POLICY FORUM

EDUCATION

Scientific Teaching

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Since publication of the AAAS 1989 report "Science for all Americans" (*1*), commissions, panels, and working groups have agreed that reform in science education should be founded on "scientific teaching," in which teaching is approached with the same rigor as science at its best (*2*). Scientific teaching involves active learning strategies to engage students in the process of science and teaching methods that have been systematically tested and shown to reach diverse students (*3*).

Given the widespread agreement, it may seem surprising that change has not progressed rapidly nor been driven by the research universities as a collective force. Instead, reform has been initiated by a few pioneers, while many other scientists have actively resisted changing their teaching. So why do outstanding scientists who demand rigorous proof for scientific assertions in their research continue to use and, indeed, defend on the basis of the intuition alone, teaching methods that are not the most effective? Many scientists are still unaware of the data and analyses that demonstrate the effectiveness of active learning techniques. Others may distrust the data because they see scientists who have flourished in the current educational system. Still others feel intimidated by the challenge of learning new teaching methods or may fear that identification as teachers will reduce their credibility as researchers (*3*).

This Policy Forum is needed because most scientists don't read reports but they do read *Science*. In addition, reports generally do not offer a guide to learning how to do scientific teaching, as we do with supporting online material (SOM) (*3*) and table (see page 522). We also present recommendations for moving the revolution forward.

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Implementing Change in Lectures

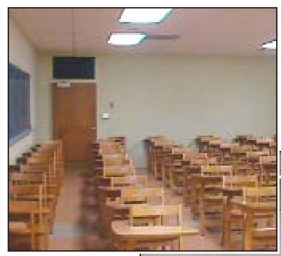
Active participation in lectures and discovery-based laboratories helps students develop the habits of mind that drive science. However, most introductory courses rely on "transmission-of-information" lectures and "cookbook" laboratory exercises—techniques that are not highly effective in fostering conceptual understanding or scientific reasoning. There is mounting evidence that supplementing or replacing lectures with active learning strategies and engaging students in discovery and scientific process improves learning and knowledge retention (*3*).

Introductory classes often have high enrollments, frequently approaching 1000 students in biology courses. This need not be an impediment to scientific teaching. Many exercises that depart from traditional methods are now readily accessible on the Web, which makes it unnecessary for teachers to develop and test their own (*3*). Quantitative assessment indicates that these interactive approaches to lecturing significantly enhance learning, and although time allocated to inquiry-based activities reduces coverage of specific content, it does not reduce knowledge acquisition as measured by standardized exams (*4*).

Faculty are also using computer systems to engage students, assess learning, and shape teaching. Students can be asked to read and solve problems on a Web site, and their answers can be analyzed before class to guide the design of lectures (*3*).

Some scientists have replaced lectures almost entirely. Laws's course "Calculus-Based Physics Without Lectures" at Dickinson University (*5*) and Beichner's program, SCALE-UP, at North Carolina State University (see figure, this page) rely on a problem-based format in which students work collaboratively to make observations and to analyze experimental results. Students who learned physics in the SCALE-UP format at a wide range of institutions demonstrated better problem-solving ability, conceptual understanding, and success in subsequent courses compared with students who had learned in traditional, passive formats (*3*).

These results are neither isolated nor discipline-specific. At the University of Oregon, Udovic showed dramatic differences between students taught biology in a traditional lecture and those taught "Workshop Biology," a series of active, inquiry-based learning modules (*6*). Similarly impressive results were achieved by Wright in a comparison of active and passive learning strategies in chemistry (*7*). Others have taught cross-disciplinary problem-based courses that integrate across scientific disciplines, such as Trempy's, "The World According to Microbes," at Oregon State University, which integrates science, math, and engineering. The course serves science majors and nonmajors, and outcome assessments indicate high content retention and student satisfaction (*8*).



A physics classroom at North Carolina State University arranged for traditional lectures (inset) and redesigned for group problem-solving in the SCALE-UP program.

