Chapter 8

Projects Without Tools

Designs for Public Improvements

Kinematics at the Traffic Intersection

When Kathleen Conn, of Media, Pennsylvania, was still in the classroom, she asked her Conestoga High School physics students to apply their understanding of kinematics to automobile travel by selecting a local intersection and identifying its traffic problems. Conn suggested they look for problems such as traffic backup while awaiting a left turn, poor visibility when turning, traffic congestion during rush hours, unusual turn angles, poorly timed signals, or inadequate drainage for water runoff. "I want students to identify the problems they will work on," says Conn, "so I spend a lot of time working with them to understand how to frame a problem statement, how to define a problem. I think a good problem statement is the major task!"

She gave the students a detailed RFP that laid out general constraints for intersection redesign and had each team execute a written contract. She provided a list of potential resources and showed teams how to keep work logs to document decision-making processes. Conn also gave them guidelines for the kinds of calculations they could do using the kinematics formulas they had learned earlier. In order to solve problems of traffic backups, for example, they might calculate the carrying capacity of the intersection using the existing speed limit, the average length of vehicles at the intersection, and the average distance between cars. Or, for an intersection governed by a traffic light, they might time the lights and calculate the number of cars that could move forward during a single change of light or the length of time a caution light would have to stay yellow for a car traveling at the speed limit to move through the intersection completely before the light turned red. She encouraged them to look at centripetal force calculations to determine the maximum speed for negotiating a left- or right-hand-turning radius without skidding.

In addition to very good analysis and design solutions, students found out a lot about the operation of the world beyond the classroom. Attempts to obtain data from state and township transportation offices were often frustrating. Carefully written requests went unanswered. Some officials expressed annoyance at being interrupted in their ordinary work.

Students also found out that obstructions can come about from misunderstandings and that, through good communication, everyone wins. At the Pennsylvania Department of Transportation (PennDOT), a team of girls received different treatment than a team of boys. Conn herself spoke with the chief engineer. It turned out that the name for her hypothetical consumer group (Citizens Working for Intersection Safety or CWIS) had put PennDOT officials on the defensive. "Who's coming down on us now?" asked the chief engineer. After the project objectives had been clarified, he apologized and assigned a traffic engineer to Conn's review board.

At the review, that engineer listened carefully to a team that had targeted what it called poorly phased signal light changes. The three-second caution light at the intersection, students claimed, was nearly two and a half seconds short of the minimum time needed for safe turning. They drove this point home with accident statistics and calculations using the principles of kinematics, friction and inclined planes, and centripetal force. The engineer questioned them closely, then disclosed that he had himself been responsible for the light timing at that intersection. The students' report went with him back to PennDOT headquarters. They learned not only that their work could be taken seriously by professional engineering, but also about tact and constructive criticism.

Although some students complained about the amount of work the project entailed, most were enthusiastic about what they had learned about applying textbook knowledge to problems outside their textbooks. "This assignment has burst our bubble from which we could separate science from the outside world," said one. "It has forced the science-oriented to learn communication, cooperation, and management skills. And had us learn that science is relevant to the world around us."

Calculating Mass Transit

When Mary Lou Derwent's South Bend, Indiana, pre-calculus teams examined the suggested topic of safety (see "Data Analysis for Pre-Calculus Teams," page 92), one team decided to focus instead on the problem of public transportation. Inspired by an article on mass transit about poor public transportation service for lower income residents, the team began with the idea that a transportation system should bring workers and jobs together in a manner as efficient for low-income workers as for more affluent suburbanites. The team defined the problem as:

> South Bend does not have a good transportation system.

Analyzing that statement for vagueness, the students redefined it as

> The "Transpo" Busing System within South Bend city limits is neither efficient nor convenient.

One more round of word clarification gave them a problem statement with which they could work.

> The "Transpo" Busing System within the South Bend city limits is in need of reform with regard to cost of use, frequency of buses, and route efficiency for customers.

The team's target customers were lower-middle-income to poor workers in South Bend. Their constraints included the need for a low bus fare, consideration of the geography of low-income neighborhoods and places of employment, and efficiency of routes and time. They also had to consider safety, affordability from the city's perspective, reliability, and environmental soundness. They brainstormed everything from subways and monorails to solar tricycles and hot air balloons, but eventually decided that the most feasible and economical solution would be to redesign the existing bus system.

