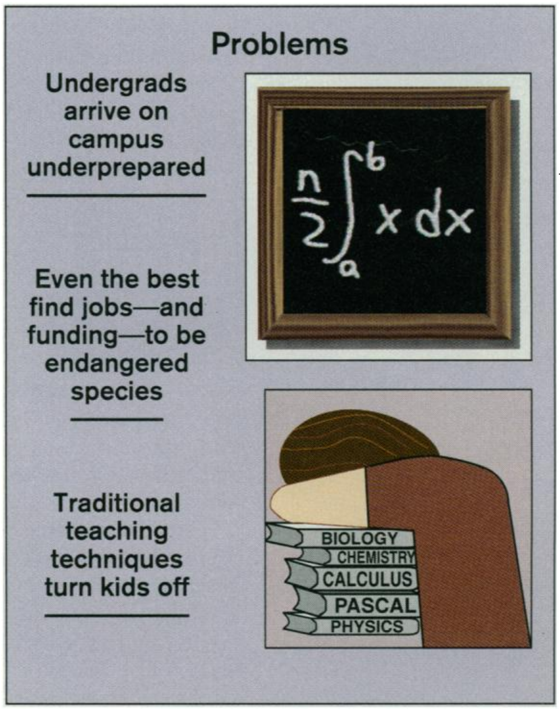
A Time of Trials and Tribulations

The world's most successful system for making scientists is undergoing profound change

Chris Putnam was only a freshman at Washington University in St. Louis when his adviser did something unusual to encourage his interest in biochemistry: He invited Putnam into his lab. A stranger to research, Putnam started out washing glassware in another professor's lab. But then molecular geneticist Craig Pikaard asked Putnam to do some cloning. By the time Putnam went home at Christmas, he had cloned a gene that promotes the transcription of RNA in the frog species *Xenopus laevis*. "I was thrilled. Here I was doing genetic engineering as a freshman!" says Putnam. "When I got back to his lab in January, I started doing research. And I've never looked back."

Now, at 21, Putnam is a first-year graduate student in the prestigious new biochemistry program at the Scripps Research Institute in La Jolla, California. Indeed, he did so well as an undergrad that he received two graduate fellowships and had his pick of institutions to attend. This was in no small part because he managed to publish papers even as an undergrad—in *Molecular and Cellular Biology* and *Nucleic Acids Research*. And it's because he was afforded a chance to do research. "I learned more in Craig's lab than I did in my courses," says Putnam. "In the lab, you're forced to think like a scientist."

All told, Putnam represents what U.S. universities do best—mold researchers (occasionally even before they reach graduate school) out of a clay of youngsters with diverse backgrounds and interests. At Putnam's undergraduate institution, biologist Sarah Elgin, who is redesigning the Washington University undergraduate biology curricula to put more students into labs, says: "Our faculty views the research program as the jewel in the crown of our biology program."



The U.S. education system has become a sort of finishing school for the international scientific community, and U.S scientists are rightfully proud of the system. To a casual observer, it is thriving, with production of Ph.D.s in science and engineering at an all-time high. But a closer look shows that all is not well. In interviews with hundreds of faculty members and students at dozens of large and small colleges, *Science* found clear signs of strain at almost every level of higher education.

Evidence? Most students entering college are poorly prepared in math and science—even those at elite universities such as the Massachusetts Institute of Technology (MIT) (p. 846). Worse, many are turned off by the old methods of teaching science (p. 875). Further, faculty members see a declining proportion of the best U.S.-born students applying to graduate programs in science, and a growing number of those slots are being filled by foreigners. And at least 40% of those students who make it to graduate school in science drop out before receiving a Ph.D.

There's more. Those who do complete their degrees often have difficulty moving beyond a series of postdoctoral fellowships into real jobs. And if they get academic jobs, they must deal with increasing pressure from government agencies to meet national goals, not just to replicate themselves. California Institute of Technology vice provost David Goodstein sees these events as symptoms of a scientific enterprise entering an era of retrenchment. "These are not short-term problems," he says ominously. "These are permanent changes we, as the scientific community, have to come to terms with."

Indeed, the severity of the problem has led some in academia and the government to suggest corrective surgery on the system. The days of teaching science primarily as a means of producing the next cohort of academic researchers are over, they say; the new goal should be scientifically literate graduates who use their training to enter a range of careers—including law, health care, human services, business, and even politics.

This shift in attitude is causing profound institutional change. Undergraduate science departments are discarding their lectures (p. 856), redrafting the curricula to appeal to more students (p. 858), and using new technologies and hands-on research to keep students engaged (p. 870). Graduate schools are even beginning to question whether they produce too many Ph.D.s, and some are voluntarily practicing "birth control" to limit their scientific progeny (p. 849). Others are trying to broaden the way they train students so they'll have skills that are useful in industry as well (p. 865). "Producing faculty is not the only goal," says National Science Foundation (NSF) director Neal Lane. "We need to prepare more young people in science for a wider range of careers."

