

Foreword

In the late 1950s, under the leadership of Dean William Kimball, the Thayer School faculty reorganized its curriculum to emphasize the *engineering sciences*. As a prerequisite to the study of engineering, students were required to take a very stiff dose of mathematics, physics, chemistry, and courses in field theory after which they would be introduced to engineering practice. Dean Kimball then recruited me to be his successor in implementing the program. On my arrival in 1961, I met Professors James Browning and Robert C. Dean, who told me of their concern that, while the strengthening of mathematics and science was necessary, they feared a steady diet of abstract theory would discourage and drive away those students of a creative bent who would be most likely to become strong contributors to the engineering profession.

I agreed with their analysis and supported their development of a new course, “Engineering Sciences 21: An Introduction to Engineering.” The idea was simple. Before undertaking the abstract theoretical courses required for advanced practice, the students were to experience the hands-on fun of actually doing something creative and useful.

In the ensuing 35-plus years, the course succeeded beyond our expectations. Many Thayer School alumni have told me what ES 21 did for them, how it inspired them and gave them a vision for life. Many have established their own companies, a few based on projects initiated at Thayer School. Some of their names will be found in the Acknowledgments section.

This book is based on that experience.

In 1991, the U.S. Department of Labor issued a report* describing five competencies students should acquire to be successful in the world of work:

- Ability to manage resources—allocating time, money, materials, space and staff
- Interpersonal skills—working on teams, teaching others, serving customers, leading, negotiating, and working well with people from culturally diverse backgrounds
- Managing information—acquiring and evaluating data, organizing and maintaining files, interpreting and communicating, and using computers to process information
- Working in and on systems—understanding social, organizational, and technological systems, monitoring and correcting performance, and designing or improving systems
- Technology—selecting equipment and tools, applying technology to specific tasks, and maintaining and troubleshooting technologies

Faced with this list of competencies and the existing educational system, most teachers have not known where and how to begin. Fortunately, this book presents a well developed and tested approach. The book goes far beyond a simple description of what to do. Based on nearly a decade of experience teaching high school teachers how to do it, the book is replete with examples of successes, a discussion of barriers and how to overcome them, and suggestions for how to adapt the general principles to your unique situation.

I am delighted to endorse this book, to commend it to serious educators at all levels, and to have had a small hand in its beginnings.

Myron Tribus
Fremont, California
May 1996

**What Work Requires of Schools: A SCANS Report for America 2000*. Secretary’s Commission on Achieving Necessary Skills, U. S. Department of Labor (1991).

Preface

In 1989, I was the assistant dean at Thayer School of Engineering at Dartmouth College in Hanover, New Hampshire. In consultation and collaboration with the dean and several faculty members, I invited a dozen mathematics and science teachers from New Hampshire, Massachusetts, and Vermont, to sit down with us for a couple of days to consider to what extent Thayer School might offer a program of value for teachers. Self-interest was in part the motivation. Thayer School wanted to develop better relations with teachers so that they might have an appreciation of Dartmouth's undergraduate engineering program and might then encourage their top students to consider applying to Dartmouth to study engineering.

From this set of discussions arose the plan for what came to be called "Engineering Concepts for the High School Classroom," a summer workshop first offered in 1990. The workshop was designed to introduce high school science and mathematics teachers to a creative problem-solving framework based on techniques used by engineers at work. This framework had been developed through an unusual but highly successful undergraduate engineering course taught at Dartmouth since the early 1960s, and developed as a means of introducing students to the practice of engineering. Teachers were quite interested in learning more about methods for approaching open-ended problems with their students and felt ENGS 21* might offer a useful model.

From the beginning, we explained to participating teachers that the workshop's success would depend on them. We could provide information about engineering and engineering problem solving, but we were not experts in pedagogical theory or technique and knew little about K-12 education. We would need to work as partners to create value from the endeavor. This approach has worked well, and what is now called the Dartmouth Project for Teaching Engineering Problem Solving truly is a partnership between Thayer School—its faculty, staff, and leadership—and a growing number of teachers involved with the program.

Teachers have been enthusiastic about the workshop. Many who had attended different professional development workshops and clinics over the years told us that "Engineering Concepts" was unique in both its content and usefulness. They urged me to find ways not only of continuing to offer it in future years, but to expand its initial goals and impact; over the last seven years they have worked with me to provide guidance for doing so. Through the partnership with teachers and the inspiration they have given me, I have learned a great deal more about education and effective teaching and learning, and expanded not only my interests and understanding, but also my circle of colleagues and friends. Teachers in the U.S. today are under-recognized and under-supported for their considerable knowledge, energy, and effective strategies for the many challenges facing them, but those participating in our workshops are among the most dedicated, thoughtful, and open-minded professionals I have met.