The team investigated the system's routes and the pattern of South Bend's streets. They performed a statistical analysis of census tract information and devised a formula that weighted normal standard scores of population, income, and places of employment. They applied their formula to the existing 30-bus fleet to determine the optimal number of stops for each residentially and commercially zoned tract. Their redrawn transit map, a multi-cloverleaf system, offered clockwise and counter-clockwise bus routes to minimize the distance between any two stops.

The plan was not perfect, the students readily admitted to the review board, but they pointed to justifications for its flaws. The small overall area of the design, they argued, was offset by increased service to lower-income areas of the city. A downtown dispatch center, a tradeoff for the efficiency of the system, might result in a rejuvenation of the inner city.

The review board praised the team's design and presentation but scored their written report low. Two team members decided to continue work on the project, meeting during the summer with the president of South Bend's Common Council and the Transportation System board. Incorporating new information, the students reworked the written report for a government honors class.

For Derwent, the project work verified her sense that these students had developed a new way of thinking and a real ability to use it.

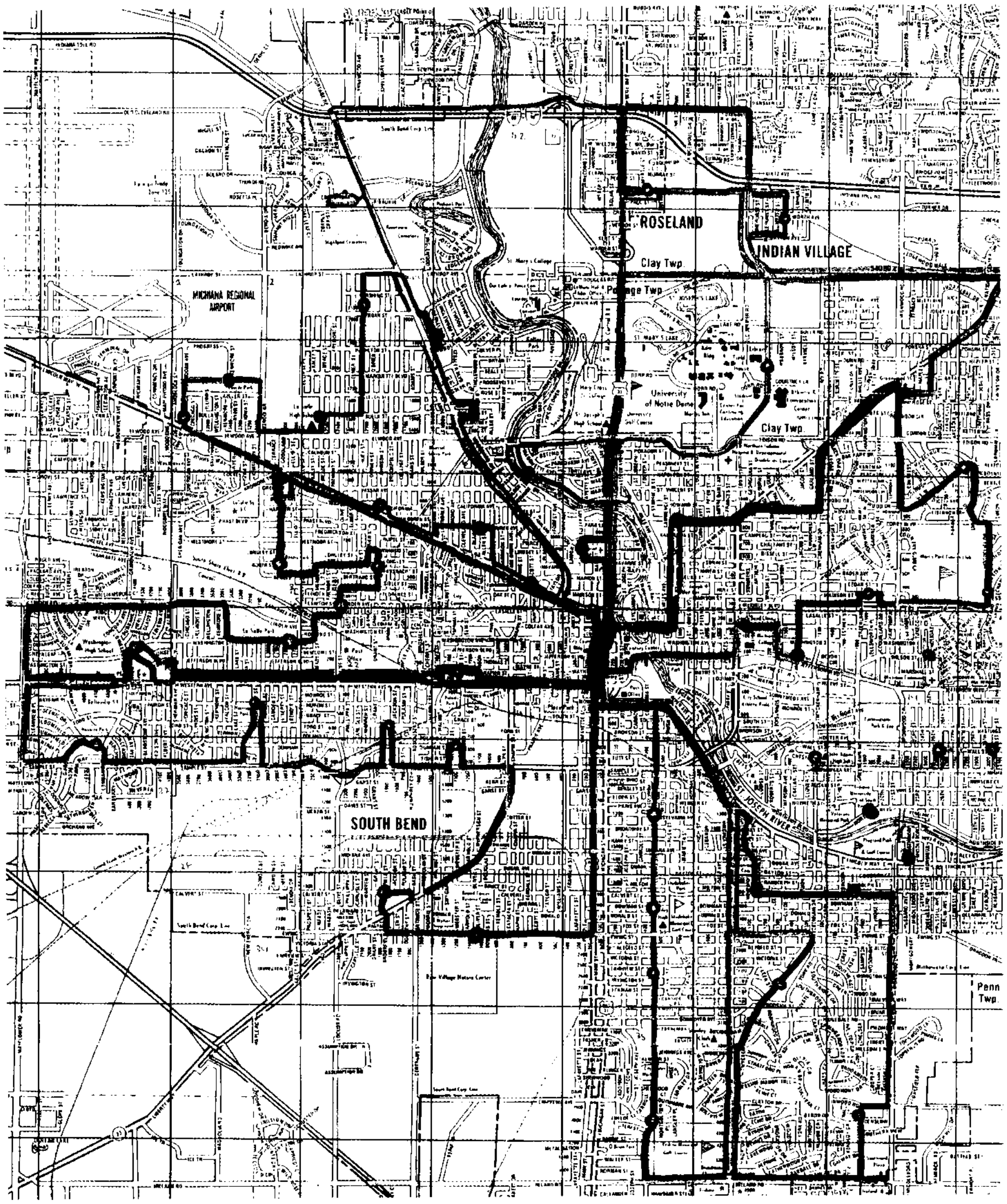

Figure 17. Student redesign of South Bend Public Transportation System

Solving Learning Problems

The Physics of Demonstrations and Lesson Plans

When Deb Hill taught at Dobson High School in Mesa, Arizona, she had no access to shop equipment. Her solution was to supplement the prescribed physics curriculum with projects that relied on materials which *were* available to students. She guided teams through projects with very specific guidelines to ones in which they designed their own problem to solve. One year, the students began by considering this problem statement:

> Select a toy whose motion can be quantified and prepare a poster board which includes all the components of motion.

The only constraint was that the toy had to be self-propelled, whether by battery, wind-up, or pull-back and release. The poster was to include an explanation of the motion of the toy and a qualitative analysis of its motion.

"The first time I did this project," says Hill, "I had students do patent searches on their toys. This proved to be a very frustrating experience. Toy companies frequently do not patent their toys. And they frequently buy one another out and destroy old records. We tried to contact toy companies, but did not find a way to get useful information. Thus, if you want to follow up this project with having students design their own toys, patent searches are less useful."

For their second quarter project, Hill's students were instructed:

> Identify a segment of a video production that demonstrates a realistic or unrealistic physics principle or concept and develop a quality, creative oral presentation that thoroughly explains the physics as applied to the video.

Here students, unconstrained in what they were to identify as a physics concept, had to apply teamwork skills to select both a concept and a video segment that might demonstrate it.

Hill puts a lot of class time into training students in teamwork. Long before they get into a project, they are working their way through team-building activities. They discuss what makes a successful team. They talk about roles, communication, participation, group process, and decision-making procedures; they document what each means and how they will incorporate it into their own team process. When project time comes, they are ready to work together. By the time they have completed two projects, they are ready for the open-endedness in what Hill calls her Sharing Knowledge project. Her students' last-quarter problem statement is:

> Develop an innovative way of facilitating the understanding of a physics concept in the real world.

In the 1993-94 school year, one team of students developed a video to teach Boy Scouts the physics underlying the motion of a bow and arrow. Another one worked on presenting free-fall physics. Each team demonstrated its final product to the class and documented how to present the lesson to its target audience. Some teams went the extra mile and actually taught their lessons to students at local elementary schools (the free-fall team engaged the assistance of the local fire department). "My students enjoyed feeling they knew enough to teach someone else something new," says Hill, "and the teachers at these schools really welcomed the guest experts."

For Hill's students, the engineering problem-solving cycle directed their attention to acute observation; the students' inventions were inventions of the mind. They came to understand first hand about the three stages of learning—understanding the concept someone is demonstrating, understanding it well enough to demonstrate it, understanding it well enough to teach it to someone else.

Designing a Multilayered Physics Course

John Van Ackerman, of Port Hadlock, Washington, applied the engineering approach to the problem of how to accommodate the variety of learning styles his physics students exhibited. His class had just completed four months of work in kinematics, special relativity, and Newton's Laws, using microcomputer-based labs, data analysis and curve fitting, graph interpretation, small projects, and traditional labs. Van Ackerman told the students that in those four months they had experienced the old model of teaching; he challenged them to come up with a new model for learning physics. He posed the problem:

> How can students and teachers take responsibility for organizing a meaningful and enjoyable class that meets their needs?

As a class, the students worked through the problem-solving cycle and came up with a layered approach—Applied, Conceptual, and Honors—each track giving students the flexibility to make choices about what they study, what projects to undertake, and how projects would be evaluated. On succeeding rounds, they refined the layered approach, listing elements of their ideal course, such as goals, activities, time management, and evaluations and determining how these parts would all fit together.

Three students selected the Honor's Physics, twenty the conceptual approach, and eight the applied physics. The Honors students chose their own textbooks—one a calculus-based textbook, and the other two (both sophomores) a college-level noncalculus text. The conceptual physics students used a regular physics text, reading chapters, taking tests, and then correcting them themselves. The applied students focused on engineering project work with no textbook.

Students at all levels had the option of completing projects. The applied physics students worked on airplane construction, digital electronics, labs using calculator-based laboratory (CBL) equipment and the Internet as well as more traditional labs, such as electrophoresis, electromagnetic induction, series/parallel circuits, or the Wheatstone bridge. Students at the other levels taught science to fifth graders, conducted interviews to find out how people use physics, and studied the physics of a bicycle.

