Chapter 7

Inventing Devices

Engineering Physics

Physics, a subject closely related to engineering, lends itself to designing and inventing devices. Students come to class with an intuitive understanding of many laws of physics, especially those that have to do with motion and other everyday human activities. High-tech areas of physics, such as radar, figure prominently in popular culture. Given a problem, students can envision physical devices to solve it. The challenge for teachers is to lead students toward understanding the concepts deeply enough to apply them in a problem situation.

Fog Navigation

Every winter in California's San Joaquin Valley, a thick Tule fog blankets the area. Every winter, automobile accidents rise dramatically. Drivers entering highways can't see whether the road is clear. Drivers making left turns can't determine whether there's traffic in the on-coming lane. Stopped at an intersection, a driver will often roll down the window to listen for an approaching vehicle, then gun the car forward, racing to beat a potential but invisible danger.

Louise Bennicoff, now an administrator for the Dinuba Public Schools in the San Joaquin Valley, was teaching at Corcoran High School when she received a $10,000 grant from the California Educational Initiatives Fund to finance a new physics program. She envisioned a two-year project, with the objective of having students learn physics concepts by inventing navigational devices for driving in the fog. At the time she made the grant application, she had a name for the project—Fogbusters—but no model. Seven days at the summer Engineering Concepts for High School Teachers workshop gave her the framework she needed. That September, her Fogbusters project began to manifest itself in the form of work styled on the engineering approach to problem solving. "A compelling need to know," says Bennicoff, "is what drove most of the Fogbusters teams. After all, students of all levels of ability pass their drivers' tests every year. They are eager to get behind the wheel and willing to do whatever it takes to get them there. Same thing for the Fogbusters project. Fog is a major problem faced by everyone in this community."

The first year of the project, the physics of color was a popular topic. "What color light is most visible in fog?" asked one team. "With human perception, what color headlight enables you to see farther in the fog?" asked another. One group noted that currently marketed foglights are yellow or orange and hypothesized that the high end of the spectrum would have the most visibility and be the most penetrating.

The teams made preliminary design sketches, researched existing technology, learned about patents, surveyed local drivers, refined their designs, and presented reports. Students used out-of-class time to scavenge some sophisticated equipment needed to evaluate their potential solutions. A radar system, discarded by the California Transportation Department, found its way into the physics lab. An ultrasonic range finder was donated by a local business. Teams experimented with equipment, created computer simulations, refined designs, and presented solutions for review.

The color investigators were surprised to find that the low end, rather than the high end, of the spectrum was more visible in their laboratory fog simulation (steam produced by ice cubes on a hot plate). In the first year of the Fogbuster project, those experimental results led to designs for blue or purple fog headlights. The second year, a different team extended the idea to invent stick-on, peel-off filters that could be placed over headlights during winter fog season and removed in the summer. Tapping the expertise of a local manufacturer that makes similar filters for welders' helmets, the team devised a set of seven filters that could be peeled off, one at a time, as they wore out.

Other Fogbuster projects were equally inventive. One team designed a system of diluted liquid CO_2 to be run through pipes attached to existing telephone poles; the liquid could be misted, they suggested, over high-density fog areas. Several teams experimented with radar devices to detect motor vehicles in fog. Student-designed experiments used simulation software to study ultrasound and infrared technologies. Investigations of the best shape for a fog light or the best height for a school-bus radar device led to improvements on available fog equipment.

Public presentations made "Fogbusters" a familiar name in the community. "I made their first presentation night a big public event," says Bennicoff. "I required each student to bring at least three people for the audience." The third-quarter poster project, which took place in a local pizza parlor owned by the father of one student, was also well attended by school, community, and family members.

For Corcoran High School students, patent work, an important part of engineering project work, is not just a trip to a nearby library to peruse patents on CD-ROM. The nearest depository library is located in Sunnyvale, three hours away. "The trip was worth it," says Bennicoff. She invited a patent attorney to visit the class. When one of her students exhibited the patent report written for his project, the attorney exclaimed, "I thought I was coming to talk to kids!" and went on to tell the student that his office would have billed $1,200 for the work reflected in the report. The young author of the report, now headed toward a career of intellectual property law, beamed.

