Engineering in K-12 Classrooms
A Revolution in Education

by Alan S. Brown

At Parkview Baptist High School in Baton Rouge, LA, Sheri Goings' algebra class prepares for a shootoff. Using shoe boxes, spoons, rubber bands, and paper, students have built catapults that hurl ping pong balls from 50 to 250 inches. Some work by twisting rubber bands, others by pulling. Some use cupped ball holders, others multiple spoons. Students have tested and calibrated each unit, graphed the results, and found algebraic equations to predict the trajectories.

At the shootoff, Goings gives them a target distance and 10 shots to reach it. Yet the winners are not immediately apparent. First, the class must debate how to score the contest. Should it give more points to individual "hits" or to greater consistency? The class is soon discussing the tradeoffs among average error, relative error, standard deviation, and tolerance.

"This was not an honors class," says Goings. "None of them thought he or she could do it, but they all proved very capable of coming up with unique designs. If I had tried to teach these concepts from a textbook, they wouldn't have absorbed what they meant."

Goings is not alone. At Hoover High School in Alabama, Mark Conner's students program a digital signal processor (DSP) to identify and add up the value of coins. "They can do that by looking at sizes and reflections," Conner explains, "but their systems are easily fooled by round blanks and surface brightness. Yet many students find a way around these problems."

In Malden, MA, Diane Perito's seventh-grade science class has discovered that animal waste from geese has caused a nearby pond to turn smelly and green. Most science classes would have stopped there; Perito's students sought a solution. When they learned that geese hated swans, they fitted two lifelike swan models onto remote-controlled boats. By the fifth day of testing, the geese fled across the pond as soon as the artificial swans appeared.

REAL ENGINEERING

Almost entirely below the radar, engineering—real, hands-on, project-based engineering—is breaking out all over America. This September, an astonishing 175,000 students in 1,306 schools in 43 states and the District of Columbia will take courses in the four-year engineering curriculum developed by Project Lead the Way (PLTW).

This is more than twice the number of schools teaching the curriculum a mere two years ago. "We've never implemented anything so deeply and so quickly," says Katherine Oliver, assistant state superintendent of education of Maryland, where 35 high schools and eight middle schools will embrace PLTW this year.

Other programs are popping up in elementary, middle, and high schools everywhere. This year, the Infinity Project will expand to 175 schools in 25 states, from 130 schools last year. Elementary and high-school courses developed by the Boston Museum of Science's National Center for Technological Literacy are widely taught in Massachusetts and at least five other states.

Unlike the past, when educators said *technology* and meant *computers*, these courses deliver a true engineering experience. They do not so much replace traditional math or science classes as give students a way to apply their knowledge to solve real problems.

Engineering education promises profound changes in the way students learn science. Instead of passively absorbing knowledge from textbooks and *packaged* laboratory experiments, students use scientific method—learn, hypothesize, test, and compare—to create something new. Because there is no one *right* answer, students expe-

Teachers are learning to use everyday objects and familiar situations to teach engineering principles.

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rience a creative freedom that is rare in any classroom.

"Engineering helps students to see a reason for what they're learning," says Gene Bottoms, who heads the Schools that Work program at the Southern Regional Education Board, the nation's largest school reform initiative. "It deepens their understanding of the academic concepts and increases retention. It shows them that mathematics and science matter."

BROADENING THE POOL

It may also broaden the pool of potential engineers. "For too long," Bottoms continues, "we've tried to fill our engineering schools from the top 20 percent of high-school students. With declining engineering enrollment and lack of enrollment in high school math and science courses, we're not producing the numbers."

Hands-on engineering education promises to turn that around. "Only about 20 percent of students can really learn from lecture-style teaching," says Richard Blais, executive director of Project Lead the Way. "A project/problem-based teaching approach accommodates a wider range of learning styles."

The passive use of packaged experiments is gone. The new curriculum challenges teachers as well as students because there is no single "right answer."

"I'm amazed at the kids who come through our courses," adds Hoover's Conner. "They're artists, musicians, and skateboarders. A lot of those kids have math ability, but nobody ever made it relevant before. If we don't give them a reason to learn something, they won't do the work."