Students as Scientists

Scientists of all disciplines have developed inquiry-based labs that require students to develop hypotheses, design and conduct experiments, collect and interpret data, and write about their results (*9*). Many of these involve simple, inexpensive materials configured so that they invite students to ask their own questions. In addition to labs that have already been tested in the classroom, resources are available to help teachers convert cookbook labs into open-ended, inquiry-based labs (*3*). Some schools provide introductory-level students with the opportunity to conduct original research in a professor's research lab rather than take a traditional classroom lab course (*3*). These opportunities are challenging for instructors, but teach students the essence of investigation.

How Universities Can Promote Change

Research universities should provide leadership in the reform movement. Faculty and administrators should collaborate to overcome the barriers and to create an educational ethos that enables change. We need to inform scientists about education research and the instructional resources available to them so that they can make informed choices. We must admit that citing our most successful students as evidence that our teaching methods are effective is simply not scientific. Instead, we need to apply innovative metrics to assess the outcomes of teaching. Controlled experiments and meta-analyses that compare student achievement with various teaching strategies provide a compelling basis for pedagogical choices (*10*), but the need for assessment extends into every classroom. Many tools to assess learning are available (*3*). Assessments of long-term retention of knowledge, entrance into graduate school, and employment and professional success should be included as well.

Research universities should overhaul introductory science courses for both science majors and nonmajors using the principles of scientific teaching. The vision should originate from departments and be supported by deans and other academic administrators. Science departments should incorporate education about teaching and learning into graduate training programs and should integrate these initiatives into the educational environment and degree requirements. This could include, for example, development of peer-reviewed instructional materials based on the student's thesis research. Funding agencies have a responsibility to promote this strategy. National Institutes of Health and the National Science Foundation should, for example, require that graduate students supported on training grants acquire training in teaching methods, just as the NIH has required training in ethics.

Universities need to provide venues for experienced instructors to share best practices and effective teaching strategies. This will be facilitated, in part, by forming educational research groups within science departments. These groups might be nucleated by hiring tenure-track faculty who specialize in education, as 47 physics departments have done in the past 6 years. Other strategies include incorporating sessions about teaching into their seminar series, developing parallel series about teaching, or establishing instructional material "incubators" where researchers incorporate research results into teaching materials with guidance from experts in pedagogy. The incubators would provide an innovative mechanism to satisfy the "broader impact" mandate in research projects funded by the NSF.

Universities should place greater emphasis on awareness of new teaching methods, perhaps ear-marking a portion of research start-up packages to support attendance of incoming instructors at education workshops and meetings. Deans and department chairs at Michigan State University and University of Michigan have found that this strategy sends a message to all recruits that teaching is valued and it helps with recruiting faculty who are committed to teaching.

Distinguished researchers engaged in education reforms should exhort faculty, staff, and administrators to unite in education reform and should dispel the notion that excellence in teaching is incompatible with first-rate research. Federal and private funding agencies have contributed to this goal with programs such as the NSF's Distinguished Teaching Scholar Award and the Howard Hughes Medical Institute Professors Program, which demonstrate that esteemed researchers can also be innovative educators and bring prestige to teaching.

Universities and professional societies need to create more vehicles for educating faculty in effective teaching methods. For example, the National Academies Summer Institutes on Undergraduate Education, the Council of Graduate Schools' Preparing Future Faculty program, the American Society for Microbiology Conference for Undergraduate Educators, and Workshops for New Physics and Astronomy Faculty are steps toward this goal (*3*).

Finally, the reward system must be aligned with the need for reform. Tenure, sabbaticals, awards, teaching responsibilities, and administrative support should be used to reinforce those who are teaching with tested and successful methods, learning new methods, or introducing and analyzing new assessment tools. This approach has succeeded at the University of Wisconsin–Madison, which has rewritten tenure guidelines to emphasize teaching, granted sabbaticals based on teaching goals, and required departments to distribute at least 20% of merit-based salary raises based on teaching contributions (*3*).

