# New Modes for Making Scientists

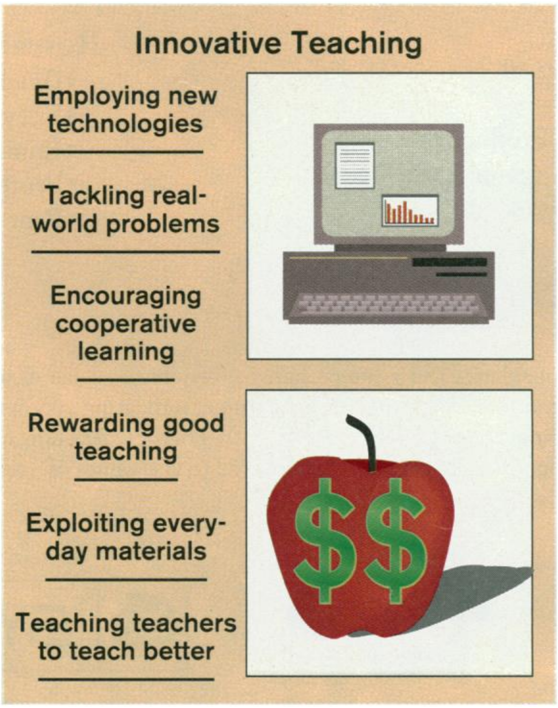
**Techniques, materials, and even the core philosophies of pedagogical engagement—all are in flux**

As a tentative prelaw student at Dickinson College in Carlisle, Pennsylvania, Jake Hopkins heard that introductory physics was a good way to satisfy the college's science requirement. He knew he'd have to compete for grades against science majors required to take the course, but he gambled on the favorable buzz and signed up. He guessed right.

On day one, Hopkins learned mechanics by throwing baseballs; later, he learned about electricity by building a stopwatch from wires and circuits, all in a most unusual atmosphere. "That class wasn't competitive like regular science classes," he recalls. "Students worked together, and you could figure things out, not just try to absorb them while they were thrown at you." The professor, Priscilla Laws, was rarely at the head of the class; she was more likely to be found helping teams of students decide which variables to graph next on their computers. Call it Laws' Law of Pedagogy: Don't lecture, coach.

Although she hasn't given a formal lecture in years, Laws' innovative technique in what she calls "Workshop Physics" has won a pile of prestigious awards. Students such as Hopkins—now a junior physics major—are one reason why. "Everything was hands-on," he points out, "and I really liked that approach, because I always understand something once I do it."

Workshop Physics is one example of a growing movement to improve not only what students learn in science class, but how they learn it. Aided by recent educational research, plus large grants from government and private foundations, science faculty around the country are running a rich mix of pedagogical experiments, especially in introductory classes. Professors are transforming lecture halls into learning crucibles, melting the barriers between lecture and lab, and letting students take the lead in shaping their education. Says noted science education analyst Sheila Tobias of the Research Corporation in Tucson, Arizona: "I've never seen such ferment, enthusiasm, and high-level respect for education."




## Acting the part

These educational efforts, although they cross disciplinary and course boundaries, are linked by common goals. First, students should learn the process, as well as the content, of science. So even freshmen are acting like scientists, working together on open-ended problems, planning and doing experiments, and reading scientific literature. Second, reformers link science to society, with classes often organized around real-world problems. Third, faculty members use strategies shown to promote active learning, such as grouping students into teams. Finally, these redesigned classrooms often employ a proliferating array of new technologies. All in all, the idea is to propel students into learning during class time, rather than in the library on the eve of the final exam.

For all their successes, reformers like Laws realize they have not yet carried the day. Most science departments offer a nontraditional course or two, usually for nonmajors, while the majority of science students scribble notes in lecture halls for 3 hours a week, then follow lab procedures many professors describe as cookbook. And although this generation of reformers documents its case with data on how well programs work, some faculty members and students still aren't convinced the new pedagogical techniques are worth the effort. "The total fraction of nontraditional instruction is still very small," says Bob Watson, director of the National Science Foundation's (NSF's) division of undergraduate education, which funds a diverse set of reform efforts. "We have a long way to go."

