating a transformed course from scratch is not much more work than preparing thirty lectures for a traditional course. Nevertheless, two things can help all faculty move toward transformed approaches to instruction: first, a community of peer practice to offer motivation and support, and second,

assistance from appropriately compensated, pedagogically knowledgeable co-workers, who can help with the tasks of course transformation: namely, formulation of intended learning outcomes and development of assessments and class activities. The following sections describe two model programs that are successfully promoting changes in the approach to science instruction at research universities by providing these resources.

Figure 1. A SCALE-UP classroom (Beichner, 2008).

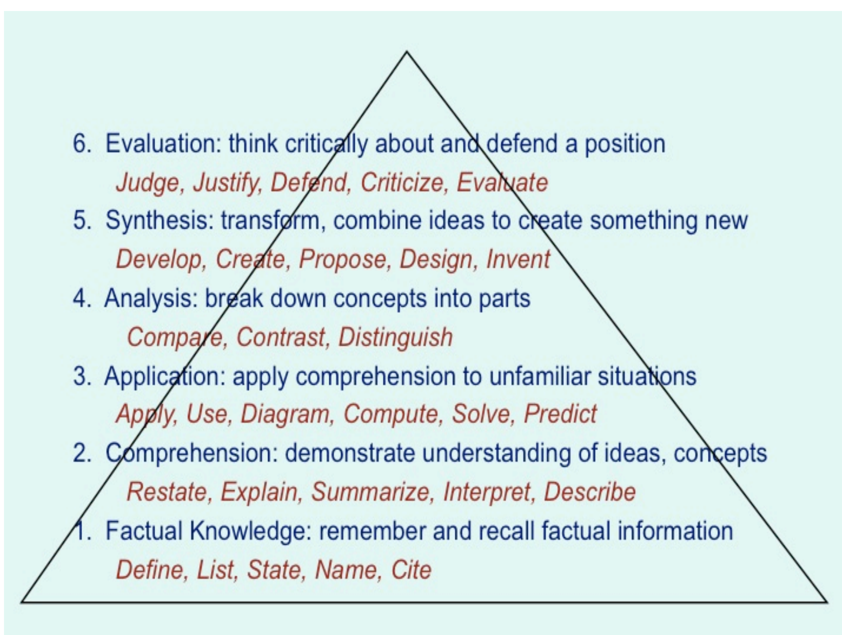


Figure 2. A representation of Bloom's Taxonomy of Educational Objectives with action verbs corresponding to the six levels of understanding (adapted from Wood, 2009).

Two model programs that are successfully promoting change

1. *The National Academies Summer Institute for Undergraduate Education in Biology*

A decade ago, the Bio2010 Report (NRC, 2003) documented the need for better preparation of future biological scientists in the face of biomedical research advances into new areas such as genomics and computational biology. One of its recommendations was to improve the teaching of large biology courses at research universities. It suggested creation of an intensive workshop on teaching and learning for university faculty, based on recent results of educational research and modeled after the intensive, research-oriented, short summer courses at the Cold Spring Harbor Laboratory and the Woods Hole Biological Laboratories. In this case, however, participants would eat, sleep, and breathe pedagogy for a week rather than biological science.

In 2002 the National Academies' Board on Life Sciences appointed a small NRC Committee, co-chaired by the author and Jim Gentile, with the charge of creating such a workshop. In 2003, we organized a pilot workshop on teaching and learning at the University of Wisconsin (UW), Madison, attended primarily by biologists already interested in teaching issues, to test the concept. Would an intensive week focused on pedagogy be rather dull, or could it be informative and inspirational like the short summer science courses? The outcome was clear: participants found the workshop rewarding and intellectually stimulating, and we decided to push ahead with the creation of a National Academies Summer Institute on Undergraduate Education in Biology (SI). A Policy Forum article in *Science* later that year (Wood & Gentile, 2003a) and a subsequent more detailed meeting report (Wood & Gentile, 2003b) described the rationale behind the SI and the results of the pilot workshop.