A major factor in our partnership's success has been Professor John Collier's generous, open-minded approach in sharing the techniques which have worked well for him in teaching, in research and development, and in life. A master teacher with obvious respect for his students as colleagues, John has also taught us that an important "spec" for problem solving, for teaching and learning, and in fact for all endeavors, is fun. A second important factor has been the Thayer staff who have worked in supporting the workshop and its

*"Introduction to Engineering," known in its early years as ES 21, is now ENGS 21, or "ENGINES 21."

participants and who are listed in the Acknowledgments. Year after year, teachers have commented on the dedication, service, and support provided by Thayer staff members whose goal has been quality in performance, and who achieve it. This endeavor also owes a great deal to Charles Hutchinson, ninth dean of Thayer School, who has supported the project and my work at every turn, frequently with his own highly effective personal energy, time, and dedication, because he thought it was the right thing to do.

Prior to the development of the Engineering Concepts for the High School Classroom workshop, the problem-solving framework which served both introductory and capstone engineering courses at Thayer School had largely been an oral tradition, passed along from one professor to another as they taught the courses. Some of the participants in the first workshop in 1990 returned as “TAs” in 1991 and began to document the framework in what they called “A Paper Partner.” The following year, the next group of TAs expanded and revised the paper partner, and we began to develop the documentation into a much larger resource manual for workshop participants. Some of that early documentation appears, somewhat modified, in this book.

As the years have gone by, the workshop has not been able to accommodate the increasing numbers of teachers interested in learning about engineering problem solving. Approximately three-quarters of the 185 teachers who participated in the workshop between 1990 and 1996 have gone on to implement the methods in their teaching, many with impressive results, a few of which are documented here. This book was developed as one means of reaching out to teachers who could not attend the workshop to provide the information, and in some part, the inspiration, for them to use problem solving in their teaching. It may also prove useful to the many other people—school administrators, school board members, policy makers, parents, and other taxpayers and donors—who care deeply and work hard to support teachers in their mission of educating the children of our nation, the future of our society.

I am particularly grateful to the John Brown Cook Foundation for providing the financial means to develop this book, and to Ellen Frye, who undertook the project of writing it with experience, skill, devotion, and a critical eye for detail and improvement. Marian Miner Cook, Greg Cook, Cia Cook, and Leo McKenna of the Cook Foundation understood the need and had faith in our vision and approach.

Carol B. Muller
Executive Director
Dartmouth Project for Teaching Engineering Problem Solving

Acknowledgments

The ideas and concepts presented in this book are the result of the efforts of many teachers, engineers, and others. Some of these individuals contributed to the development of the Engineering Concepts for the High School Classroom workshop and to documenting the course of engineering problem solving in the classroom. Others contributed ideas on the ways engineering problem solving can be an effective tool in the world beyond the classroom. Others read the book in manuscript and offered constructive feedback.

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INTRODUCTION

Why Engineering Problem Solving?

Three high school students are explaining their underwater navigational device. “What do you get out of this kind of learning experience?” they are asked.

“Well, take me,” responds one. “In my regular physics class, I’m failing right now! I’ve been building things and doing experiments since I was a kid, but I can’t seem to learn from a textbook. If I didn’t have this class, I’d think I wasn’t any good at science.”

Schools are filled with students who think they aren’t “any good” in science. As America heads toward the twenty-first century with an urgent need for citizens literate in science, mathematics, and technology, bright students—students who love “doing” science—turn away from traditional courses.

Engineering problem solving can propel those students (along with their peers who excel in traditional courses) into rigorous learning experiences within the context of solving problems of the “real world.” Working in teams to develop viable solutions, students learn to value their own thinking and trust their own judgment. They develop an appreciation for how science and mathematics work outside the classroom. They learn how to communicate their ideas to business and professional people as well as to teachers and fellow students. Most important, they become fully engaged as they grapple with the less structured problems they will encounter in their future in classrooms and in employment.

A Different Approach to Learning

Imagine a darkened room, an overhead projector showing a prototype design for a wheelchair braking system. A team of inventors is explaining why the disc brake was their system of choice over fly-wheel, ratchet-action, or lever-wedge systems. Team members take turns explaining the testing procedures used and results of the tests, the potential market for the device, the projected variable and fixed costs of a start-up company, and the profit analysis for manufacturing and selling the device over ten years.

An engineering firm pitching a venture proposal? No, these inventors are high school students, their wheelchair braking system the result of a “Product Design Engineering” course given at The Governor’s School for Mathematics and Science in Roanoke, Virginia. The theme for the course was “Improving the Quality of Life for Citizens with Disabilities.” Other team inventions include a rain shield for wheelchairs and special nail clippers for arthritics. Each team identified a problem, then designed and constructed a device to solve it. The presentation before the professional review board was the students’ final exam.