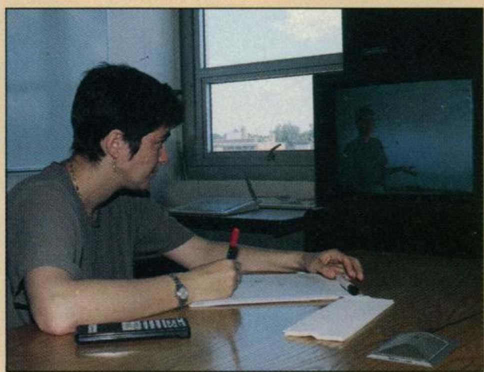
If "we" get there, it will largely be because of dissatisfaction with the results of traditional instruction. Many courses, especially at the introductory level, weren't doing justice either to the subject or the students, say educators like Laws. Lists of scientific facts failed to convey the nature of science. And many professors told *Science* they were dismayed by how little students actually understood, even after doing reasonably well in a course. Biochemist Harold White of the University of Delaware recalls a student who wrote a paper on the life and work of Linus Pauling, but couldn't present the structure of vitamin C. Physicist Jack M. Wilson, who directs the Center for Innovation in Undergraduate Education at Rensselaer Polytechnic Institute in Troy, New York, puts it bluntly: "We pretended to teach them, and they pretended to learn."

It wasn't always thus: 50 or 100 years ago, points out NSF's Watson, science majors represented "a very small number of very focused students." Those students possessed excellent math skills and scientific backgrounds, learned rapidly, and planned to become scientists themselves. No more. Today, even the brightest stu-

## Harvard Succeeds in the Teaching of Teachers

It's never easy watching oneself on videotape, but Harvard University physicist Melissa Franklin was especially nervous because she was about to witness what her students see. Worse, after 4 years in the classroom, she still rated her teaching abilities as merely "less than execrable"—so how would she look on tape?

The exercise was not as painful as Franklin imagined. Instead, she actually learned how to improve her teaching skills: Not only will she never again talk while erasing a blackboard (the students, she learned, need such moments to digest what they've been hearing), but she has cut down on those self-deprecating remarks offered to lighten the mood but which, instead, made her appear lacking in self-confidence. "Once you see it for yourself," she explains, "you don't need to be Piaget to figure out [its impact]."



LAURA WULF/HARVARD UNIV.

**Self-improvement.** Melissa Franklin watches herself in action.

The venue for Melissa Franklin's epiphany was a session at the Derek Bok Center for Teaching and Learning, founded in 1976 and one of the oldest of a handful of such university centers. The idea behind the program is that proven teaching ability is rarely a requirement for initial employment—indeed, it is too often lacking—despite the fact that graduate teaching assistants and junior faculty carry the bulk of the teaching load at most research universities. "The old approach was, 'Here's the textbook and good luck,' " says Daniel Goroff, a Bok Center associate director and a senior lecturer in Harvard's mathematics department. "Now we try to provide some real support."

Goroff has several weapons in his arsenal. The simplest are generic teaching tips like the one learned by Margot Seltzer, an assistant professor of computer science. Like most other teachers, Seltzer rarely endured more than a few seconds of silence after asking the class a question. Instead, she'd let the students off the hook by providing her own answer. Not long enough, Bok counselors told her. "Now I allow an uncomfortable, growing silence of 15 seconds or more, after which I tease and abuse the students into offering some kind of answer," she chuckles.

But the Bok Center also tackles more complex issues. Consider the experience of biologist Daniel Branton, who each year teaches a large lecture class. Ten years ago, Branton brought in a dozen teaching assistants who lacked confidence and the skills to lead the students through the problem-solving techniques Branton wanted to instill. The solution was "microteaching"—that is, having the assistants conduct a 10-minute slice of a lecture in front of the others and a camera. Each performance was critiqued by Branton and the assistants, guided by Bok Center counselors.