In Bennicoff's first year, she had her students juggle project tasks and textbook physics. Project work took precedence, of course, and by the fourth quarter, the students had to focus on the areas of physics the project investigations had not touched. By then, says Bennicoff, they were so used to working independently and finding their way through matter they didn't understand, they literally taught one another the fundamentals of mechanics, thermodynamics, and motion. "After all the work they had done on the Fogbusters projects, they found textbook learning a snap!" she says. "I suspect they covered the material as well as if they had done all the regular lab work. They understand the basics and they certainly know how to do in-depth work."

Most of the students agreed that the Fogbusters project was both difficult and time-consuming. Most also said that the effort had paid off. "It made me feel like a real scientist," said one. "We had to figure it out for ourselves. The teacher didn't answer all the questions. We were doing something original. We—and our parents—were much more interested because it was a problem of local concern."

Bennicoff misses the classroom but is pleased with her legacy. Her replacement, Cheryl Hunt, had no choice but to continue engineering project work—the students demanded it! They were used to brainstorming ideas and discussing as team members the pros and cons of alternative solutions. They had become adept at laying out alternatives and specifications on a matrix. They wanted to continue to solve problems by building and testing something they themselves had designed.

Walking into the Corcoran High School physics lab at the end of the 1994-95 school year, a visitor might have seen clusters of animated students preparing decision matrices to redesign their third-quarter devices—projectile launchers—into bean-bag launchers that would accurately throw twenty bean bags in 60 seconds. The students would have been preparing for their final exam, a contest of bean-bag throwing. Every team wanted to win, of course, but the students also knew that winning or losing was less important than meeting the challenge of learning physics by applying theory to design something they cared about.

Figure 11. Corcoran students brainstorming

Since Fogbusters, Bennicoff has moved into administration. As an elementary principal, she saw that a simplified version of the Thayer School approach to problem solving might be applicable even to primary students. For example, she says, when first graders read "The Three Little Pigs," why not have them predict the success of straw, sticks, and bricks against such specifications for a house as "strong," "easy to build," and so forth?—a very early introduction to matrix decision making on a level appropriate to the decision makers.

Project Work on Ten Minutes a Day

In 1990, physics teachers Tony Komon and Joe Bena proposed a course in engineering physics for Niskayuna High School just outside Schenectady, New York. They wanted students to focus on the application of physical principles as much as on the theory. They envisioned students using some specially designed laboratory equipment to replicate physics and engineering experiments. The course was approved and ready to go. Then Komon attended the 1991 Thayer workshop.

"Cookbook lab experiments don't tax the mind," says Komon. "Using laboratory equipment to invent does." Accordingly, he has set his students to inventing. Komon segments the year with a number of problem statements for one- to five-week projects. For longer projects he expects students not only to design a device but also to build and test a working prototype. In one-week projects he looks for CAD diagrams and evidence of the problem-solving process. Because Komon has a rigid curriculum, which includes preparation for New York State Regents examinations, students spend only the first ten minutes of each class working on a part of the project; the rest of the work is done outside class. Komon frames the physics work with problem solving and still covers the required curriculum.

Komon often sets up a scenario for students. For one project, with an RFP calling for aids to the elderly, he asked them to think of the difficulties an older or disabled person might have accomplishing a simple chore. Focussing on the problems of elderly people with arthritis, one team of four young women conducted library and field research, getting to know both the facts of the disease and some people in the community dealing with its effects. After considering a number of problems drawn from conversations with their arthritic informants, they decided that opening a door was both common and crucial. The students studied doorknobs and examined each step of the opening process.

In their final report, they wrote about the way friction, force, and torque work in the turning of a doorknob. Their retrofitable EZ Door—a simple doorknob extender made of a rubber tube and a wood dowel—increased the knob's radius sufficiently to reduce the force required to open the door, thereby reducing pain in hands that need to open it.

The team's invention not only impressed five engineers from the General Electric Research and Development Center who sat on the project's review board, it also placed in that year's NYNEX competition, whose panel of judges included three Nobel Laureates.

Another year, when the topic was aiding the handicapped, a team designed an arm bike for paraplegics. Their ten-speed bike—an egg-shaped shell that ran on three wheels—was operated by handles similar to those on a rowing machine. The rider, in effect, "rows" down the street, alternating arm stroke and simultaneously exercising arms, shoulders, and back.

Komon's students, year after year, use ten minutes per class to invent creative solutions to common problems—a motorized window opener for elderly homeowners, a "foot-in-the-box" crutch for accident victims frustrated by the clumsiness of common crutches. Each year, as they move from project to project, students become increasingly adept at plotting specifications against ideas and making decisions based on what they know instead of what they think.