Van Ackerman is enthusiastic about the multilayered approach. "Many students like having a set structure to follow," he notes. "Others like the freedom that this method provides them. I give them plenty of options, such as reading and documenting chapters, completing labs, reading and documenting library articles or popular physics books, conducting interviews, working with a mentor, learning and using computer software or CBL equipment or interface hardware. I encourage them to choose options that require taking risks. Some select activities such as reading the textbook or doing set labs—which is certainly O.K., but I still try to get them to step out of their comfort zone and pick something different."

Chemical Inventions

Patenting New Molecules

Chemistry is not a discipline that invites easy implementation of engineering projects. The subject matter does not lend itself to construction of "devices." Students can design experiments, but any chemistry laboratory, even one in which everyone does the same cookbook experiment, creates safety concerns. Most chemistry teachers cannot envision half a dozen teams working away at separate experiments without major risk. And there is always the problem of disposal.

Kathleen Conn, whose physics students took on traffic safety problems (see "Kinematics at the Traffic Intersection," page 101), invited her ninth-grade physical science students to design a pencil-and-paper invention focussed on the chemistry of carbon compounds. They were to apply their understanding of the rules of chemical combination and the structural properties of hydrocarbons, she told them, to solve a problem of either local or global importance. They obliged her by combining carbon, hydrogen, and oxygen atoms to assemble the hydrocarbon skeleton in linear chains, branched arrays, rings, and even "buckyballs." Working in teams, they applied the rules of covalent bonding and valence to draw the structural formula of a new, substituted hydrocarbon that would, in terms of the project, "make the world a better place."

The projects went forward under two major constraints: first, all valence electrons had to be appropriately bonded; second, each team had to incorporate into their final design three of a set of five reactive elements pulled out of a "grab bag" of elements.

Conn introduced the project by analyzing with the students a pair of relatively simple chemical patents from the U.S. Registry of Patents. Once the teams had brainstormed ideas and determined the target problems, each team had to determine which general class of hydrocarbon compounds might accomplish the goal. The students also had to apply an understanding of the characteristics of the different types of hydrocarbons—linear, branched, or aromatic, monomer or polymer, and research the history and properties of the grab-bag elements to determine which work best in the synthesis of the new molecule.

Conn set up an unofficial branch of the U.S. Patent Office in her classroom to evaluate the students' patent applications. Each team filled out a special application form modeled on the official one. Student applications demonstrated both ingenuity and an understanding of chemical facts. A non-polluting fuel that produces water vapor instead of carbon monoxide would contain its own "lubricant, igniter, and cleaner." A see-in-the-dark plastic toilet seat would include an "alpha-emitting radioactive element promethium as a germ-killer additive in a plastic polymer." A "Highway Construction Bomb" proposed lightweight titanium and plutonium for road construction, and a "Fertile Insecticide Plastic Pot Material" would use a blue color to attract harmful insects which would then be zapped by an alpha-emitting element gadolinium.

"Whatever the product they invented," says Conn, "students not only learned chemical facts, but they also applied them immediately to a real-life problem that they personally had identified as important. Applying for a patent in the ninth grade is certainly one way to excite learners in physical science class."

Designing Chemistry Labs

Lisa Torres, of Lebanon, New Hampshire, solves the problem of how to do problem solving in chemistry by working from a problem defined narrowly enough to let her control the parameters of the experiment but open enough to allow multiple approaches. She often begins the second semester of her chemistry classes with a question of stoichiometry, or how quantities of chemical reactants and products can be determined. In 1995, she had her students form companies and consider this problem:

> Can our company produce gypsum more cheaply than we can buy it?

The students' task is to research those chemicals which, when combined, create gypsum, and to find the best conditions for the process. They experiment in the laboratory until they can control variables such as concentration and temperature and create a small quantity of gypsum from which to project mass production figures. They document their process in the lab journal, keeping track of material costs and time. After factoring in disposal costs, personnel costs, electricity, and other overhead expenses, they compare the total cost to the wholesale price of commercially produced gypsum.

It is not a full-blown engineering process, Torres admits. The problem is teacher-defined within a narrow context. "If it were truly an open-ended question, then students might realistically decide to find another product to do the job or look for other ways to synthesize gypsum. I want them to work with specific chemical reactions. Plus I have three sections of chemistry. That's 24 groups. If the problem were open-ended, I would have 24 different setups. In a 50-minute lab they could spend the whole period just getting what they need." But Torres credits the engineering approach to problem solving for giving her the frame for the problem. Even with its narrowly defined constraints, the problem offers a number of different approaches with no single right answer. In the process of gathering data, teams consult official resources such as OSHA's Materials Safety Data Sheets or the Flinn Catalog on safe chemical disposal.