Three other individuals were instrumental in organizing the pilot workshop and subsequently launching the SI. We recruited Professor Jo Handelsman from UW Madison, a member of our NRC committee, to be Director, with the author as Co-Director. The SI's subsequent success has been largely the result of Handelsman's energetic leadership, with help from her able associates in the UW Program for Scientific Teaching. Peter Bruns, a Vice President of Howard Hughes Medical Institute (HHMI) in charge of education programs, arranged for funding of the pilot workshop and has continued to be a strong supporter of the SI. Jay Labov of the National Academies (NAS) has continued to provide valuable advice and logistical support through the NAS as its representative on the SI faculty.

We convened the first "real" SI in Madison during the summer of 2004 (Wood & Handelsman, 2004). Although we have fine-tuned the workshop over subsequent years, its design up to the present has retained the same central features, listed below. We have continued to be supported by HHMI, with some additional funding from the Research Corporation and the National Academies.

- Recruitment of participants has targeted faculty involved in large courses at large research universities, where the teaching problems are often most acute. Teams of two or three faculty are recruited, including at least one junior and one senior faculty member. Applications are competitive, and teams from about 20 institutions are generally admitted, resulting in about 50 participants each year.
- The workshop is designed around the concept of "scientific teaching" (Handelsman et al., 2004; Handelsman, Miller, & Pfund, 2007), that is, applying the same approaches to pedagogy that participants would normally apply to their scientific research: namely, experimentation (with new teaching methods) and measurement (of the resulting effects on student learning). The distinguished faculty has included biology educators representing several areas of the life sciences as well as physics educators.
- Workshop sessions are highly interactive, involving hands-on participation in the learning activities being presented; i.e., faculty session leaders model the kind of teaching they are promoting. Table 2 lists the major topics of workshop discussions.
- In addition to the large workshop sessions involving all participants, smaller teams of about six work together throughout the week to design a "teachable unit," that is, a set of active-learning activities for mastering a concept the team has found difficult to teach in their previous experience. Interdisciplinary teams that focus on the challenges of teaching quantitative skills in introductory courses are encouraged. Teams present their draft units to each other for constructive feedback, and at the end of the week each team presents their unit and actually teaches one component, a "teachable tidbit," to the SI participants, faculty, and a few outside educators for informal evaluation. These instructional materials are posted on the SI website (www.academiessummerinstitute.org) for future use by participants at their home institutions as well as others.

- The HHMI grant covers participant costs at the SI, but institutions sending a team must provide travel support as well as a small stipend for subsequent use (currently $6,000 per team). Using these funds as they deem appropriate, participants are expected to disseminate the teaching approaches of the SI (essentially the promising practices described in the earlier sections of this paper) through seminars or workshops on their home campuses. About six months after their SI participation, one member of each team returns for a one-day winter meeting at HHMI headquarters in Chevy Chase, MD to discuss the successes and challenges they experienced in their own teaching and in their attempts to disseminate "scientific teaching" among their colleagues.

How much of an impact has the SI had? A Policy Forum paper in *Science* summarized participant outcomes during the first six years of the SI, from 2004-2009 (Pfund et al., 2009). Between 2004 and 2010, 304 faculty from 96 institutions, including almost all the research-intensive universities in the U.S., have attended the SI as participants. Many of these universities have sent two or more teams in successive years, in order to have a larger nucleus of SI-trained instructors on their faculties. Because most of the faculty participants teach large courses, we estimate that the new teaching approaches learned at the SI are now impacting more than 30,000 undergraduates annually.

Most of the outcomes evidence on dissemination activities and changes in teaching behavior is so far based on self-reporting, in response to four surveys of participants, at the beginning and end of the SI, as well as one and two years later (Pfund et al., 2009). Some of these data are shown in Figures 3a and 3b. In general, respondents report substantially increased knowledge of scientific teaching approaches and high rates of implementing these approaches in their classes. Many report measurement of increased student learning gains in their classes, and more than 20 have published evidence for these gains in educational journals. Table 3 lists other dissemination activities reported by participants on their home campuses.