Komon sees growth also in the students' willingness to take on challenges. Some students who enroll in his engineering physics course as juniors return as seniors to his AP physics class where their risk-taking behavior stands out against the wariness of AP students who have not engaged in engineering problem solving. Early in the Spring 1995 semester, for example, Komon asked for volunteers to demonstrate the latest CBL (calculator-based laboratory) equipment at a conference of New York state supervisors of mathematics teachers. "Three hands shot up," said Komon, "and all from those had taken my engineering physics. While others were considering the extent of the project, these three were ready. They knew they could devise experiments on their own, and they weren't intimidated by the idea of presenting to fifty or sixty math supervisors."

Komon offers one warning to teachers embarking on engineering problem-solving projects. “Avoid being critical of the students’ ideas. When I first saw the sketch of the idea of the EZ door, I thought, ‘They’ve invented a doorknob.’” Fortunately, he didn’t say that to the team, and the project went on to its success. Afterward, the girls heard about those early misgivings. One commented, “And if you had seen the hula-hoop when it was invented, you would have thought, You’ve invented a circle.”

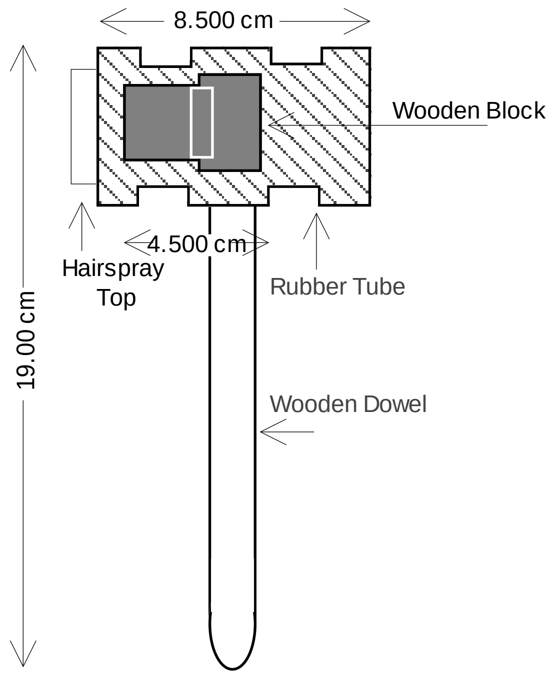
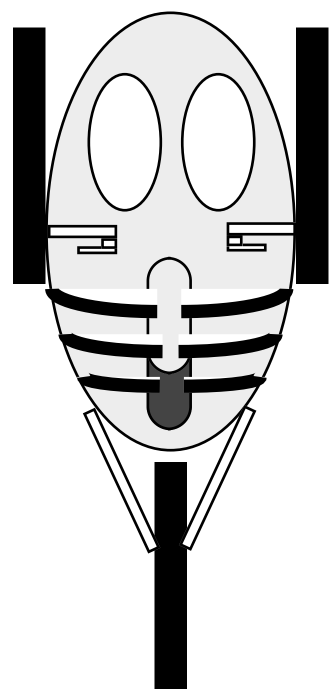


Figure 12. Student CADs: doorknob extender for arthritics and arm-bike for paraplegics



Mathematical Connections to the Business World

For mathematics teachers, engineering problem solving is an ideal vehicle for implementing the NCTM standards, especially the first four: mathematics as problem solving, mathematics as communication, mathematics as reasoning, and mathematical connections.

Traditional mathematics curriculum is sequential, with one course building specific skills prerequisite to another. Engineering projects, however, enhance any mathematics course by giving students opportunities in data analysis that allow them to see that mathematics is crucial to all scientific endeavors. And the other skills demanded by project work—teamwork, oral presentations, report writing—should all be in the toolkit of any developing mathematician.

Interdisciplinary Geometry

Geometry, with its focus on spatial mathematics, is one branch of mathematics in which connections to art and to the world beyond the classroom are obvious. Nancy Borchers, of Taylor High School just outside Cincinnati, Ohio, directed a project that gave students the opportunity to explore connections among mathematics, art, and the world of commercial baking. Like geometry students in other schools, Borchers' students worked with geometric shapes that tessellate and created designs with rotational and flip transformations. They examined drawings by M. C. Escher to see how geometry is the foundation of some art.

Then Borchers asked them to consider the problem statement:

> The Keebler Baking Company is looking for new ideas for a cracker or cookie.

