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.

Implementing Change in Lectures

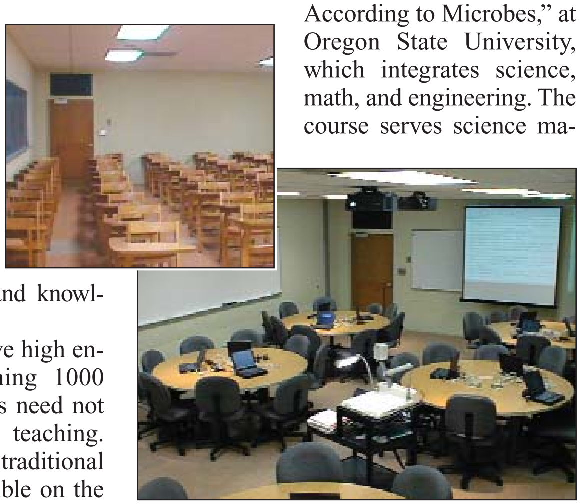
Active participation in lectures and discovery-based laboratories helps students develop the habits of mind that drive science. However, most introductory courses rely on "transmission-of-information" lectures and "cookbook" laboratory exercises—techniques that are not highly effective in fostering conceptual 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 tradition-

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al 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.

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/

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.

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).
10. L. Springer *et al.*, *Rev. Educ. Res.* **69**, 21 (1999).

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