Table 2. Major topics of workshop discussions at the SI

Scientific teaching
How people learn
Active learning
Assessment
Diversity
Mentoring
Development of instructional materials

Table 3. Dissemination activities reported by SI participants on their home campuses

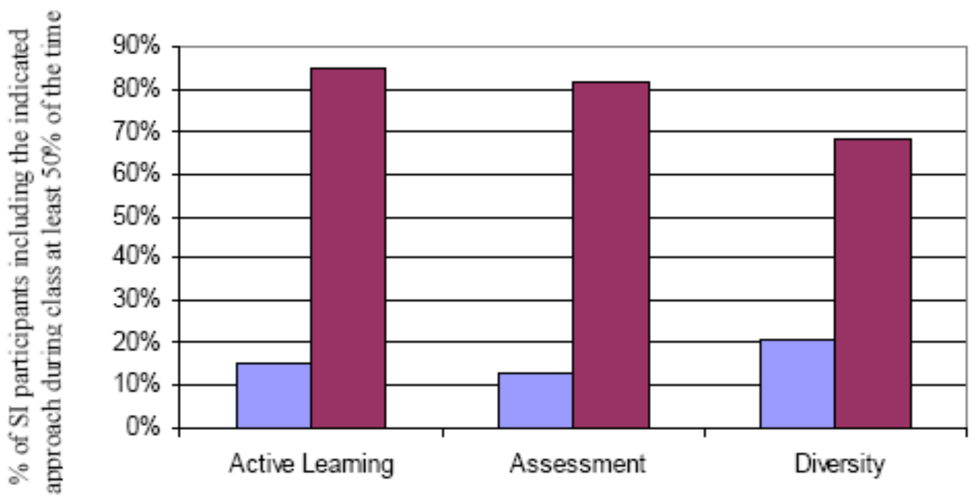
Dissemination activity	Percent of respondents who engaged in activity [a]
Mentored a colleague in teaching	89
Presented a seminar or workshop on teaching	72
Submitted a manuscript on teaching for publication	25

[a] Since these data were collected, changes in dissemination expectations have led to nearly 100% of attendees participating in at least two of these activities (Pfund et al., 2009).

HHMI has recently approved additional funding for expansion of this program to eventually include up to nine regional workshops, which will be directed by current SI faculty and conducted similarly to the parent SI in Madison. Four new regional workshops will be offered in 2011. The new funding will also permit a more rigorous evaluation of program outcomes, including reported changes in teaching philosophy, analysis of video-taped classes to document changes in teaching behavior, impact on participant departments, and changes in student learning gains.

At the 2009 AAAS-sponsored Vision and Change Conference on biology education in Washington D.C. (Brewer & Smith, 2011; http://visionandchange.org), Peter Bruns asked from the podium how many former SI participants were present, and about 10% of the approximately 500 audience members stood up! This show of strength was one indication that the SI is not only succeeding in disseminating research-based teaching approaches among life sciences faculty, but is also creating a national community of practice, whose members are committed to educational change.

a.



b.