The nine-week project was coordinated with the art department. Art teacher Susan Schramm was enthusiastic. "Linking art with a core discipline validates art as an important subject," she said. Borchers added that linking mathematics and art with the corporate world "helped students understand that different subject matters are needed in industry." It also answered the age-old question, "When are we ever going to use this again?"

The project was much more than tessellation design. Steve Nichols, a technical manager at Keebler, demonstrated for the students the precision mathematics required to run a production line. Determining cookie production on an eight-hour shift, he explained, requires knowing the number of cookies that can be placed on a die-cutting tool and the number of revolutions per minute the die cutter makes. The students conducted market surveys to help analyze their decision matrices. After choosing a type of cookie and its tessellating design, they constructed paper dies to show how their concepts could be reproduced. They designed appropriate polyhedral packaging, taking into account the number of cookies to be fit into a box and that different production departments would need to work together to prepare the product for shipping. They crunched numbers to determine the cost for cookie production and packaging.

The review board, which included Nichols and Keebler's Operations Manager Jerry Morgan as well as school district officials, praised the innovative and thoughtful designs. "Hexo-Honeys," a hexagonally shaped honey cracker, was packaged in a reusable hexagonal box; "Tribites," a triangular cookie that fit snugly into its triangular box, was designed both for reduced breakage of cookies and for efficient shipping because the box itself could tessellate.

The students were enthusiastic about the process. "I learned that it takes a lot more math and calculations than I thought to make cookies," said one. "I never knew how much work went into the precision in the machines."

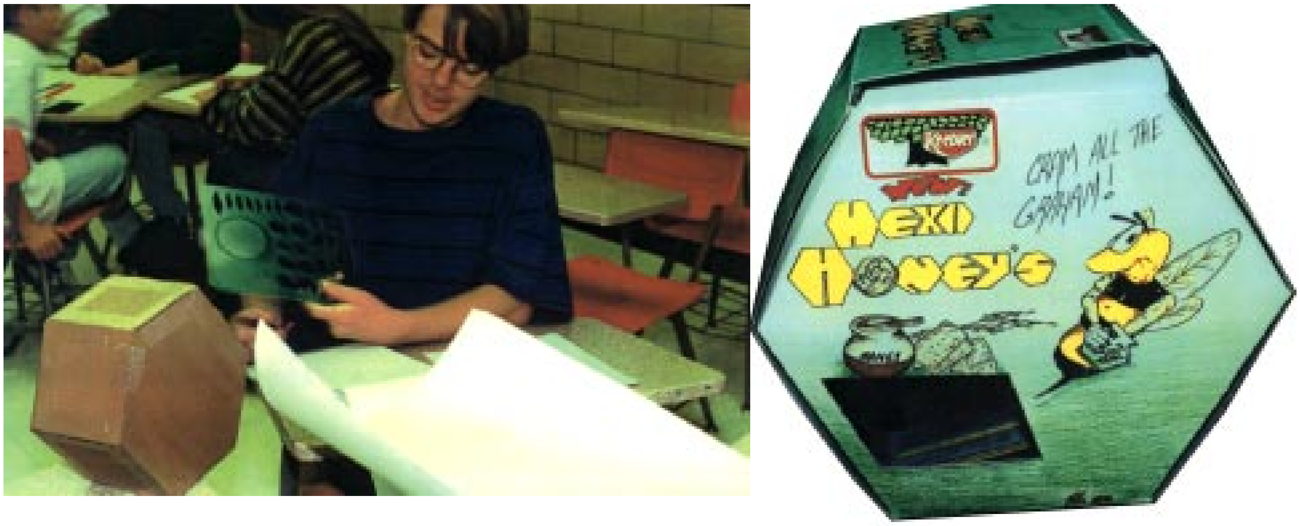


Figure 13. Student working on tesselating cookie packaging.

Another project teamed geometry students with others from four different disciplines—Spanish, computer science, physics, and history—to design features for a theme park. The teams paired with physics students were required to build working prototypes; other teams constructed non-working models. They heard Randy Smith, a design architect from Rouse Wyatt Associates, a firm specializing in planning and design theme parks, talk about the realities of theme park design. As with the cookie project, the teams gathered marketing information from target customers and graphed the results of their surveys. They considered the amusement attractions from an operator's point of view and drew up instructions for safe operation. They created job descriptions for personnel and submitted formal work contracts to the art department. Their final reports included at least one geometry problem related to their work.