If research universities marshal their collective will to reform science education, the impact could be far-reaching. We will send nonscience majors into society knowing how to ask and answer scientific questions and be capable of confronting issues that require analytical and scientific thinking. Our introductory courses will encourage more students to become scientists. Our science majors will engage in the process of science throughout their college years and will retain and apply the facts and concepts needed to be practicing scientists. Our faculty will be experimentalists in their teaching, bringing the rigor of the research lab to their classrooms and developing as teachers throughout their careers. Classrooms will be redesigned to encourage dialogue among students, and they will be filled with collaborating students and teachers. Students will see the allure of science and feel the thrill of discovery, and a greater diversity of intellects will be attracted to careers in science. The benefits will be an invigorated research enterprise fueled by a scientifically literate society.

SCIENTIFIC TEACHING EXAMPLES

Group problem-solving in lecture

www.ibscore.org/courses.htm

http://yucca.uoregon.edu/wb/index.html

http://mazur-www.harvard.edu/education/educationmenu.php

Problem-based learning

www.udel.edu/pbl/

www.microbelibrary.org

www.ncsu.edu/per/scaleup.html

http://webphysics.iupui.edu/jitt/jitt.html

Case studies

www.bioquest.org/lifelines/

http://ublib.buffalo.edu/libraries/projects/cases.case.html

http://brighamrad.harvard.edu/education/online/tcd/tcd.html

Inquiry-based labs

www.plantpath.wisc.edu/fac/joh/bbtl.htm

www.bioquest.org/

http://biology.dbs.umt.edu/biol101/default.htm

http://campus.murraystate.edu/academic/faculty/terry.derting/ccli/cclihomepage.html

Interactive computer learning

www.bioquest.org/

www.dnai.org

http://evangelion.mit.edu/802TEAL3D/

http://ctools.msu.edu/

References and Notes

1. AAAS, "Science for all Americans: A Project 2061 report on literacy goals in science, mathematics, and technology" (AAAS, Washington, DC, 1989).
2. AAAS, "The Liberal Art of Science" (AAAS, Washington, DC, 1990).
3. Supporting online material provides further references on this point.
4. D. Ebert-May *et al.*, *Bioscience* **47**, 601 (1997).
5. P. Laws, *Phys. Today* **44**, 24 (1991).
6. D. Udovic *et al.*, *Bioscience* **52**, 272 (2002).
7. J. C. Wright *et al.*, *J. Chem. Educ.* **75**,986 (1998).
8. J. Trempy *et al. Microbiol. Educ.* **3**, 26 (2002).
9. J. Handelsman *et al.*, *Biology Brought to Life: A Guide to Teaching Students How to Think Like Scientists* (McGraw-Hill, New York, 1997).
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11. We thank C. Matta, C. Pfund, C. Pribbenow, A. Fagen, and J. Labov for comments and A. Wolf for contributions to the supplemental materials. Supported in part by the Howard Hughes Medical Institute.

Supporting Online Material

www.sciencemag.org/cgi/content/full/304/5670/521/DC1

Science Supporting Online Material
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www.nscu.edu/per/SCALEUP/Classrooms.html

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www.plantpath.wisc.edu/fac/joh/incub.htm

Workshops on Teaching for Science Educators

W. Wood, J. Gentile, *Cell Biology Education* 2, 207-209 (2003).

www.preparing-faculty.org

http://www.academiessummerinstitute.org/

Changes in Reward System to Reinforce Teaching

http://wiscinfo.doit.wisc.edu/secfac/divcomm/biological/TenureGuidelines.pdf

www.ohr.wisc.edu/grants/facsabb99-2000.html

Table S1. Examples of Scientific Teaching Methods.