Such relevant courses may also help reach two groups long under-represented in engineering—women and minorities. According to the American Society for Engineering Education, women make up 55 percent of all college undergraduates but only 20 percent of engineering majors. Blacks and Hispanics comprise 17.2% of all undergraduates, but only 9.9% of engineering students.

Goings has seen women's fears surface during her ping pong project. This year, one of her teams consisted of four girls. "They wanted to know, 'Why can't we have a guy on our team?' They didn't believe they could do it when they started, but they did by the end."

Tammy Richards, assistant dean of engineering at Southern Methodist University and executive director of the Infinity Project sees the same issues. "We have to show young women this is interesting and exciting," she explains.

Richards points to studies that show that women who become engineers most often start with a love of math. (Men enjoy both science and math.) "The key is to reach women through their high-school calculus teachers," she continues. Engineers also need to clear up the misperception that engineering is about widgets. "It's really about solving problems for people," she says. Women will thrive in creative, team-oriented project-based engineering classes, she adds.

WHAT ENGINEERS DO

In some ways, the hurdle for minority students is even higher, says Dr. John B. Slaughter *[Washington Beta '56]*, president of the National Action Council for Minorities in Engineering (NACME) and a former director of the National Science Foundation. "Only about four percent of minority students have taken the necessary math and science to take college engineering," he explains.

NACME is teaming with Project Lead the Way to develop hands-on courses for sixth graders in minority communities. By exposing them to hands-on science, Slaughter hopes to capture their interest. Yet he warns this will not happen automatically.

Minority students in poorer districts are more likely to have science and math teachers who did not major, minor, or receive certification in their subject, he says. Many go to poorer schools that cannot afford sophisticated equipment. Students do not live in communities where engineers live next door. "There's a greater need for a stronger safety net that informs and encourages them," says Slaughter.

Of course, minority students are not the only ones who know so little about engineers, says Christine Cunningham, vice president of research for the Museum of Science in Boston. "Kids typically think they're construction workers, auto mechanics, or computer technicians," she says. "Younger children think they drive trains."

WHY NOW?

K-12 engineering programs promise to change all that. Yet if they hold so much promise, why are they only now becoming part of the curriculum? "We've always seen cyclical spasms of activity that correspond with a crisis of confidence about America's place in the world," replies Eric Iversen, who manages the American Society for Engineering Education's outreach programs. "It was Sputnik in the 1960s, the energy crisis in the 1970s, and the increasing commoditization of knowledge work through information technology in the 1990s," he explains. "The information technology and Internet booms showed

where economic growth is coming from, yet standardized tests show U.S. students doing worse in math and science than their peers in other countries."

Policy makers have begun to address the undeniable need for engineers. One state, Massachusetts, has even set state standards for K-12 engineering education and now tests for it on statewide examinations.

Teachers initially resisted teaching those standards. "Their attitude was, 'we don't have time. Let the kids take their knocks,' " recalls Cunningham. Then Massachusetts issued tests in which engineering counted for 25 percent of the fifth- and eighth-grade science assessment. "Even if kids got everything else right, they could only get a 75 percent grade if they couldn't answer the technology questions," says Cunningham. "Parents went nuts, and now we can't meet school districts' needs fast enough."

Fortunately, Cunningham and other pioneers were ready with off-the-shelf engineering curricula. To people outside the K-12 community, it's often hard to appreciate how important that is.

A student proudly displays a ramp designed and fabricated as part of the new curriculum aimed at teaching engineering skills to students in elementary, middle, and high schools.

Most school districts lack the resources to write curriculum for a four-year sequence of courses similar to Project Lead the Way, says Blais. Most schools make do by paying teachers to modify existing courses over the summer. This makes it very difficult to introduce an entirely new subject like engineering, especially one based on projects rather than textbooks.

Blais' PLTW curriculum delivers everything needed to inject engineering into a school. Teachers receive two weeks of intensive training. They get lesson plans that reinforce state standards in math and science (and even English), as well as tests, grading guidelines, and workbooks. They can access a website with class materials, share ideas on a teacher listserver, and even watch online movies of master teachers delivering a lesson.