Branton was initially skeptical—"I believed some people are unchangeably terrible explainers," he recalls—but the experience has changed his opinion. "Getting people to focus on presentation instead of subject matter is extremely helpful," he says. "It gave my assistants experience and confidence." Even as a 20-year chalkboard veteran, Branton learned a few things: His posture was sloppy, and he waved his hands too much. Now he dutifully herds each year's new batch of assistants to the center.

Branton's not the only newly convinced shepherd. The word has spread to the point where many departments actively promote the center's services among faculty. The economics department has even made it a requirement for continued employment, providing faculty with an appropriately economic incentive. And the center also tries to meet the special needs of every discipline. Graduate students scheduled to teach calculus observe other teachers and teach two practice classes in front of Bok Center counselors before striking out on their own. And physics grad students, often required to teach from day one, get a crash course.

For all Harvard's enthusiasm with the program, however, the Bok Center scrupulously avoids sharing its files with anyone but the teacher. That means no input on tenure or other academic decisions. "We'll tell a department if the teacher was here, but not how they did," says Goroff. "We're not the teaching police. We're here to help."

**–David Freedman**

*David Freedman is a science writer in Brookline, Massachusetts.*

dents may be turned off by a focus on memorizing and abstract theories. And students now are much more diverse in their goals and backgrounds. At the Massachusetts Institute of Technology (MIT), for example, a changing student body prompted an experiment this fall in introductory physics, in which freshmen learn in small classes with less lecturing and more activities.

To accommodate student diversity, the new classrooms aim to nurture talents beyond memorization and good note-taking. So, be it at Dickinson or MIT—and whether the subject is physics, biology, or chemistry—more educators are adopting what is called discovery learning. Students make predictions, perform an investigation, and then analyze results. If this sounds a lot like research, there's a reason: The idea is to give students the flavor of the experimental process.

One example of this approach is the chemistry curriculum at the College of the Holy Cross in Worcester, Massachusetts, which is centered around lab investigations rather than the lecture. On the first day, freshman students explore whether pennies get heavier or lighter with age; that leads to experiments on the composition of pennies and the concept of density. Several semesters later, advanced students use the same discovery mode to explore the kinetics of reactions of cobalt compounds. "We wanted students to learn chemistry the way chemists actually do chemistry," says department chair Richard Herrick.

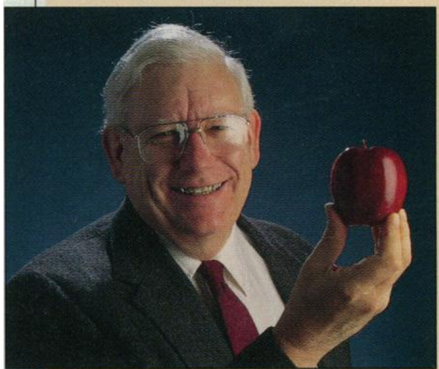
### Dipping into science

To engage those students who aren't inherently interested in abstract theories, many of these discovery courses are organized around real-world problems. For example, on the first day of introductory chem lab at the University of California, Berkeley, there's no one actually in the lab: Students have fanned out along the shores of a lake in a nearby park to see if the water is safe to drink. They plan their strategy, take samples, and test

## Rewards—at Last—for Top Teachers

Ohio State University plant biologist William A. Jensen was addressing his first class of the new term when a commotion broke out in the back of the lecture hall. To his amazement, Jensen spotted OSU's president, Gordon Gee, striding down the aisle ahead of various university and department officials, along with a camera crew. In his hand was the largest apple Jensen had ever seen—Gee's way of letting Jensen know he was one of eight faculty members chosen for excellence in teaching. "Let me tell you, I was pleased," says Jensen, the 2-year-old incident still fresh in his mind. It didn't hurt that the surprise "fruiting" was accompanied by a $1500 check and a $1200 raise.

Although most school administrators lack Gee's dramatic flair, the concept of rewarding good teaching is taking hold at universities across the United States. Science departments at small liberal arts colleges have long been known for their emphasis on classroom excellence, but university science departments have tended to hire and promote on the basis of research grants, publications, and scientific awards. Now, thanks in part to public displeasure with rising tuitions and falling test scores, that's starting to change—although whether the changes are dramatic enough remains open to question.