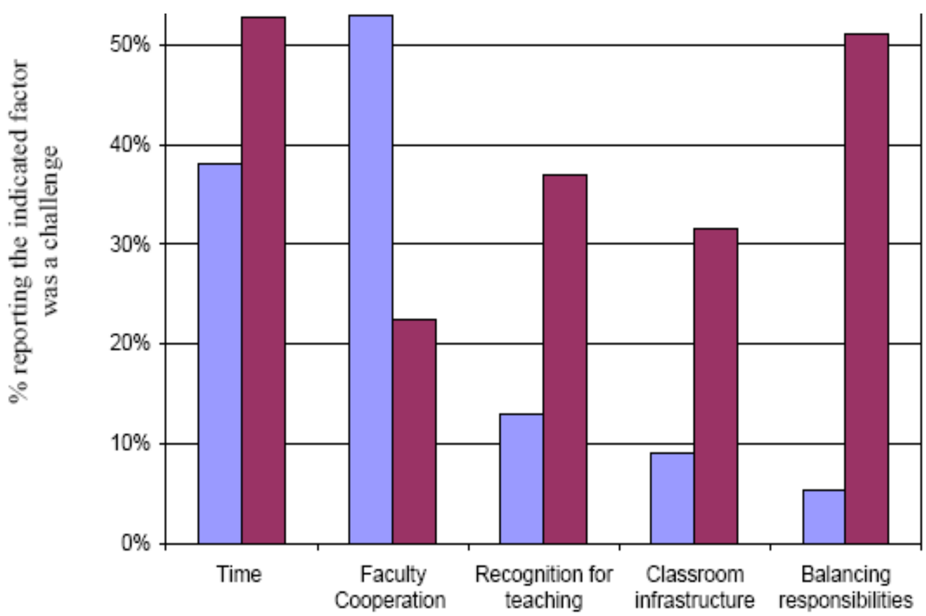


Figure 3. Outcomes data from the SI (Pfund et al., 2009). Panel 3a shows self-reporting data from participants on use of promising practices taught at the SI before (blue) and one year after the SI (red). Assessment refers to both formative assessment techniques in class as well as pre-/post-testing to estimate student learning gains during a course (see text). Diversity refers to awareness of diverse backgrounds, preferred learning styles, and possibly students with disabilities, in the design of instruction. Panel 3b compares barriers to implementation that participants anticipated immediately after the SI (blue) with those that they actually experienced as reported one year later (red).

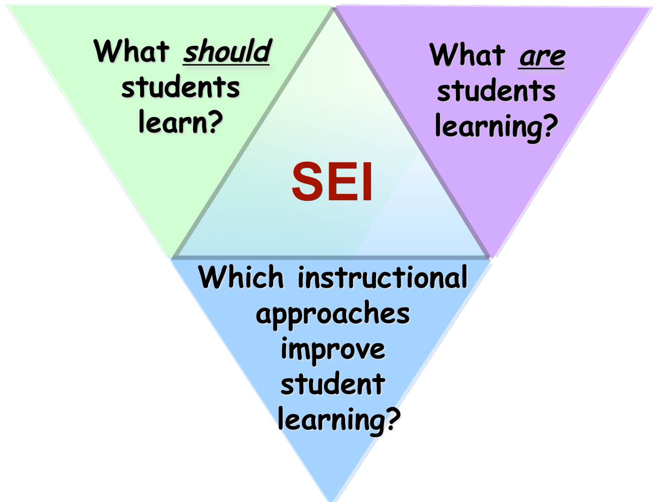


Figure 4. Logo representing the three major components of change committed to by departments participating in the Science Education Initiative (adapted from Wieman, Perkins, & Gilbert, 2010; see text for further explanation).

2. *The Science Education Initiative at University of Colorado (CU), Boulder*

In 2005, physics Nobel Laureate and educator Carl Wieman persuaded CU to invest about $4.5 million in a 5-year experimental program, the Science Education Initiative (SEI), designed to change the teaching culture of several science departments concurrently (www.colorado.edu/sei/). The goal was to spur adoption in large undergraduate science courses of the research-based promising practices described above (Wieman, Perkins, & Gilbert, 2010). Wieman and a small committee judged competitive applications solicited from science departments on the basis of commitment to the change process and plans to implement it over the grant period. The four departments chosen to participate in 2006 were Molecular, Cellular, and Developmental Biology (MCDB), Integrative Physiology, Earth Sciences, and Chemistry; Physics was added a year later. All these departments teach large numbers of undergraduates, and their faculties are strongly research-oriented, generally considering research to be primary and teaching only their secondary mission. The author serves as SEI Director in MCDB.