Method	References and Websites
Group brainstorming or problem solving in lecture	(*S1*,*S2*, *S3*) ConcepTests http://mazur-www.harvard.edu/education/educationmenu.php Integrated Biological Science Courses Organized around Research Experience (IBSCORE) www.ibscore.org/courses.htm Workshop Biology http://yucca.uoregon.edu/wb/index.html
Problem-based learning	(*S4*, *S5*, *S6*) Problem-Based Learning www.udel.edu/pbl/ Case Studies in Problem-Based Learning www.microbelibrary.org/newsletter/nltrs00.pdf Student-Centered Activities for Large Enrollment Undergraduate Program www.ncsu.edu/per/scaleup.html Just-in-time Teaching http://webphysics.iupui.edu/jitt/jitt.html
Case studies	National Center for Case Study Teaching in Science http://ublib.buffalo.edu/libraries/projects/cases/case.html LifeLines Online www.bioquest.org/lifelines/ Harvard Medical School Case Studies http://brighamrad.harvard.edu/education/online/tcd/tcd.html
Inquiry-based labs	(*S1*, *S2*, *S7*) Biology Brought to Life: A Guide to Teaching Students to Think Like Scientists www.plantpath.wisc.edu/fac/joh/bbtl.htm The BioQUEST Curriculum Consortium www.bioquest.org/ Introduction to Biological Inquiry and Analysis http://campus.murraystate.edu/academic/faculty/terry.derting/ccli/cclihomepage.html Project IBSCORE, University of Montana http://biology.dbs.umt.edu/biol101/default.htm
Interactive computer learning	The BioQUEST Curriculum Consortium www.bioquest.org/ DNA Interactive www.dnai.org Technology Enabled Active Learning (TEAL) Studio Project http://evangelion.mit.edu/802TEAL3D/ http://ctools.msu.edu/

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S2. J. Handelsman, B. J. Houser, H. Kriegel, *Biology Brought to Life: A Guide to Teaching Students How to Think Like Scientists* (McGraw-Hill, 1997).

S3. C. Dreifus, "A conversation with Shirley Tilghman; Career that grew from an embryo," *New York Times*, 8 July 2003, F2.

S4. J. Trempy, M. Skinner, W. Siebold, *Microbiology Education* **3**, 26-36 (2002).

S5. W. Wood, J. Gentile, *Cell Biology Education* **2**, 207-209 (2003).

S6. www.preparing-faculty.org.

S7. D. Udovic, D. Morris, A. Dickman, J. Postlethwait, P. Wetherwax, *Bioscience* **52**, 272–281.

Table S2. Teaching Materials and Online Resources.

Teaching Materials and Online Resources by Subject Area	**URL**	**Type of Material or Resource**	**Description**
Biology			
Biology Brought to Life: A Guide to Teaching Students to Think Like Scientists	**www.plantpath.wisc.edu/fac/joh/bbtl.htm**	Classroom activities, inquiry-based labs	These online book chapters offer ideas for cooperative exercises and inquiry-based labs that can be integrated into biology courses. Chapters include how-to instructions, rationale, and full-length labs with teacher guides.
BioQUEST Curriculum Consortium	http://bioquest.org	Multimedia	This collection of computer tools allows students to *pose* their own problems, solve these *problems* through investigations of their own design, and *persuade* their peers that their conclusions are correct: the BioQUEST "3 P's."
Concept mapping tool (CTOOLS)	www.ctools.msu.edu	Multimedia (assessment)	This Web-based concept mapping tool provides students and faculty with a visual representation of principles and relationships among concepts. It includes computer-based scoring capabilities.
DNA from the Beginning	www.dnaftb.org	Multimedia	This technology-rich Web site includes concept lists, graphics, animations, and more for teaching about DNA.
DNA Interactive	www.dnai.org	Multimedia	This interactive Web site teaches students about the structure, function, and history of DNA through fascinating animations and problem-solving scenarios.
Frog Deformities	www.first2.org/resources/inquiry_activities/frog_activity.htm	Online activity	In this activity, students engage in experimental design and data analysis to understand complex interactions between environmental variables and frog populations.
Genetics Education Center	www.kumc.edu/gec/	Online resources	This Web site is designed for educators who are interested in human genetics and the human genome project. It includes links to lesson plans, the human genome project, networks, and programs.
Genome Consortium for Active Teaching (GCAT)	www.bio.davidson.edu/Biology/GCAT/GCAT.html	Online activities	This online resource brings functional genomic methods into undergraduate curricula through student research and is a collection of information and data for teaching genomics.
Guppy Simulation	www.first2.org/resources/inquiry_activities/guppy_activity.htm	Online activity	In this computer-based activity, students build understanding of natural selection, sexual selection, and fitness.
Integrated Biological Science Courses Organized around Research Experience (IBSCORE)	www.ibscore.org/courses.htm	Course materials	This course uses a teamwork approach that involves all students in a classroom, promotes critical thinking, and teaches communication skills in science.