Lane is only one of several powerful figures lending their voices to the cause of reform. This spring Senator Barbara Mikulski (D–MD)—whose fingers are on the purse strings of several science agencies—told *Science* (8 April, p. 192): "The men and women coming into science, many of whom are first-generation college graduates, are really scared. The word on the street is, 'Don't major in these fields.' And unless we really begin to give them specific guidance, there is going to be a major pullback."

And it's not just rhetoric. NSF is encouraging universities to rethink the way undergraduate calculus and chemistry are taught by offering large grants for comprehensive reform. The National Research Council of the National Academy of Sciences is engaged in a grassroots re-evaluation of "the changing environment for the physical and mathematical sciences." Major philanthropic organizations, such as the Howard Hughes Medical Institute, are awarding millions to universities to systematically change the way they teach biology and related fields. Many scientific societies, including the American Physical Society and the American Chemical Society, are holding discussions about curricula reform at their annual meetings, and some, such as the American Geophysical Union, report packed audiences for workshops on sharpening teaching skills. In the pages that follow, we present the results of our reporting, divided into three sections:

- Generic problems facing undergraduate and graduate education;
- Innovative programs aimed at restructuring the traditional curricula, as well as what individual teachers are doing to improve their courses; and
- Promising experiments with new teaching methods tailored to this brave new world of science education.

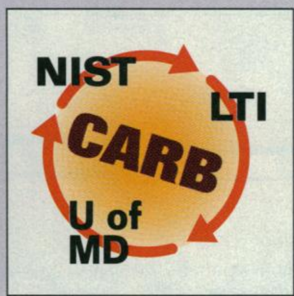
Each section outlines both the problems and challenges facing educators all across America, as well as some potential solutions. Because we will be revisiting this important topic next year—covering disciplines neglected this year as well as concerns outside the United States—we encourage you to write us with suggestions. (See page 873 for a response form and e-mail, fax, and postal addresses.)

Innovations

Overheads and lecturing are out; mentoring and interaction are in

Curricula are broadening; disciplinary walls are tumbling

Field work and real-world problems are capturing hearts and minds



A plethora of problems

But first, here's a lightning tour of the major conundrums facing the scientific community:

Underprepared undergrads. The best students are still as good as ever, but the diversity of those studying science has increased, and their level of preparation varies wildly. Even at top science schools such as MIT and Caltech, faculty members can easily point to undergrads lacking such basic knowledge as the fact that white light is a composite of different colors (p. 846). But good grades are no guarantee that students can apply what they've learned. A quiz by David Hestenes of Arizona State University that tests basic understanding of Newton's laws of mechanics suggests a startling ignorance of seemingly simple questions—even after a year of physics (p. 890).

Teaching troubles. The old ways of teaching science don't work for the MTV generation. Faculty are beginning to realize that lecture courses and cookbook-style labs—still the predominant model at most universities—do not nurture the critical thinking skills students need. "I used to teach introductory biochemistry, 300 students at a whack," says Russell Doolittle, a protein biochemist at the University of California, San Diego. "I think it's absurd—nothing is being learned." Coursework that emphasizes equations over real-world problems, combined with a lack of early hands-on experience in the lab or field, can bore students to tears and send up to half running to the registrar's office for drop-add forms.

Faculty at the graduate level may not be doing much better. Something is seriously wrong when at least 40% of all graduate students drop out before they earn their Ph.D.s in science, says economist William G. Bowen, president of the Andrew W. Mellon Foundation, former president of Princeton University, and co-author of the landmark book, *In Pursuit of the Ph.D.* In a study drawing on data from 36,000 graduate students at 10 major universities, Bowen and Harvard University president Neil Rudenstine found rising attrition rates at all levels of graduate study. Within that group, smaller graduate programs had the best track record for producing Ph.D.s (p. 850). "Many of these students are disappearing into the night," Bowen says. No one knows why, but suspects include the narrow education graduate schools now offer—as well as fears that a Ph.D. may not lead to the job of their dreams.

Job-search blues. Log on to the Young Scientists' Network electronic mail bulletin board, and one message is obvious: It's a bad time to be a young scientist looking for work. Stories of applying for jobs in academia or industry against overwhelming odds are legion (p. 849). Job searches are taking longer, and the success rates for most fields are grim—particularly for Ph.D.s and even in many of the biological sciences, where pharmaceutical and biotechnology companies are anxiously awaiting the outcome of the current debate on health care reform. Many professors dismiss these complaints as the whinings of those who erroneously assumed they would be guaranteed lifetime research jobs. But not all scientists are so hardened.