The review board for the final presentations, which included Smith as well as a facilities manager for Paramount's local theme park, several educators, and an alumna of the school, praised the projects both for innovation and for integrating the subject matter of the paired disciplines. A team working with Spanish students blended research on Mexican architecture and food to create a Mexican food snack shop. A team working with history students built a scale model of a swimming pool, and presented their research on the history of the swimming suit in America. Teams collaborating with physics students used a variety of materials to construct working models including an erector-set flying car ride with a manual drive system and a "Dino-Slide," inspired by Fred Flintstone's commuter vehicle, in which a water-filled syringe created a hydraulic lift to raise and lower the dinosaur's head.

Data Analysis for Pre-Calculus Teams

Mary Lou Derwent, a pre-calculus teacher at St. Joseph's High School in South Bend, Indiana, sees as her primary responsibility helping students build the mathematical skills needed for science rather than having her students actually "doing" science. Although her students do mathematical curve fitting and work on individual mathematics projects, Derwent feels that a typical full-scale engineering project makes little use, beyond data analysis, of the kind of specific mathematical skills her students are developing.

The engineering approach to problem solving, however, clearly pervades her teaching. No matter what the problem or project, she demands that students be precise about stating a problem, defining terms, determining biases, and redefining the problem when necessary. "The value of the approach is the process of problem solving," says Derwent, "and that I have well integrated into my teaching with technology."

Derwent guides honors students through one engineering project each year. At the beginning of the third quarter, she gives the students a timeline, a group organization plan, a point-grade equivalency, and the evaluation sheets that she and the external review board will be using. Because it is an honors class with an intense schedule, she spends only a total of five class days taking them through the engineering problem-solving cycle; the rest of the work is done outside class.

In the spring of 1994, Derwent proposed the topic of safety.

> As members of the South Bend community, we are concerned about safety. Identify a problem that you will attempt to solve in the area of safety.

Teams had two weeks to define their problem and six to complete the project. Along the way they researched their chosen area, interviewed potential customers, and prepared progress reports. In their final report, they described both process and product, including marketing plans and cost analyses. After a Sunday practice session with a video camera, the students were ready for oral presentations before the official review board, composed of two engineers, an economics forecaster, a bank manager, and an engineer salesman from IBM.

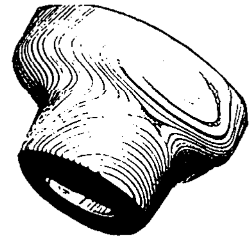
The work log of each team documented the process: the problem statement and its redefintions, brainstormed ideas, specifications and their quantifications, decision matrices, background articles, rough drafts of reports, marketing targets, design sketches, cost analyses, projected expenses. Everything each team member had done found its way into the log. Derwent checked these logs weekly, commenting on ideas, making suggestions, asking questions to push the team further along. Going through a log, one could recreate the ups and downs of the project: a long list of brainstormed ideas followed by the comment, "Decided to call it quits," then notes on a couple of research articles and another brainstorming session.

One team researched the area of accidental poisoning of children. The first matrix analysis helped them choose from different categories of child-proof safety devices—sensors, lids, nonphysical and physical deterrents, and security measures; a second matrix weighed different types of safety lids. Their solution, a "Kid-Stopper" lid to be fitted over a standard lid, was designed to be too large for a child's hand to manipulate yet easy for an adult to attach to the original lid on the dangerous substance. A spring and rubber gripper completed the assembly.

Two members of the team tapped a pair of graphic designers (the parents of one member) as resources for the marketing displays and advertisments. Another worked with a carpenter, a neighbor, to execute the design for a working model. In their evaluations of one another, they were clear about individual roles and the way different aspects of the project fell into place. Calling their company Protect-A, Inc., the team presented a professional demonstration of their invention and a plan to market it.