Introduction to Biological Inquiry and Analysis	http://campus.murraystate.edu/academic/faculty/terry.derting/ccli/cclihomepage.html	Course materials	In this course, students learn basic concepts in biology and engage in science as a process of active inquiry that serves as a framework for further study. The Web site includes 10 in-class assignments and an introduction to basic statistics.
LifeLines	http://bioquest.org/lifelines	Online activities (case-based learning)	This collection of online cases is designed by community college teachers and is based on real-life scenarios.
Microbes Count!	http://bioquest.org/microbescount	Multimedia	This collection of multimedia resources, simulations, and tools is an interactive, open-ended forum for learning about microbiology.
MicrobeLibrary	www.microbelibrary.org	Online activities	This searchable portal provides a peer-reviewed, Web-based collection of resources about the microbial world, including visual images and animations, curriculum activities for both classroom and laboratory, and articles. The collection is linked directly to a recommended core curriculum for introductory microbiology education.
Problem-based Learning	www.udel.edu/pbl/	Online activities (problem-based learning)	This collection of problem-based learning (PBL) activities challenges students to work cooperatively in groups to solve real-world problems.
Teaching Case Database	http://brighamrad.harvard.edu/education/online/tcd/tcd.html	Online activities (case-based learning)	This collection of online cases is designed for medical students at Harvard Medical School.
Teams and Streams	http://surf.to/teamstreams/	Inquiry-based labs	These labs provide a framework for teachers to move from traditional, confirmatory approaches to student-driven inquiry. Students post results on Web sites of their own design.
Workshop Biology	http://yucca.uoregon.edu/wb/index.html	Course materials, resources	This program is designed to improve biology teaching for non-biology majors. The Web site includes many resources, including a downloadable, 230-page curriculum development handbook, and more.
Chemistry			
ChemLinks	http://chemlinks.beloit.edu/	Multimedia	This collection of modules is designed to enhance the appreciation and learning of chemistry.
Peer-led Team Learning	www.sci.ccny.cuny.edu/~chemwksp/	Classroom activities	This Web site outlines strategies for teaching in a “workshop format” where teams of students are guided by a peer leader. This model provides an active learning experience for students, creates a leadership role for undergraduates, and engages faculty in a creative new dimension of instruction.

General Science			
Calibrated Peer Review	http://cpr.molsci.ucla.edu/	Online activities	This Web-based program provides resources for implementing frequent writing assignments in large classes with limited instructional resources.
Just-in-time Teaching (JITT)	http://webphysics.iupui.edu/jitt/jitt.html	Multimedia	This program provides teacher resources and computer-based activities that use technology and problem-solving skills to improve learning. Students complete Web-based assignments prior to class so the instructor can revise teaching "just in time."
National Center for Case Study Teaching in Science	http://ublib.buffalo.edu/libraries/projects/cases/case.html	Online activities	This Web site offers instructions and rationale for case-based learning, and includes a collection of online cases for many science disciplines.
National Institute for Science Education	www.wcer.wisc.edu/nise/	Online activities and assessment resources	This institute provides literature about teaching and learning, strategies for improving science education, and assessment guides for teachers and students.
Student-Centered Activities for Large Enrollment Undergraduate Programs (SCALE-UP)	http://scaleup.ncsu.edu/	Multimedia	This program offers pedagogical methods and classroom management techniques that include hands-on activities, simulations, questions, problem-solving scenarios, and hypothesis-driven labs.
Physics			
Activity-based Physics	http://physics.dickinson.edu/~abp_web/abp_homepage.html	Multimedia	This suite of textbooks, computer software, and other materials is based on physics education research. The activity-based materials help students learn difficult physics concepts.
Cooperative Group Problem Solving in Physics	http://groups.physics.umn.edu/physed/Research/CGPS/CGPSintro.htm	Teaching strategies and inquiry-based labs	This Web site contains information about how to implement cooperative group problem-solving into physics classrooms, as well as a downloadable lab manual.
Peer Instruction	http://mazur-www.harvard.edu/education/educationmenu.php	Classroom activities	This article suggests strategies that can be used to embellish lectures with activities where students teach each other, as well as rationale for these activities, and ConcepTest examples.
Physlets	http://webphysics.davidson.edu/Applets/Applets.html	Multimedia	This Web site and companion book contain physics problems with animated physics applets.
Technology Enabled Active Learning (TEAL) Studio Project	http://evangelion.mit.edu/802TEAL3D/	Multimedia	These computer simulations are designed to help freshmen develop intuition about and conceptual models of physical phenomena. The tools are based on an active-learning approach that merges lecture, lab, and discussion sections. Course notes, graphics, and animations are available.