In accepting funding, the faculty of each department committed to the following change process, symbolized by the three points of the SEI logo shown in Figure 4. First, define what departmental majors students *should be learning*, that is, reformulate the majors curriculum in terms of specific intended learning outcomes. Second, determine what students *are learning*, by designing and administering assessments to measure gains in learning toward the intended outcomes. Third, determine *which instructional approaches improve student learning*, based on assessment of learning gains (i.e. "scientific teaching").

As pointed out above, the greatest barrier to such changes has traditionally been time constraints on research-active faculty in the face of minimal incentives for implementation. To circumvent this barrier, each participating department used the SEI funding to recruit two or three Science Teaching Fellows (STFs), post-doctoral scientists with degrees in the discipline and either some training as educators or a strong desire to obtain such training. Incoming STFs took a crash course in pedagogy and the educational research literature from Wieman and his staff, and then worked with departmental faculty to transform individual majors courses along the lines outlined above, generally beginning with the introductory course and moving up through the majors curriculum in subsequent years. Most of the departments have encouraged STFs to attend faculty meetings and keep faculty informed about the progress of the program. STFs have also continued meeting regularly as an interdisciplinary group to discuss their successes and challenges, as well as education research papers from the current literature. The STFs have done little actual teaching; instead their roles have been to assist with formulation of learning goals, development of assessments, and creation of homework and classroom activities, jobs that faculty have neither sufficient time nor, initially, sufficient pedagogical expertise to do as effectively on their own. In addition, the STFs have directed research with participating faculty on the effects of course transformation.

Over the past five years, the SEI has substantially impacted the teaching of science at CU (Wieman, Perkins, & Gilbert, 2010) [2]. Based on responses (N=114, a 70% response rate) to a 2010 survey of faculty from the five participating departments, over 100 faculty members have worked with STFs on aspects of course transformation in more than 55 majors as well as non-majors courses, with a combined enrollment of about 10,000 students annually. 75% of responding faculty reported an increase in substantive conversations about teaching approaches, both in faculty meetings and informally. About the same percentage reported less lecturing and more active learning in their classes. 62% had formulated intended learning outcomes for their courses, and 57% had collected and used information on student thinking and attitudes to help guide their teaching. 47% had developed and used pre-/post-assessments to measure student learning gains. Participating faculty and STFs have co-authored over 30 peer-reviewed research publications on aspects of teaching and learning, including evidence for increased student learning gains and development and validation of two new CIs for biology (Smith et al., 2008; Shi et al., 2011). The SEI has recently obtained funding to support further evaluation of the program's impact at CU.

The SEI has also had an impact beyond CU. In 2008, Wieman moved from CU to the University of British Columbia (UBC) in Vancouver, where he initiated a sister program involving five science departments, statistics, and mathematics (www.cwsei.org; Wieman, Perkins, & Gilbert, 2010). Both programs have archived all the intended learning outcomes, assessments, and classroom activities that they developed, and these materials are now publicly available in databases on their respective websites.

Because this sort of departmental change is difficult to accomplish (Dancy & Henderson, 2008), it is worth enumerating some of the SEI features that contributed to its success. The program was not administratively mandated; rather it was department-based, with strong central faculty leadership. Funding was competitive; departments had to commit to the change process in advance in order to participate. The process was incremental, one course at a time, but carried out within frameworks of departmentally agreed-upon learning outcomes. STFs, the major drivers of change, possessed the content knowledge required for development of learning materials but were not threatening to faculty, as specialists with education degrees might have been. They had no authority over faculty; their influence depended on their enthusiasm, energy, pedagogical knowledge, persuasiveness, and willingness to undertake aspects of course transformation that faculty viewed as worthwhile but had little time for. In addition, the STFs maintained an interdisciplinary synergy between participating departments, and they directed research to document success of the program.

Establishing a program like the SEI should be possible at any research university that can provide effective leadership by respected members of the faculty and funding for post-doctoral scientists with strong interests and some expertise in education. Initiation of similar programs could be facilitated if funding agencies with interests in improving undergraduate education would provide institutional and fellowship support for such postdocs in the future.