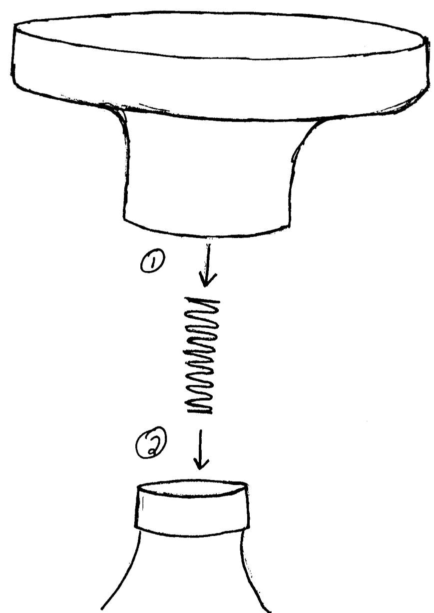
PROTECT YOUR CUSTOMERS' KIDS
SELL KID-STOPPERS

Many accidents occur every year when parents don't properly secure their household chemicals. Protect-A, Inc. has developed a new line of lids to keep children safe from dangerous chemicals. Kid-Stoppers are available to accomodate most sizes of containers. So stock Kid-Stoppers, by Protect-A, Inc., and help promote a safer environment for our children.



PROTECT-A, INC.

To Order Kid-Stoppers call 1-800-KID-STOP. Or write PROTECT-A, INC., 3900 Edison Lakes Parkway, Mishawaka, Indiana 46515.



Assembly:
1. The spring is attached to the center hole on the bottom of the Kid-Stopper.
2. The spring is attached to the top of the cap on the bottle.

To open:
The Kid-Stopper is depressed, and the rubber grip placed on the inside of the 1-7/8 inch hole grips the cap on the bottle. This allows the cap to be opened by turning the Kid-Stopper.

Figure 14. Diagram, ad, and prototype for child safety lid.

A Whole Year of Inventions

If you could do anything you wanted to do with the engineering approach to problem solving, what would you do? Several teachers, who recognize the stress of juggling traditional curriculum with engineering project work, managed to convince their school administrators of the value of a whole course devoted to problem solving through invention.

Engineering for Everyone

When Karen Falkenberg returned from her first summer at Thayer School, she worked hard to integrate the problem-solving approach into her physics and chemistry classes at the Shadyside Academy in Pittsburgh, where she was then teaching. She had her physics students demonstrate physics concepts to an external review board, her chemistry students design their own experiments. “I was challenged,” she recalls, “because I didn’t have time in the curriculum or the facilities to design a device.” When she moved to the Webb School in Knoxville, Tennessee, as a mathematics teacher, she again found project work limited by the curriculum. She dreamed of an elective in which the engineering approach could be fully implemented. In the 1994-95 school year she got her chance.

Setting course prerequisites low enough to make the course available to students who did not see themselves as science-oriented yet high enough to assure quality project work, she attracted students with a variety of skills. She worked with mathematics colleague Stephanie Ogden to conceptualize a course that moved from tightly defined problems, such as the design and construction of model bridges, through open-ended problems in electronic circuitry or mechanics to a final project for which teams defined their own problems and applied all the skills they had developed during the year.

Falkenberg also guided her students through a unit on business constraints and marketing. Or rather, the students, by then accustomed to working independently, took responsibility for researching marketing topics and presenting them to the rest of the class. Falkenberg believes the business section of the course is necessary for students to understand the whole of engineering. Engineers, she tells the students, do not invent just for the joy of it. “If an engineer does not understand the customer or client, then the solution may not be optimal. I’ve worked as a research engineer myself, and I’ve seen plenty of engineers who didn’t understand the business aspect of their work…as well as business professionals who don’t understand science. I want my course to open the eyes of the traditional science student interested in becoming an engineer and also the eyes of the non-science student who may end up in business.”

Falkenberg worked with English teacher Jeff Walkington to ground students in writing technical reports. Together they devised a format that allowed students to demonstrate the technical and business concepts they had mastered in the course of solving their problem. Walkington devoted five class periods to discussions on the finer points of technical writing and made himself available to teams for consultation.

In the spring of 1995, teams of students invented “something to solve a problem or aid a person in everyday life.” They met regularly with Falkenberg to consult on their progress and with Walkington for advice on shaping their reports. One team designed a washcloth wringer for people with arthritis, another invented an “Alert-Line” towline to help water skiers communicate with those operating the boat towing them, a third developed a lighting sequence for automobile brake lights that would show a car following the amount of pressure being applied to the brakes. The students’ final reports blended a narrative of their work process with technical concepts underlying their device and details of a marketing plan.

Bill Pfeifer, director of the Webb School the first year Falkenberg’s course was given, praised the course as a model for assessment. Falkenberg’s reviews included written and oral presentations, with the first orals given to members of the class, the second to a review panel composed of Webb School faculty, administrators, and staff, and the third and final presentation to an external review board. Falkenberg remembers one oral review that coincided with mid-term exams. Her students were so focussed on the power-lifting devices that some skimped on studying for other mid-term exams. "Few of the students regretted it," says Falkenberg. "They said it was a choice they made." Other teachers weren't so happy. Still, Falkenberg reasoned, if students say they "can't wait for a mid-term exam" in one course yet fail to even study for another one, that says something about the direction assessment needs to go.

