Teaching Young Biologists New Tricks

Long the science where math mattered less, biology increasingly demands powerful quantitative skills. Teaching students the math they'll need, though, is more than just 1+1=2.

by Marc Wortman
illustration by Luke Best

On the first day of a year-long introductory chemistry course at Atlanta's Emory University, students walked in to find three large round tables surrounded by white boards, no lectern, and a professor who didn't stand still. Their instructor, Tracy Morkin, really baffled them. She projected some charts with numbers on the wall and told the students they would be teaching *one another* chemistry.

"They didn't know what they were getting into when they arrived last fall," Morkin recalls with a smile on an early February morning. She bounds around the room, stopping occasionally to check in with students and their tablemates as they study data sets on the freezing and boiling points of solutions with differing concentrations and under different pressures. They need to figure out, from the data she gave them, which formulas can be used to come up with the numbers. "It's an inversion of the typical way of doing things," says Morkin. The room buzzes as they puzzle through the problem. Finally, she asks a student to step up to a whiteboard. With Morkin's coaching and input from other students, he lays out the equations from which the freezing and boiling points had been derived.

Such nontraditional, active-learning approaches to introductory science and math courses are being tried at other colleges as well, among them North Carolina State University and the Massachusetts Institute of Technology. Morkin's students are delighted to be the first at their school to experience the alternative to a standard lecture-style course. Sitting in a lounge after class, freshman Amol Koldhekar says, "If you talk to people taking the regular chemistry class, they get the right answers, but they don't understand it. They plug 'n chug," putting numbers into memorized equations without knowing where those equations come from.

Fellow freshman Remy Weinberger agrees. "In this class," he says, "you have to understand the theory behind the formulas so you can derive them yourself and know how to use them."

Like most of their classmates, they want to attend medical school or pursue a career in another health care or biomedical science field. Morkin designed her chemistry course to give them a running start in acquiring the quantitative, problem-solving, and interdisciplinary scientific skills they will need.

Recent reports showing an ever-increasing need for biomedical scientists with stronger math skills and a yawning gap between the need and the preparation being offered. So, Emory and a growing number of other academic institutions are experimenting, even at the precollege level, with new ways to integrate quantitative reasoning into the traditional biological sciences curriculum.

Putting more mathematics into biology and related courses, though, is not a simple matter of adding statistics, calculus, and computer science to already challenging subjects. It requires changing minds about the importance of such skills in a field that historically shortchanged them and revamping longstanding attitudes about how to educate future biomedical scientists.

The Rules Have Changed

MANY TEACHERS AND STUDENTS QUESTION THE NEED FOR change. "There's an uphill battle," attests Emory neuroscientist Ronald Calabrese. "I've heard faculty members at department meetings say, 'Why do premed students need differential calculus? They're going to *medical* school!'"

His colleague Dieter Jaeger notes that resistance among students is also a factor. "You have to convince them," he says, "that it's more than just making biology harder."

In fact, even though some students might never need to derive an equation in their biomedical careers, studying math contributes significantly to those careers. A recent study of 8,500 students at 77 U.S. colleges and universities showed that the stronger a student's high school preparation in math, the better he or she is likely to do not only in chemistry and physics but also in biology. Writing in *Science* last July, the study's authors—Philip M. Sadler, director of science education at the Harvard-Smithsonian Center for Astrophysics, and Robert H. Tai, a professor of science education at the University of Virginia—described "more advanced study of mathematics in high school" as one of the "pillars supporting college science."

Perhaps the most important factor driving the increased emphasis on quantitative skills is the changing nature of biology. From discoveries about neural networks, genetics, and cardiac blood flow to understanding disease pathways within cells and throughout entire populations, many of the most important advances in the field now rely on mathematical modeling, quantitative analysis, and bioinformatics (see sidebar).

"I wasn't good at math in high school," admits biology professor Karl Joplin, and that influenced his choice of career. "I thought biology was a field with no math. But boy, was I wrong." Accepting that the rules have changed, he now leads efforts at East Tennessee State University, in Johnson City, and a consortium of other universities to promote more quantitative education in biology.

Fernán Jaramillo, a neuroscientist at Carleton College in Northfield, Minnesota, agrees that "the nature of the problems we study has changed in the past 20 to 25 years. Quantitative issues are much more central, and that is an accelerating trend. Students have to realize they won't do well without some quantitative competencies." Jaramillo directs the Interdisciplinary Science and Math Initiative, an HHMI-funded multidepartmental effort to bring more quantitative and interdisciplinary approaches to science courses at his school.