[2] Science teaching fellows (STFs) are referred to in this article as science education specialists (SESes).

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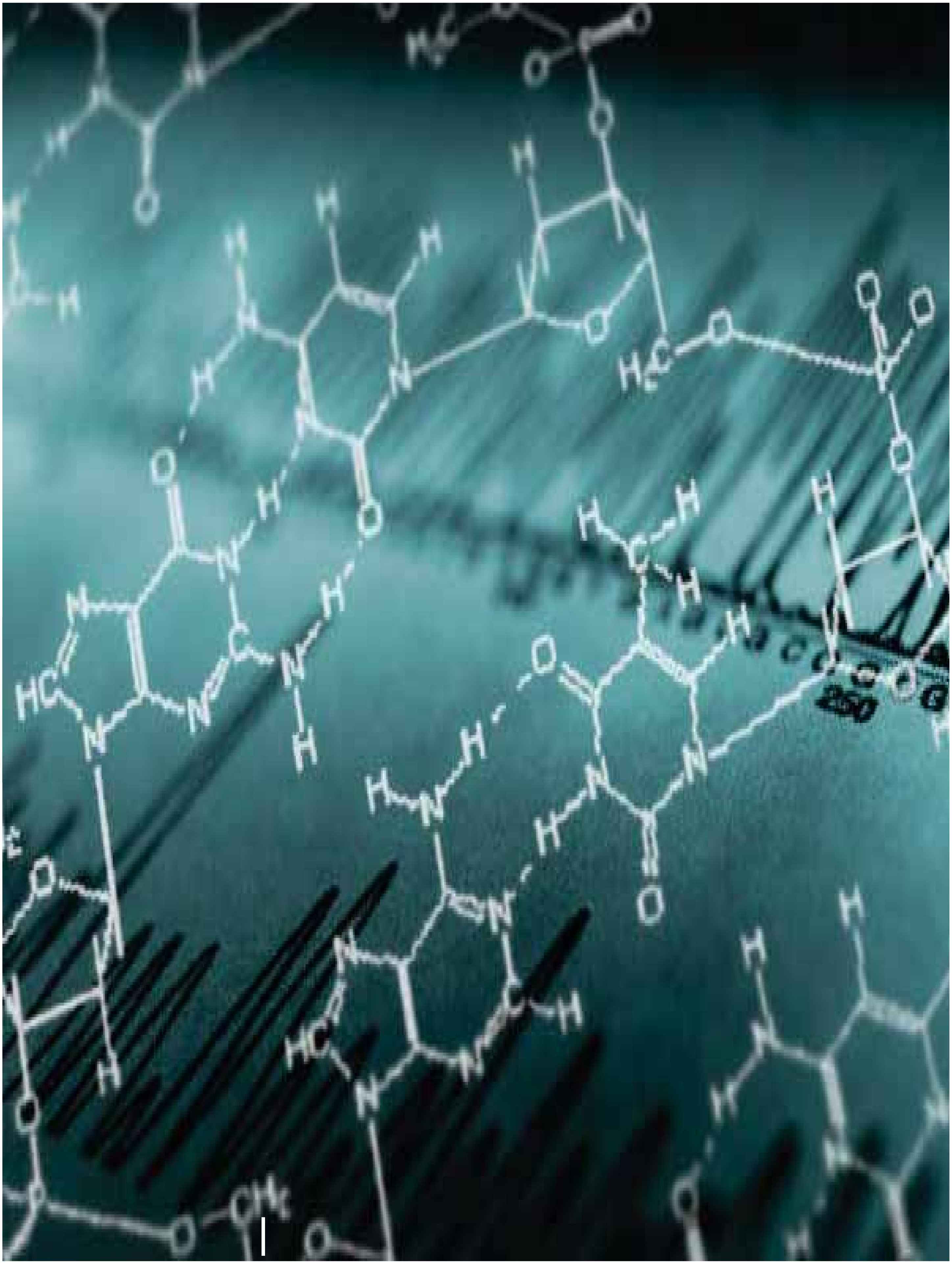