OSU PHOTO SERVICES

**Apple of his boss's eye.** William Jensen was honored by Ohio State president Gordon Gee—not for his grants, for teaching!

OSU's program, dating from the mid-1970s, was among the first. But many others have since joined the ranks of schools reordering their priorities. "We're paying a lot more attention to teaching when it comes to promotion and tenure decisions than we did a decade ago," says physicist June Matthews, undergraduate academic officer of the physics department at the Massachusetts Institute of Technology. The department also has started asking for three letters of recommendation addressing teaching ability, and student evaluations play a role in promotion decisions.

As with Ohio State, many schools are offering awards to drive home the notion that good teaching gets noticed. The University of California, Davis, pays $25,000 each year to a single professor with an outstanding teaching record. The Virginia Polytechnic Institute and State University gave out 35 teaching awards last year, valued at up to $20,000. Some went for individuals and others to departments to develop curricula. Individual winners are inducted into the school's "Academy of Teaching Excellence," and departments are marked by a special seal in college publications. For sheer generosity, though, it's hard to top the University of Florida. Last year, the school gave 165 faculty members raises of $5000 each in base salary because of their performance in the classroom.

Although nobody objects to such teaching-based promotions and awards, some professors think their colleagues need more than cash to refocus their attention on the classroom. Subhash Minocha, a plant biologist who has been teaching at the University of New Hampshire for 20 years, says teaching needs a higher profile; he suggests "teaching chairs," dissemination of articles on teaching styles, and greater representation of teaching-oriented faculty on long-term planning committees. "This shouldn't only be about money or plaques," he says. "What we really need is continuous talk about the importance of good teaching."

The message also needs to be brought home to university administrators focused too narrowly on the short-term payoff of research excellence, says William Spicer, a professor of applied physics and electrical engineering at Stanford University. "An appreciation of teaching has to be built into the culture of the place," he says. "You have to get the feeling that the administration really cares." A few more presidents toting apples couldn't hurt.

–David Freedman

for various compounds; the results are turned over to county officials. As in research, students learn by making mistakes. "They'll get all excited over a peak at sample site number 5, want to see their duplicate measurement, and then find out they forgot the duplicate. Next time they remember," says Susan Kegeley, who designed the course with associate professor Angelica Stacy.

Teamwork is another tactic that nudges students into active roles and also prepares them for jobs in the real world. Educators call it cooperative learning, and former NSF program officer Stanley Pine got a vivid view of its power during a site visit last year to an NSF-funded experiment in an introductory chem lab at Clemson University in South Carolina. Pine attended a traditional lab, then crossed the hall to a cooperative section of the same course and was shocked at the difference. In the traditional sections, he says, students "were so quiet, and the expressions on their faces were so dull; they just wanted to get done and get out of there." In the new class, "the kids were so excited about what they were doing; they were really communicating."

In the cooperative sections, student interaction and group output on both written and oral reports are so high that Chem 101 now meets the university definition of a "communications-intensive" course, says lab director Mèlanie Cooper. Educational studies have suggested that this approach also promotes gender equality, and Cooper found that to be true at Clemson. Only about 13% of the women dropped out of the cooperative sections, compared with 22% in the traditional sections. (For men, the rates were 8% and 9%, respectively.) Women in the new lab sections also performed better on the lecture exams.

Part of the impetus for cooperative learning comes from data showing that students who have just recently mastered a concept are sometimes better than a professor at explaining things to their peers (p. 890). Also, since a shrinking percentage of today's students will be remaining in academia and vying for faculty slots, there is less reason to rely on science classes to "weed out" the best and the brightest. Not only is experience in teamwork a valuable asset for grads seeking jobs in industry, it's also a crucial part of building a natural science community, says Jeanne Narum, director of Project Kaleidoscope, based at the Independent Colleges Office in Washington, D.C. The project identifies and disseminates successful programs and, like many of the new educational efforts, is funded by diverse sources, including NSF, the Department of Education, and several private foundations.