Building Solid Foundations

RECENT SURVEYS HAVE SHOWN THAT AMERICAN COLLEGE students tend to perform poorly in tests of quantitative skills compared with students in other countries. "The rest of the world is catching up, and by some measures has already overtaken us," according to a 2006 report from a federal Commission on the Future of Higher Education. The problems persist among some with advanced degrees as well. A study published September 5, 2007, in the *Journal of the American Medical Association* found that 75 percent of U.S. physicians-in-training surveyed did not understand the statistics they encountered in medical literature, thereby calling into question their ability to interpret important clinical research data.

Advocates for science education reform at several national organizations, including HHMI, have been urging educational institutions to rethink how they prepare their students in the biomedical sciences. A National Research Council (NRC) committee commissioned by HHMI and the National Institutes of Health to investigate education in the biological sciences issued an influential 2003 report, called *Bio2010: Transforming Undergraduate Education for Future Research Biologists*. It outlines a strategy to improve the quantitative skills and math, chemistry, and physics comprehension of students preparing for biomedical careers. The report encourages faculty to implement teaching strategies that promote the skills required for problem solving in an increasingly interdisciplinary world.

"Biologists of the future are going to need additional skills, more quantitative reasoning being chief among them," says Adam P. Fagen, a program officer at the NRC's Board on Life Sciences. "Bioinformatics, for one, didn't even exist until a few years ago. Now it's a field in itself and essential to more and more people across the life sciences."

"All of us are driven by *Bio2010*," says Joplin. But even before the appearance of the report, HHMI—in conjunction with other supporters of science education reform—invested heavily in helping schools design and implement innovative strategies to bring more math into biology classrooms at all levels.

For example, with HHMI support Joplin helped develop a three-semester introductory biology course at East Tennessee

East Tennesee State University's Karl Joplin pulled together 30 academic institutions to revamp how biology majors are taught quantitative reasoning skills.

Fresh Air Photo

As a science education leader at Emory University, Patricia Marsteller encourages faculty members to cross departmental boundaries to make math come alive for students in the sciences.

State that integrates calculus, statistics, modeling, and other mathematical skills into the traditional curriculum. He also initiated an HHMI-sponsored consortium of 30 academic institutions working to develop strategies and materials for teaching students quantitative methods. (That group will hold its second annual summer workshop at HHMI's headquarters in July.) "We're trying to generate the resources to teach this type of material," says Joplin. "It's so brand-new."

Those working to develop new approaches and teaching materials find themselves facing many other hurdles, including the legacy of mathematical concepts being taught without showing how they apply to biology. "The textbooks haven't changed," Joplin observes. "There's lots of quantitative information, but no connection between the different subjects. It's not conceptual." So he has been developing mathematics-teaching modules based on biological examples. "We want students to look at a data set and not see a blank wall. Instead, they should be able to describe the data and see something interesting in them." However, just coming up with data sets to teach quantitative reasoning skills for biologists requires starting virtually from scratch.

Claudia Neuhauser, an HHMI professor and applied mathematician at the University of Minnesota, is a pioneer in teaching biology undergraduates the calculus and other math they will need (see Perspectives and Opinions, "Making Math Relevant"). "There's a problem with the way we teach," she says. "Teaching is being done in silos"—within traditional departmental boundaries—"but now we're asking faculty and students to do work outside those silos, and it's a challenge."

Building Bridges

PATRICIA MARSTELLER CALLS HERSELF EMORY'S "DIRECTOR of subversive studies" because of her work to build bridges between traditionally distinct departments, courses, and laboratories. That's one of her charges as director of the university's Center for Science Education.

To push faculty members to rethink how and what they teach and get them to reach beyond their traditional disciplinary boundaries takes provocation and rewards, according to Marsteller. "It's difficult," she says, "because it requires collaboration and cooperation between departments that don't work in the same way and don't think in the same way about education. Faculty are torn by their disciplinary loyalties, and of course it's always hard to teach old dogs new tricks."

When *Bio2010* appeared, she saw it as an opportunity to spark interdisciplinary conversations, if not out-and-out insurrection. She sent copies to every faculty member of Emory's biology department and to many in the chemistry, physics, and mathematics and computer science departments. Soon discussions began and an interdepartmental working group on science education started meeting regularly.

Other efforts were already under way to bolster math preparation at the undergraduate level, including a two-semester calculus course, now a requirement for all biology majors. Mathematics professor Dwight Duffus, who created the course a decade ago, covers differential equations, probability and statistics, and modeling by using a range of biological topics—such as predator–prey systems, movement of species across regions, the spread of disease, and the firing of muscle neurons—to make the math immediately relevant.

Duffus is still learning how to teach math for biology students. "The problem that I have, as a mathematician," he says, "is understanding the math and computing skills and knowledge biologists need in their majors. Should they be able to construct a mathematical model on their own or just be familiar with the main concepts? You have to be aware of the diverse math backgrounds and aptitudes of students."