Chemistry is challenging for problem solving, says Torres. Building a device to identify gasses, for example, would be a very sophisticated task, beyond the comprehension of most of her students. Her students do often invent small devices as part of their experiment design. When Torres asks her students to find a way to demonstrate one of the properties of gasses, they may come up with a method that requires specially design equipment. A team might choose, for example, to design a gas-law experiment to demonstrate the effect of volume on pressure and redefine the problem as

> How can I measure the pressure of air coming out of a balloon?

Then they might discover that the only two standard pressure gauges in the lab have already been claimed. To make their measurement, they might build an alternative gauge. "In the same way that physics students need to design experiments to test their inventions," says Torres, "chemistry students often need to invent a device in order to complete student-designed experiments."

The chemistry of producing gypsum is her students' first encounter with a problem for which there is no right answer. The process is often a struggle.

The units that follow the stoichiometry unit are often less difficult. For example, teams design experiments to demonstrate the laws of gasses or students prepare a "what-if" scenario for a particular property of liquids that might operate under a different law. Why begin with the hardest? "I want them to get past the idea that science is always sequential and convergent," says Torres. "Plus after this struggle, they gain the confidence to tackle just about anything."

Improving School Environments

Eliminating Fumes in the Library

Tony Komon's physics students (see "Project Work on Ten Minutes a Day," page 88) don't always invent devices. Sometimes Komon pulls problem statements out of local situations and asks for design solutions. One November day in 1992, for example, he went to the school library and came out with a headache. He talked to the librarian: headaches, it turned out, were a common complaint. Those who used the library between 8 and 9 in the morning or 2 and 2:30 in the afternoon often noticed the smell of the diesel fumes from buses that idled outside the building.

Komon challenged his students to solve the problem of the fumes in a week, using two double periods and three single ones. Teams interviewed members of the library staff and students who used the library frequently. They researched diesel exhaust to learn about acceptable levels and test procedures. They brainstormed possibilities. The best solution came from a team who spent a good part of the week poring over blueprints of the library's ventilation system, tramping on the library's rooftop, and examining the controls in the power room. The students analyzed the present ventilation, heating and air conditioning systems; they eventually recommended re-directing the air flow so that the air intake would draw from the clean air of a nearby courtyard rather than from the air polluted by idling buses.

The students' solution was not only sound, it was also as good as a professional's. Only a few months after the project, the board of education hired an outside engineering firm to assess the library situation. The professionals discovered that the ventilating fans had, in fact, been installed backwards!

Improving the Environment at School—and at Home

Lisa Torres (see "Designing Chemistry Labs," page 107) sometimes teaches Applied Science, a class designed for students not directed toward college. In this class she can involve students in complete engineering projects. One year, in a unit on improving the environment at Lebanon High School, her students formed environmental consulting companies. Several faculty members, acting as a potential team of clients, drew up a list of problems. Each team selected a problem. Interviews with teacher-clients helped the students redefine the problem. Constraints were developed by meeting with all parties potentially affected by the plans—the principal, the custodial staff, teachers, and other students.

Teams worked on improving air quality in a classroom, reducing noise pollution from lawn mowers, improving the school's recycling program, and designing landscape plantings around the grounds. The design solutions were both practical and sound; some had far-reaching effects. The team that designed a nature walk in a lot adjacent to the school took pride the following year when the school board decided not to sell that lot for a proposed police station. A board member who had acted as mentor to the team explained his vote at the board meeting: "After all the work they did on that nature walk, we can't let the kids down."

What Torres remembers most about that class, though, was the return of one student some time after graduation. He told her that the water in his sister's well had been found to have high levels of nitrate. Plus, he said, a farmer in the watershed was planning to use sewage sludge for fertilizer. Although Torres had spent minimal class time discussing the "facts" of water quality and nitrates, this student remembered that sewage contains high concentrations of nitrates and that nitrates are not filtered out by soil. More important, he knew how to draw conclusions from facts and how to tackle a problem. He had already looked up the RSA and New Hampshire statutes regarding water quality and watershed rights; he had contacted lawyers who had declined the case; and he had instructed his pregnant sister to buy bottled water until he could solve the problem. He came to Torres as a further resource. She gave him some legal references and praised his problem-solving skills. He gave her the reward that makes a teacher's day: "I learned how to do all this stuff in your class."