Narum's point is exemplified by the introductory physics course at the University of Delaware, where 180 students work in teams of four or five—and are graded as a group. "When you observe them, you find that they aren't talking about Saturday night's date," says professor David Onn. "They're actually talking about the problem, talking physics." Reports Tobias, who visited the class during a noisy group quiz, "The intensity of the conversations was absolutely thrilling."

The fourth major shift in pedagogical approach is technological, although not always in the gee-whiz vein. At Clemson, students used low-tech equipment, an economic necessity in some cases and part of a growing trend in chemistry (p. 889). But at other institutions the sky is the limit, with students using computers to run experimental simulations, communicate by e-mail, organize their courses, graph data, write reports, and lots more (pp. 869 and 893).

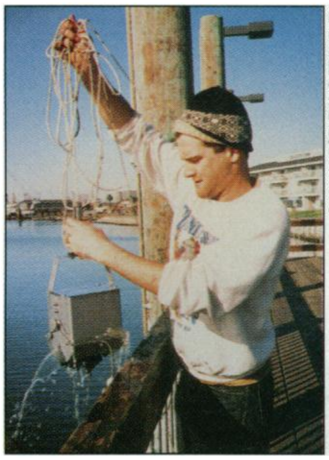
One common approach literally gives students a new perspective: the use of 3D visualizations in biology and chemistry to help students see the structure of cells, proteins, and other molecules. "The hardest topics for me to get across are the things that I can see in my head that the students don't have a clue about," says chemist Nathan Lewis of the California Institute of Technology. "We want to put those things on screen for them." Such efforts run the gamut from low-budget programs that run on basic Macintosh computers to efforts like Lewis's, which involves a team of student animators led by a Hollywood special effects producer. The 10-minute videos show complex processes in 3D; at the end of the $2-million project, you'll be able to watch atomic orbitals dance with *Jurassic Park*–style special effects.

### Satisfying the customers

What do the students say about all this upheaval? According to course evaluations and interviews, most of them like it—although perhaps not at first. "The initial response is very negative," says Delaware's Onn. "Then, except for a core of about 20%, they all come to realize that they're learning at least as well as before and usually better."

Why would students balk at pedagogical reform that brings vivacity to the classroom? Students, educators explain, are likely to be wary of any change in the tacit contract between themselves and faculty. The new rules give them more responsibilities, and the demands of group projects make it more difficult to skip class.

Still, the majority of students respond to the new classrooms the way Hopkins did: They like it. In Berkeley's environmental chemistry laboratory, students "pour time into the lab—I think they shortchange the lecture," says chemist Stacy. Last spring, 83% of the students said they learned more than their classmates in traditional chem labs. At Rensselaer, 93% of students said they would highlight the problem-based calculus class as a positive reason for attending Rensselaer; only 63% of those in traditional classes made that statement, says Wilson. Students are also voting with their feet: Many faculty members using the new approaches report higher attendance rates, often above 90%.



SUSAN KEGELEY/UC BERKELEY

**Hands-on chemistry.** Berkeley freshman takes water samples from the shore.

Of course, the final decision on how to structure classes rests with faculty, not with students. And most science professors aren't ready to toss out their lecture notes yet. Discoveries and problem-solving are fine, they say, but not for every class. Biologists, facing an explosion of both knowledge and students, seem particularly concerned.

"You run into what I call 'the bit-rate problem,' " says professor Sarah Elgin of Washington University in St. Louis, who is redesigning the undergraduate biology curriculum with help from the Howard Hughes Medical Institute (HHMI) and other granting agencies. "In the discovery method, the amount of information you can transfer per hour spent with the students is low. These students still have to pass the standardized admissions test for medical school. There is no more efficient, up-to-date means of information transfer than a good lecture." Biologist Yolanda Cruz of Oberlin College in Ohio agrees. "You can't get away from memorization in biology," she says. "They just have to know some vocabulary."

Still, most faculty members see some value in the new techniques. At Oberlin, chemistry department chair Robert Thompson is sold on cooperative and problem-based learning and is convinced his students are learning more. Biochemist White of Delaware thinks that lectures have their place, but that active learning is also essential. "What are we trying to teach students anyway?" he asks. "Knowing how to think and deal with problems is much more important than covering everything."