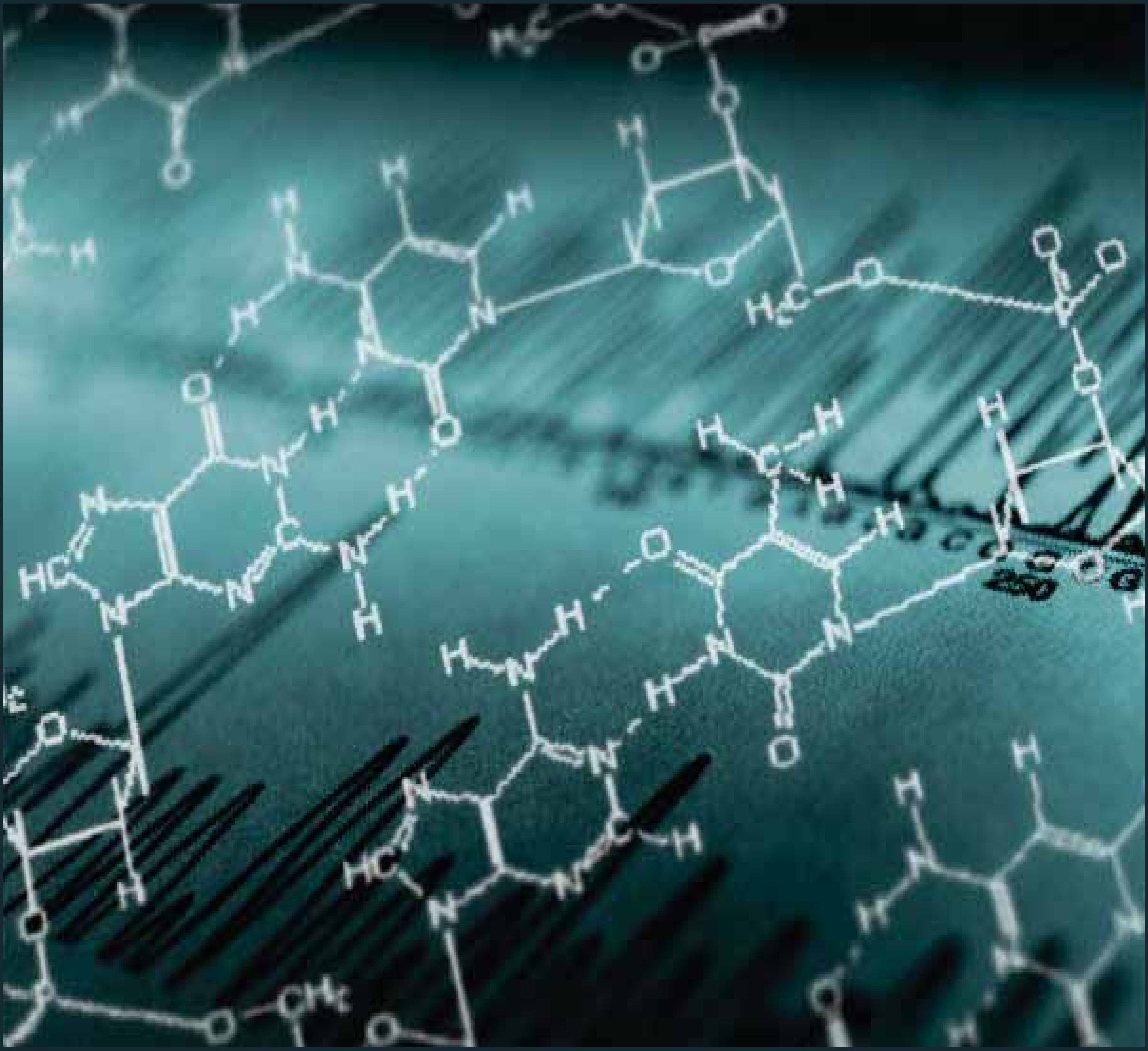

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