General Teaching			
The Active Learning Site	www.active-learning-site.com/bib1.htm	Bibliography	This comprehensive bibliography lists articles about active learning.
Center for Science and Math Teaching	http://ase.tufts.edu/csmt/	Teaching strategies and resources	This Web site provides references and software (microcomputer-based laboratory tools) that enable students to learn physical concepts.
Center for Teaching Effectiveness	www.utexas.edu/academic/cte/resources/teach.html	Teaching strategies and resources	This online, how-to guide offers advice for all aspects of developing a university course, including teaching strategies, references, media aids, advice about diversity, and more.
HHMI New Generation Program	http://newgenerationprogram.wisc.edu	Teaching strategies and resources	This program provides strategies for teaching graduate students and postdocs to teach and mentor, including syllabi, evaluation tools, and peer-review information.
KnowledgeRoom Networks	www.knowledgeroom.com/	Multimedia tool	This innovative Web site enhances classroom education by providing user-friendly, virtual space where students can research, explore, collaborate, and communicate.
Online Databases			
Biology Education Online (BEoN)	www.accessexcellence.org/LC/BEoN/		This is an online, peer-reviewed journal for K-16 educators in the life sciences.
BioScienceEdNetwork (BEN)	www.biosciednet.org		This digital, searchable database of biology instructional materials and resources is designed to help undergraduate educators to improve their teaching through resources, collaboration, and network building.
The Learning Matrix	http://thelearningmatrix.enc.org/		This site provides access to peer-reviewed digital resources that promote inquiry- and problem-based learning in college mathematics, science, and technology classes. Instructions are included for posting new instructional materials.
Multimedia Educational Resource for Learning and Online Teaching (MERLOT)	www.merlot.org		This electronic database is a "free and open resource" of instructional materials, including peer reviews and comments. Instructions are included for posting new instructional materials.
National Science Digital Library	http://nsdl.org/		This digital library contains resource collections and services for science, technology, engineering and mathematics education.
Science, Math, Engineering, and Technology Education	www.smete.org/		This digital library offers access to online teaching and learning materials for students and teachers.
Professional Society Web sites and other Publications			
American Association for the Advancement of Science	www.aaas.org/education/		Education homepage

American Association of Physics Teachers	www.aapt.org		Journals: *Physics Teacher* and *American Journal of Physics*
American Chemical Society	www.chemistry.org/portal/a/c/s/1/educatorsandstudents.html http://jchemed.chem.wisc.edu/		Education homepage Journal: *Journal of Chemistry Education*
American Physical Society	www.aps.org/educ/		Education homepage
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American Society for Cell Biology	www.ascb.org www.cellbioed.org		Online Journal: *Cell Biology Education*
American Society for Microbiology	www.asm.org/education		Journals: *Microbiology Education* and *ASM News*
Association of College and University Biology Educators	www.acube.org		Journal: *Bioscene: Journal of College Biology Teaching*
Ecological Society of America	www.esa.org/education/		Education homepage
National Association of Biology Teachers	www.nabt.org		Journal: *American Biology Teacher*
National Association for Research in Science Teaching	www2.educ.sfu.ca/narstsite/		Journal: *Journal of Research in Science Teaching*
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