### Implementing reform

Even for those faculty members who are ready, change takes time. "It really is easier just to put on a good show, to organize the material and do nice demonstrations," says Berkeley's Stacy. The pressure is acute at large research universities, where faculty members are typically working on their next grant proposal as well as operating a lab and teaching undergraduates. Stacy says she manages thanks to an extremely qualified teaching staff, including Kegeley. "We have no time for this kind of development," says Stacy. "We literally get zero credit for this. And you can't be topnotch in research if you spend half your time or more in courses."

A number of schools are seeking new ways to reward faculty for outstanding teaching, such as weighing student evaluations in promotion and tenure decisions, as done at MIT (p. 883). And NSF and HHMI officials say they hope the lure of megagrants—up to $5 million in NSF's chemistry program—will help. Indeed, says Pine, two thirds of the planning awards for those grants went to research universities—and one of the requirements is to show how teaching is rewarded on campus.

However, not all the disciplines are moving at the same rate. In undergraduate education, as in precollege teaching, the mathematicians have taken the early lead. "My observation was that the two areas where communities were most active and most ready to do things were mathematics and engineering," says NSF's Watson. So NSF launched specific curricular programs in those areas in the late 1980s. Last year the chemistry project was started in response to a growing clamor for change and because almost every science major takes chemistry.

And what of the biologists? "They're coming," says Narum firmly. Many biology departments are redoing their curricula (p. 856) and have embraced educational technologies (p. 888). But the biological community is less organized in its educational goals than is the mathematics or chemistry community, admits Narum, in

RENSSELAER POLYTECHNIC INSTITUTE

**"We pretended to teach them, and they pretended to learn."**

**—Jack Wilson**

part because of the difficulty in achieving consensus across its many fields.

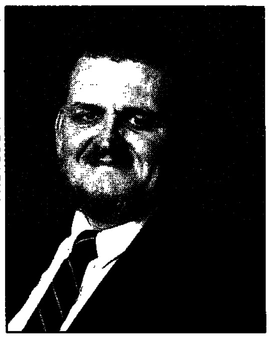
Meanwhile, although the reformers are generally headed in the same direction, they don't always agree on a particular strategy. For example, there's a controversy brewing over whether computers can replace lab courses. "On a computer you can do multiple runs, it always works, and no glassware is ever broken," says biologist Charles Ralph of Colorado State University, who taught freshman biology labs on computers for half a dozen years. On the other hand, chemist and NSF officer Pine thinks there's no substitute for getting your hands wet.

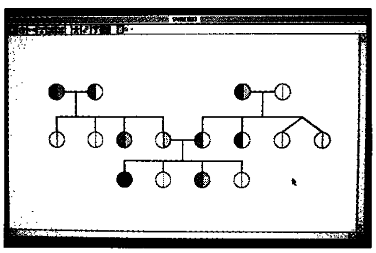
However that dispute is resolved, reform efforts appear to be picking up steam. At Rensselaer, where the reform spirit has penetrated almost every department, science faculty members generally find they like the change, says Wilson. "I'm learning a lot more," says biochemist White. "I'm not using the same overheads I did 4 years ago. The students are asking me new and unexpected questions. It's exciting, dynamic." If that feeling spreads, undergraduate science classes may never be the same.

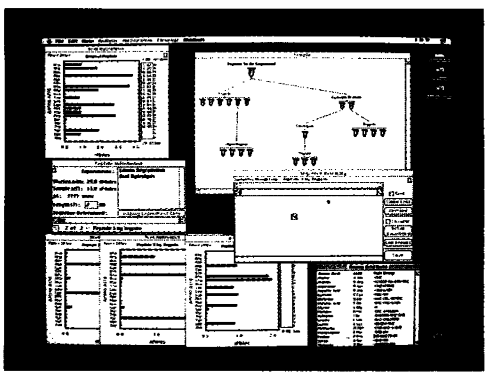
**–Elizabeth Culotta**

## John Jungck: Godfather of Virtual Bio and Genetics Labs

PHOTOS BY BELOIT COLLEGE







**Genetic diversity.** John Jungck's *(top)* growing BioQUEST computer library includes software to carry out clinical genetics case studies *(middle)* and to simulate a protein sequencing lab *(bottom)*.