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—David Goodstein

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Some feel their profession has failed to provide alternate career models or more realistic advice and training (including practical terminal master's programs) to young scientists.

In search of solutions

As faculty members see more and more of their best students struggling to find a niche, a growing number are beginning to re-examine all levels of the scientific educational enterprise. Some of the most notable changes emerging on campuses nationwide include:

■ **Creative curricula.** Teachers are throwing away their tired overheads and blurry slides and coming out from behind their lecture podiums to interact more with their students. At Occidental College, a small private school outside Los Angeles, biologists have ditched the department's introductory course. Instead, students are required to take six of nine fundamental courses that cover the same ground, but in more depth. The university also provides four vans for faculty to use to take students to the desert or the mountains, not to mention an 85-foot research vessel for ocean-based research.

Some faculty members are deploying new high-tech tools to reach their students, ranging from using computers to help them visualize the abstract laws of physics to performing chemistry experiments on their computer screens (p. 893). Others are redesigning their curricula. Says Washington University's Putnam: "Lab work gets you thinking like a scientist. You ask, 'How does this work? How did we find out what we know? How do we find out more?' "

Research also builds confidence, fosters relationships with faculty mentors, teaches teamwork, and encourages students to pursue graduate studies, according to a report from a faculty committee at Carnegie Mellon University in Pittsburgh. CMU's Undergraduate Research Initiative features undergraduates building mobile robots, sequencing genes in yeast, and developing new digital communications technology.

All these changes reflect a subtle but significant change in the goals of science education. "The old weed-them-out mentality is now passé in many places," says Elgin. "The idea is to educate more people in science and to accommodate different learning styles"—whether or not students decide to pursue careers in science. NSF's Lane agrees: "A degree in science really does prepare young people for a range of careers. Many professions are going to require a foundation in science and technology to be part of the future of this nation."

■ **Applied studies.** As more students move into the lab and field, they are clamoring to work on real-world problems. At the University of New Hampshire, undergraduates enrolled in ocean engineering work in teams to design a better lobster trap, which gives them experience in following a budget and adapting to engineering constraints (p. 889). At the University of Maryland, six graduate students are enrolled in a new Center for Advanced Research in Biotechnology and are performing basic research on problems of interest to the biotech and drug industries (p. 863). Says Bowen: "There is a pronounced movement from basic to more applied sciences." This trend even prevails in the lecture halls. "I use problems out of the current literature," says CMU chemist Rick McCullough. "I think students need to be dazzled by how research ties into the real world."

Such problems can't always be solved within the strictures of one discipline. "There's also a movement toward improving interdisciplinary research," says Lane, who was instrumental in starting a new interdisciplinary effort in nanotechnology at Rice University in Houston before he left to head NSF (p. 864). Other hot areas of interdisciplinary research that Lane identifies include programs that study global climate change, environmental problems (p. 863), advanced materials, biotechnology (p. 863), and electronic communications on the data superhighway.

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—Neal Lane

■ **Broader scope.** Faculty members are recognizing that many students are poorly served by a system that trains them for narrow, specialized disciplines. For the small number entering academia and industry research labs, specialized training in a subdiscipline is fine. But it is not appropriate for most students studying science at the undergraduate level and for many in graduate school. "We tell our students to have a Plan A and a Plan B," says Washington University's Elgin.

At her school, that means learning biology to prepare for a broader range of jobs. "We try to make sure they have lab skills so when they graduate they can work first as a lab tech or as a biologist with a second major in business, health economics, social welfare, psychology, or education," says Elgin. "And I hope some of them will become members of Congress."

■ **Academic birth control.** The same practical thinking is also beginning to infiltrate graduate programs. At the University of Pittsburgh, neuroscientist Michael Zigmond is teaching a "survival skills" course for graduate students and postdocs with practical information on how to apply for grants, look for jobs (including interviewing techniques and negotiating skills), write scientific papers, balance teaching and research, and handle ethical quandaries (p. 872). And at CMU, North Carolina State University, Stanford University, and MIT, business schools are offering scientists the chance to learn about the business and finance side of science (p. 865).

But all the practical courses in grantsmanship and job-search skills will not help every newly minted Ph.D. find a job. The best way to ensure that is to reduce supply, says Goodstein. An electronic-mail survey earlier this year of 50 physics departments found that about a dozen of the best departments were hoping to reduce by one quarter the number of graduate students they admitted this fall (p. 849). And graduate schools in many other disciplines of science and engineering are at least giving lip service to the idea of academic birth control. Goodstein and Bowen want to go even further, however: Shut down marginal doctoral programs, they say, despite the inevitable political and institutional opposition.

Whatever the outcome, there is a consensus that change is in the air, and that the system of educating scientists is going to look quite different in the 21st century. "We're in a period of dramatic retrenchment," says Bowen. "The question is whether it will be done wisely."

–Ann Gibbons