Such robust curricula do not come cheap. Blais estimates PLTW has spent $12 million developing its program. Cunningham says it takes 2,000 to 3,000 hours to develop eight hours of classroom curriculum. "When I tell people, they can't believe it," she says.

WATER FILTERS

One of the reasons it takes so much time is that Cunningham wants to make sure it is a curriculum teachers will actually use. So she began by asking school teachers and science coordinators how she should proceed. "The message we heard was that teachers wanted nothing new," she says. "They already have so much to teach, especially in elementary school where they teach six different subjects."

That meant building on existing science lessons. Starting with elementary school, Cunningham distilled the most popular hands-on science programs down to 20 common topics. She then paired an engineering project with each one.

One unit fused the water cycle with four lessons on environmental engineering. First, students read an illustrated story. Like other books in the series, it features a problem, a child (often a girl, a minority, or someone from another country), and a relative or neighbor who is an engineer.

In this story, Salila, a young girl from India, learns how her mother makes local water safe to drink. After reading the book, the teacher asks: Who are the engineers? What problem did they try to solve? What solutions did they find? "In some books, the solutions don't work the first time," says Cunningham.

The second lesson describes other tasks undertaken by environmental engineers. Students then collect pictures of these concerns and create collages of city sewers, lakes, air pollution, and soil.

Students begin to gather information about cleaning dirty water in the third lesson. They test each element of their dirty water—cornstarch, soil, and tea—on screens, cotton balls, sand, and gravel filters. In lesson four, they design and build a water filter out of a two-liter soda bottle. Using such metrics as water color (for purity) and cost, they assess their filters and redesign.

Such classes motivate teachers and students alike. "We had one girl whom the other kids called *the big oaf*," recalls Cunningham. "Three months after the class completed the unit, she came into class and said she had gotten the water perfectly clean. She had gone home and worked on it for three months. Now she's going to a gifted and talented program."

The teachers also like the program. "They don't see it as new; they see it as a way to get kids engaged," says Cunningham. "They're also surprised by how much they know about engineering. If the project is to build a 12-foot-long bridge, any teacher can tell you it will sag in the middle. A six-year-old doesn't know that. So the teacher asks, 'What can you do about that?' It's not something you need a bridge building course to know. It's common sense, and it helps them become more comfortable with the curriculum."

FILLING THE PIPELINE

If Cunningham wants to introduce every student to engineering, Project Lead the Way's Blais wants to increase the number and diversity of students ready to succeed in college engineering courses.

Preliminary data from Rochester Institute of Technology (RIT) suggests that PLTW is doing just that. Of the 112 PLTW students who entered RIT last year, 104 went into engineering or applied science. Only seven had dropped from those programs by the start of the spring quarter. "That's over 92 percent retention," says George Zion, who chairs the school's computer engineering technology program. "Our typical freshman retention rate is in the low seventies."

PLTW's rigor makes such achievement possible. It consists of three year-long foundation courses: introduction to engineering design; principles of engineering; and digital electronics. Students can also take specialized courses in computer integrated manufacturing, civil engineering and architecture, biotechnical engineering, and aerospace engineering.

In their capstone course, students team up on an independent project and defend their design before a panel of reviewers from college and industry. The results can be extraordinary, says Blais, who had to sign a nondisclosure agreement before he could review one school's PLTW projects.

Yet PLTW is not just for high fliers. It grew out of courses Blais pioneered in upstate New York. "Our valedictorians came from this curriculum seven years in a row, but we also had students who had to work very hard to prepare for two-year college," he says.

"Both types of students succeeded because the program answered the two questions kids always ask: 'Why do I need to know this?' and 'Where will I ever use it?' Once you answer those questions, students are empowered. They see the relevance and it motivates them."

COMMITMENT

PLTW demands similar motivation from its schools. They must agree to offer at least five PLTW courses and cover the entire curriculum of each course. They must administer PLTW's final exam and report the results. They must also promise to send teachers and guidance counselors for training.

"There have been turnkey programs in the past," says RIT's Zion, who also trains PLTW teachers. "The difference with PLTW is the schools' commitment to send teachers to training and keep them trained." His typical class includes math, science, shop, and technology teachers, as well as people who entered teaching as a second career.