Ethel Stanley, a biologist at Illinois's Millikin University, thinks something "neat" happens when she uses BioQUEST in her classroom. "Not only is the computer room busy," she marvels, "but the lounge is full of students who are actually talking about genetics." BioQUEST—a virtual lab—disproves a notion students acquire in school, Stanley says, that the lab is "a sterile place where nothing unexpected happens. Now they see it's a place where you make discoveries."

Stanley's fervent praise is not for a single commercial software package but rather a collection of 17 biology and genetics simulation programs that John Jungck, a molecular evolutionist at Beloit (Wisconsin) College, has godfathered into existence over the past 8 years. Most of the programs, such as the "Genetics Construction Kit" and "Sequence It!," mimic the long-term strategies used in the lab. Others include a heart simulation program, an environmental decision-making model, and a program to teach statistics to biologists. The idea, according to Jungck, is to give undergraduate students the experience of research—from setting up experiments to presenting a paper—without having to build additional facilities meant for undergraduates. "A lot of science teaching is poor because it doesn't let students play at the game of science," says William Sofer, a molecular geneticist at Rutgers University who uses several BioQUEST programs with his students. "This gives students a feel for the fun of research."

Jungck designed the genetics kit, his first simulated computer lab, on an Apple II. A few years later, Jungck met Nils Peterson, a Washington State University hacker who shared Jungck's goal of giving students science experience via computer simulations. With money from the Department of Education's Fund for Improvement of Post-Secondary Education (FIPSE), Peterson was then creating a computer model of the inner workings of the heart. In 1986 the two men joined forces—and simulations—and founded the BioQUEST consortium. The acronym stands for "Quality Undergraduate Educational Simulations and Tools in Biology." Jungck and Peterson next recruited 12 academicians—biologists, mathematicians, computer scientists, and educators—to develop more programs and landed a 3-year, $360,000 grant from the Annenberg Fund of the Corporation for Public Broadcasting.

Last year, after several large-scale field tests, the first edition of the BioQUEST library (including 14 different lab courses) was released on CD-ROM. It has proved a tremendous hit with professors in undergraduate—and even graduate—biology and molecular biology courses across the country, from the Massachusetts Institute of Technology (MIT) to the University of Oregon. The level of sophistication ranges from graduate level to junior high school.

The key to the software is what Jungck calls the three Ps: problem posing, problem solving, and persuasion. In the genetics kit, for example, students are given a number of "field-collected" organisms with the genetic traits of *Drosophila*. Students then mate the fruit flies and from these crosses try to explain the inheritance patterns (and thus, the genes) that they see. Students must convince their teacher and classmates that their solution is a reasonable one.

"The question students ask me the most is, 'When am I done?' " says Jungck. "And, of course, nothing is ever really finished in science. But scientists—and the students—do reach a kind of closure when they are ready to communicate their results."

Yet for all the excitement the simulated lab can generate in a classroom, Jungck warns that it was not designed to replace the real lab. "I know that there are schools that want to use it that way, that see it as a means of cutting costs; but it will never replace a wet lab," he says. "Nor will it ever replace the teacher, although it does change the way students and teachers interact."

Professors using BioQUEST agree on both points. "If you only used these programs, it'd be like looking at drawings of organisms and never looking under the microscope," says Vernon Ingram, a molecular biologist at MIT. "But what the programs are good at is teaching students how to design hypotheses and set up experiments."

The BioQUEST consortium now has more than 30 people developing programs for it and recently received a 2-year, $400,000 NSF grant. "We expect to have 13 more programs ready by the end of this summer," says Jungck. "And while those writing the programs don't get financial remuneration, they do get a lot of satisfaction from serving science and the educational community."

**–Virginia Morell**

For more information on BioQUEST, contact: John R. Jungck, Biology Dept., Beloit College, Beloit, WI 53511; 608-362-1570.