Students gain more than the concepts of physics and mathematics they come to understand through their work, believes Falkenberg. At the end of the course, the students discussed with her the hesitation they felt at the beginning of the first, very narrowly defined project. One recalled panic at having no homework assignment, at having to come up with a time management plan on her own. By May, that student was laughing. She certainly did not need a teacher, she said, to help her plan the day-to-day tasks of a twelve-week project.

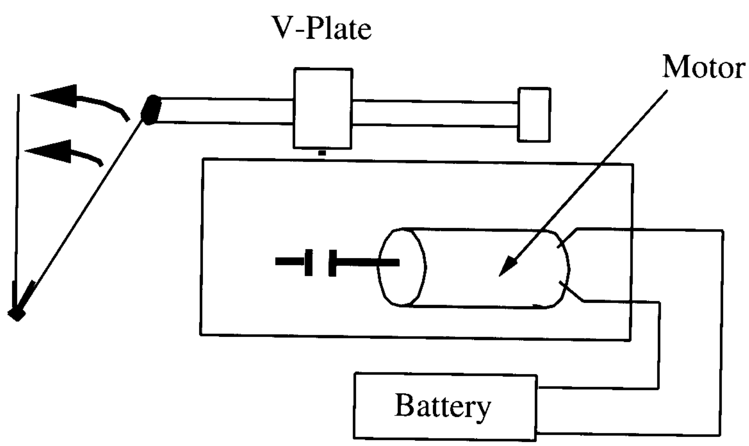


Figure 15. Student CAD of a washcloth wringer for arthritics

Engineering Concepts for Advanced Students

Carl Mehrbach is an artist. He began an advanced degree in oceanography, but balked at the low ratio of ocean work to lab. After a stint of making art in New York City and a master's in fine arts, he returned to science education. Teaching physics and chemistry at Hanover High School in Hanover, New Hampshire, he found he missed the hands-on problem solving that was so much a part of painting. "Learning by self-invention is what artists do," says Mehrbach. "Painting *is* problem solving. One thing I was taught to do as an artist was to take risks. And risk-taking is what makes science run. Plus the cookbook approach to lab work in the typical chemistry and physics courses doesn't teach students how science works."

Mehrbach's course, called CAPPS (Chemistry and Physics Projects for Seniors), is designed for those who have completed both chemistry and physics or who have completed one and are enrolled in the other. The course, which he team teaches with technology instructor David Johnson, is a magnet for students who excel in science and students struggling with standard science textbook fare but who have done well in shop. Both kinds of students join in what Mehrbach calls "a community of knowledge seekers, sharing one another's ideas, and supporting one another throughout the entire creative process."

Mehbach begins each year with a closely defined problem that eases students into the engineering approach, followed by a related problem that extends the research and pits students against other high school inventors at the University of Vermont's Design TASC (Technology and Science Connection) Competition for high school students. In 1994, CAPPS teams placed first and fourth in the perfomance division and second in design portfolio. Small wonder. The problem—inventing a solar-driven device to launch projectiles—let them build on the work done earlier when they designed and built a solar-energy machine to lift a coffee can full of salt.

Mehrbach's CAPPS students are given an RFP project at the end of the first semester, then devote the second semester to a single project of their own devising. For the final endeavor, they can work in teams or as individuals, they can choose a full patent-design portfolio or a scientific paper. They have two weeks to come up with a topic; then they head into the culminating work with a good grasp of how to juggle all the aspects of scientific research—the work log, the scientific articles related to the project, the patent search, the design reviews, the oral presentations, the final research paper or design portfolio.

Mehrbach brings in outside speakers and connects students to local engineers and scientists who can act as mentors. His own role during the final project is to help students keep the problem manageable, identify technical constraints, counsel them if team members seem at odds with one another, ask questions to make them think about the direction of the project, and act as a sounding board when a team is up against a knotty technical problem. He says he has his most fun, in fact, when students are stuck. Then he draws them out in discussion and gives them a nudge sufficient to get them over the hump on their own. "They're not used to intellectual 'messiness,'" he says. "They need to get used to the way problem solving works."