Each two-week course is an intensive workshop in how to deliver a single year-long PLTW course. "Every summer, principals tell me they've never seen teachers so motivated to start the school year," Blais enthuses. "The harder we make it, the more they like it."

Schools do not pay to join PLTW, though training costs $2,000 to $3,000 per teacher. Yet the money needed to outfit a PLTW classroom is impressive. Assuming a school starts with computers, desks, chairs, and other infrastructure, Maryland's Oliver estimates that it costs an additional $63,000. This goes towards specialized PLTW equipment, which includes laser printers, stress analyzers, computerized machining systems, and other hardware and software.

Despite the commitment, though, PLTW has only had to disenroll 11 of its 1,300 schools in the past eight years.

INFINITY PROJECT

The Infinity Project, the nation's third major engineering curriculum, was developed by Southern Methodist University and Texas Instruments, Inc. "Their mindset was to show students something about engineering that would capture and keep their attention," says Hoover's Conner.

To do that, they focused their course on digital signal processors, which are used for digital audio and video, data compression, encryption, and networking. Students design the processor using software that lets them drag and drop mathematical functions into block-diagram programs.

At Hoover, Conner's single infinity course has blossomed into a four-year engineering academy. His planned curriculum includes an introduction that includes robotics, engineering drawing and instrumentation, engineering calculations, and a senior-level project.

Conner puts special emphasis on math-based physics: "Most students who drop out of engineering in college actually fail calculus and physics, so I structured the courses to help."

He is also seeking college credits for his offerings, so students taking his rigorous courses receive the same credit they would earn from advanced placement courses. Otherwise, he says, bright students might opt for AP classes because they look better on college transcripts.

TOWARD THE FUTURE

Seemingly overnight, K-12 engineering education has begun to spread throughout the country. Yet its very success raises issues. There are not enough qualified teachers, says Conner. "The three physics teachers in my high school have 35 years of experience among us; yet I don't think any of us has ever had a student teacher."

Any hands-on, no-one-right-answer engineering curriculum makes special demands on teachers. "You have to be comfortable with some level of chaos," explains Cunningham. "If everybody's building a different design, it's a lot different from a science experiment where everyone drops three beans into the container."

Moreover, teachers must find the time to prepare students for high-stakes standardized examinations in other subjects. "Really good open-ended projects are incredibly time-inefficient," says Cunningham. "Sometimes its hard to meet all the standards and still spend time on projects that really engage kids."

Yet Cunningham believes it is time well spent: "The creativity is incredible. Kids will sit there and redesign again and again. Every time they test it, they figure out what they couldn't prove before. The teacher doesn't have to make them do it. They want to do it."

Hands-on courses also promise to broaden the number and diversity of students ready to take up engineering in college. Almost every educator interviewed for this article said that the number of *average* kids who excelled in their classes surprised them. Hands-on projects engage many students that lectures leave behind.

Almost every teacher has a story to tell. Parkview Baptist's Goings, for example, was reluctant to offer engineering to non-honors students. So it was with a certain amount of trepidation that she allowed one of them to bring a video game that used digital color matching to track the position of a player in the game. "He came and spent 20 minutes reverse-engineering the game," she recalls. "He and another non-honors student were clearly the most imaginative and creative engineers in the class."

Yet neither student earned an *A* from Goings. "It made me crazy that I couldn't give them top grades, but I didn't want to give them false expectations about what college-level engineering classes are about."

Yet Goings and hundreds like her have ignited a spark in students who might have otherwise slept through their math and science classes. By awakening a thirst for invention in ordinary students, they have not only expanded the pool of potential engineers but have shown that so-called ordinary students have the potential to make extraordinary contributions. Perhaps one day, their students will take his or her place beside such distinguished engineers as race-car driver Henry Ford, farm mechanic Cyrus McCormick, and bicycle mechanics Orville and Wilbur Wright.

Perhaps an *average* student inspired by Going's catapults will one day build the spaceship that lets his or her friends fly to the moon the way we now fly to New York. As Maryland's Oliver notes about Project Lead the Way and similar engineering curricula, "You can become a rocket engineer with this program, but you don't necessarily have to be a rocket engineer to do it."

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