Vaidy Sunderam, who chairs the department of mathematics and computer science at Emory, believes that more interdepartmental dialogue is needed. "There's still this gap," he says. "Mathematicians talk of matrices and equations, and biologists talk about structure and function."

However, Sunderam and chemistry department chair David Lynn come together regularly as codirectors of the university's Computational and Life Sciences Initiative, launched two years

Gregory Miller

ZEROING IN ON CANCER GENES

What do math and cancer research have in common? A lot, according to Bert Vogelstein. An HHMI investigator at Johns Hopkins University School of Medicine, Vogelstein searches the human genome for genetic mutations that cause cancer. "There are about 20,000 genes, and each gene has on average 2,000 DNA bases," he says. "That's about 40 million bases we have to look at" in each tumor cell, and "billions if we're looking at a bunch of tumors." With all that data, "mathematical analysis is essential," he says. Vogelstein says finding cancer-causing mutations among all these bases is especially tough because a mutation doesn't necessarily mean cancer. "Genes are mutating all the time in both normal cells and cancer cells," he says. Furthermore, the mutations that play a causal role in cancer aren't always the same; most show up in only a small fraction of tumors. The only effective way to identify them, he says, is to use computational tools from the field of bioinformatics. Vogelstein, who majored in math as an undergraduate at the University of Pennsylvania, calls bioinformatics a way to "distill the wheat from the chaff." He says the first step is to run computer simulations on DNA sequences from the Human Genome Project to get a sense of how often individual mutations happen due simply to chance. Then, he uses algorithms to compare those mock mutation frequencies with real data from cancer cells. Cancer cells will, on average, have more of some types of mutations than the random baseline created by the simulation, says Vogelstein, and the algorithms flag those mutations. However, not all of them are worthy of further study; some are just "passengers—along for the ride but not actually driving the cancer." Using researchers' knowledge of gene function, computers prioritize each mutation based on its precise characteristics and the gene in which it occurs. "At the end you end up with a relatively small list of genes" that are worth examining further in laboratory studies, says Vogelstein. Those studies, which "knock out" genes of interest from cancer cells or the genomes of mice, require huge effort and time. "Before you invest any time in those detailed studies, you need some sort of overall picture," he says. "The only way to do that right now is to use bioinformatic tools." —*Benjamin Lester*

ago to foster interdisciplinary scholarship. They have begun hiring faculty and bringing in graduate students who pursue interdepartmental research in emerging areas that require powerful bioinformatics and other quantitative capabilities. Lynn, an HHMI professor, has also tapped this workforce as a source of teaching skills geared to the new emphasis in biology. For example, he developed a freshman course in which graduate students from a variety of disciplines teach about their research.

Emory's Computational and Life Sciences Initiative has quickly "captured the imagination of a broad spectrum of the community," says Lynn. "We don't want to weaken the departments, but we do want to catalyze new opportunities between them. That's where the future discoveries will emerge."

Active Learning

AT THE BEGINNING OF EMORY'S SCHOOL YEAR, THE STUDENTS taking introductory chemistry had a choice between a regular lecture format and Morkin's innovative version. Few had ever experienced such an interactive approach to learning, especially in a course considered so fundamental to their future, and "they had to be sold on it," she recalls.

She showed them studies done at North Carolina State University demonstrating that students who had taken this type of course—so-called "active learning" in a nontraditional classroom setting—earned better grades than their peers in traditional lecture classes. She told them they would need to learn to work together and "figure out the chemistry." Her enthusiasm—and the data—won them over.

Now, seven months later, the students talk back and forth across the tables. Papers rustle as they share notes and calculations. "If it gets too quiet," Morkin says, "they know I'm going to bother them. It's tough for me not to talk too much, but as long as they have each other, they don't need me."

Several students confirm what she says. Premed freshman Weinberger says, "It's nice to have your peers explain concepts to you. Their thinking is more similar to yours than the professor's is."

Adds classmate Ryan Makinson, who wants to attend graduate school in neuroscience: "I understand a theory better by explaining it to a classmate. It's pretty cool."

According to Lynn, the success of Morkin's experimental course is spurring the department to "completely change the way chemistry is taught" at Emory. At the department's urging, the university has begun restructuring its principal lecture hall into an "active-learning environment," while redesigning courses to fit it.

Marsteller, who helped the chemistry department launch Morkin's course with HHMI support for its development, thinks active learning is a useful tool for boosting math competence among science students. She hopes other Emory courses will adopt a similar active-learning approach. "We've been training a lot of scientists who don't understand the quantitative methods they are using," she says. "Students need to struggle with them. If they're just hearing the solution, all they do is write it down and forget it."

For students in Morkin's class and others like it around the country, the numbers have started to add up. They will know how to get the answers they need long after the course grades are in. ■