Mehrbach stresses patent research. All teams do patent searches to make sure their ideas are not already products. One team took its patent work a step beyond and experienced the reality of invention. For a first-semester project, they designed an automatic cigarette lighter for the automobile. When their initial patent search unearthed no other products, the team decided continue to improve the design and to apply for a patent for the device. Only weeks before the end of the course, they were informed by the U.S. Patent and Trademark Office that a similar device had just been granted a patent. Mehrbach was sympathetic but also saw the experience as a learning opportunity for all his students. Early each year he warns his students that "new knowledge is found not by simply forging ahead, but with disappointments and failures." Disappointment that their cigarette lighter would never realize product form was mitigated by the recognition that the invention was on the cutting edge.

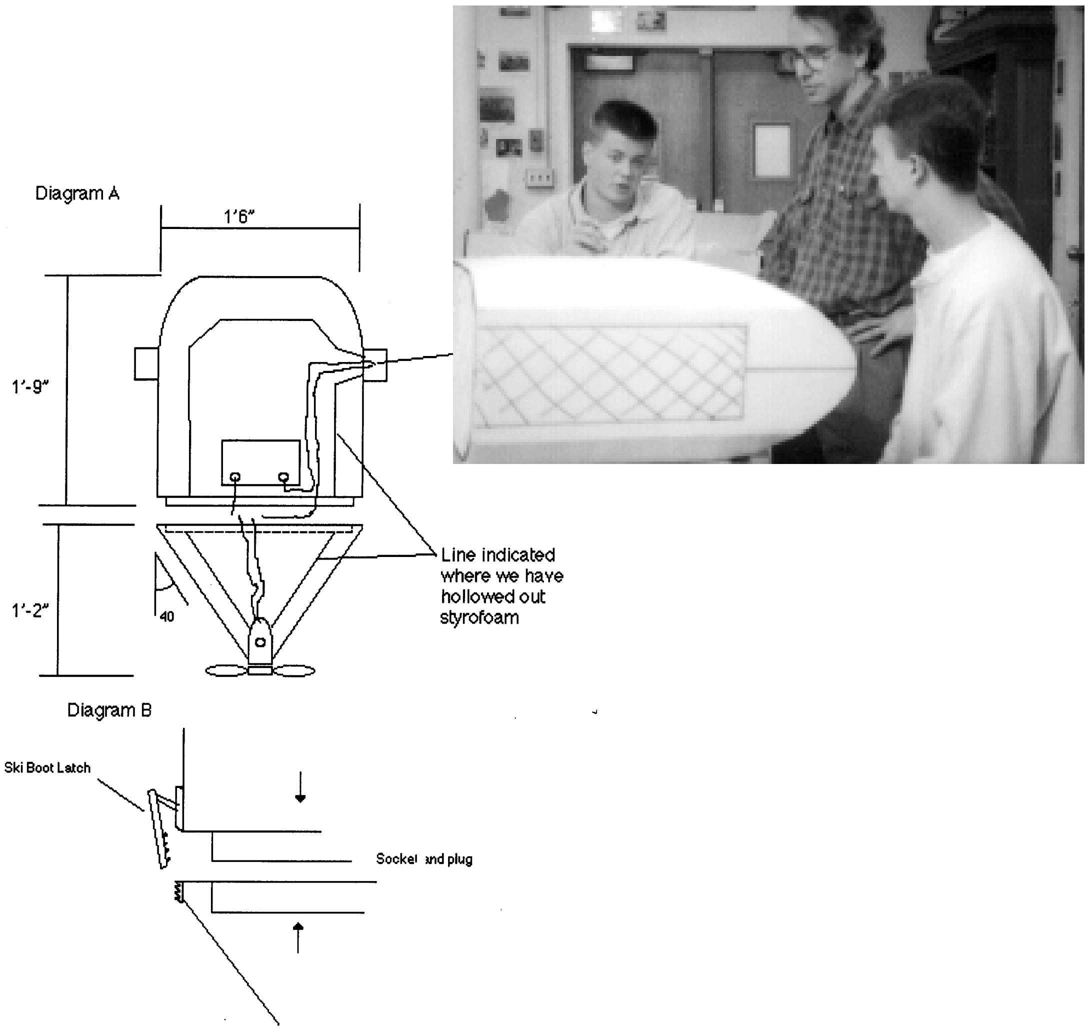


Figure 16. Student sea sled diagram and team in review