Now picture a high school classroom in South Bend, Indiana, where a team of pre-calculus students demonstrates its map of a reorganized city transportation system. The cloverleaf design could be a polar curve traversed in either direction. The students explain their formula—the weighting of normal standard scores of population, economic level, and available jobs to give precedence to areas that most need public transportation.

How about a team of high school physics students in Corcoran, California—sons and daughters of migrant farm workers—explaining to members of the Corcoran City Council how to apply the physics of light to determine the optimum color for a headlight to penetrate the dense fog that blankets the community every winter? Or geometry students from Cincinnati, Ohio, discussing the tessellating design they turned into a cracker and its packaging for the Keebler Baking Company? Or biology students on Long Island, New York, demonstrating a design for a sonar device to prevent the accidental netting of dolphins in tuna fishing?

These student teams and others across the country are approaching problems from an engineering perspective. Each team defines and redefines its problem, sets specifications, brainstorms solutions, and selects a single potential solution to explore. As they work together, they know they will iterate the cycle, perhaps many times, until they have devised a solution—a design or a device—that is unique, timely, and useful in the everyday world.

Engineering Problem Solving and Science/Mathematics Reform

Since the early 1980s, high school teachers of mathematics and science have been working toward reform of traditional curricula. Emphasis has been on problem solving, creative thinking, and connections to the world beyond the classroom. Forward-thinking educators from both fields have looked for new ways to foster problem solving in cooperative learning environments. They want to expose students to interdisciplinary approaches. They talk about having students take responsibility for their own learning. They want them to construct their own understandings of the scientific and mathematical worlds.

Teachers, in effect, are describing an engineering approach to problem solving.

Although science and mathematics teachers are often constrained by state- or district-mandated curricula with required topics and tests, many teachers have managed either to integrate the engineering approach into their courses or to supplement traditional coursework with out-of-class project work.

How do they do it?

There are as many solutions as there are teachers. Some challenge their students with problems that take them far from the classroom; others have their students design experiments or solve narrowly defined, discipline-specific problems. Project timelines are as short as a week, as long as a semester. Some teachers expect their students to accomplish the lion's share of project work after school or during study periods; others devote hours of class time; a few have the luxury of designing an entire course devoted to engineering problem solving.

A Working Method for All Students

If the methods of implementation are varied, so too are the students. Reform movements in both mathematics and science call for literacy in mathematics and science for *all* Americans; any educational thrust that targets only high achievers is of marginal value in education reform.

Fortunately, field evaluations confirm anecdotal evidence that student populations traditionally underrepresented in science and mathematics courses—minority students, female students, low-income students, inner-city students, students whose parents may not have finished high school—reap equal benefits.

Louise Bennicoff initiated her Fogbusters project in Corcoran, California (see “Fog Navigation,” page 85) with students whose parents are either farm workers or employees of the California State Prison. The student population is 65% Hispanic, a large number of them classified as migrant. Observers of the Fogbusters project—from external review boards to a professional evaluator from Cornell University—have been consistently impressed with the quality of the work done by these students.

Mike Jabot, a physics teacher in Oneida, New York, gives all his students—Regents, Advanced Placement (AP), and “local level”—the same problem statement. The local-level students often have better backgrounds in building or tinkering and so can act as “mentors” to the others, both in evaluating the feasibility of an idea and during construction of the prototypes. Jabot reports that outside review board members, without knowing which teams are Regents or AP and which are local-level, generally assign scores for the local-level teams equal to and often higher than those for the AP and Regents groups.

The problem-solving cycle also works beyond mathematics, science, and technology. Laurel Macartney, a chemistry teacher from Redmond, Washington, used the framework to help students design their senior projects, a year-long requirement for graduation supervised by the English department. Students who have had trouble selecting a project, who have, in fact, few interests in school and want only to “get by,” use the problem-solving cycle to find areas to which they can apply themselves. For some students, engineering problem solving not only helps them hurdle a requirement, it propels them toward college careers they've never considered.

Realities and Visions

Teachers whose ideas are described in this book have applied engineering design concepts to foster all kinds of student projects. While their work fulfills the new mathematics and science standards, it also functions within the curricular constraints of their particular schools. These teachers know that the approach is an idea in motion, that as they adapt the basic methodology to fit their particular situation, their teaching develops to incorporate finer points. The fluidity of engineering problem solving allows them to work in the realities of today while moving toward the visions of tomorrow.

Chapter 1

The Engineering Problem-Solving Cycle

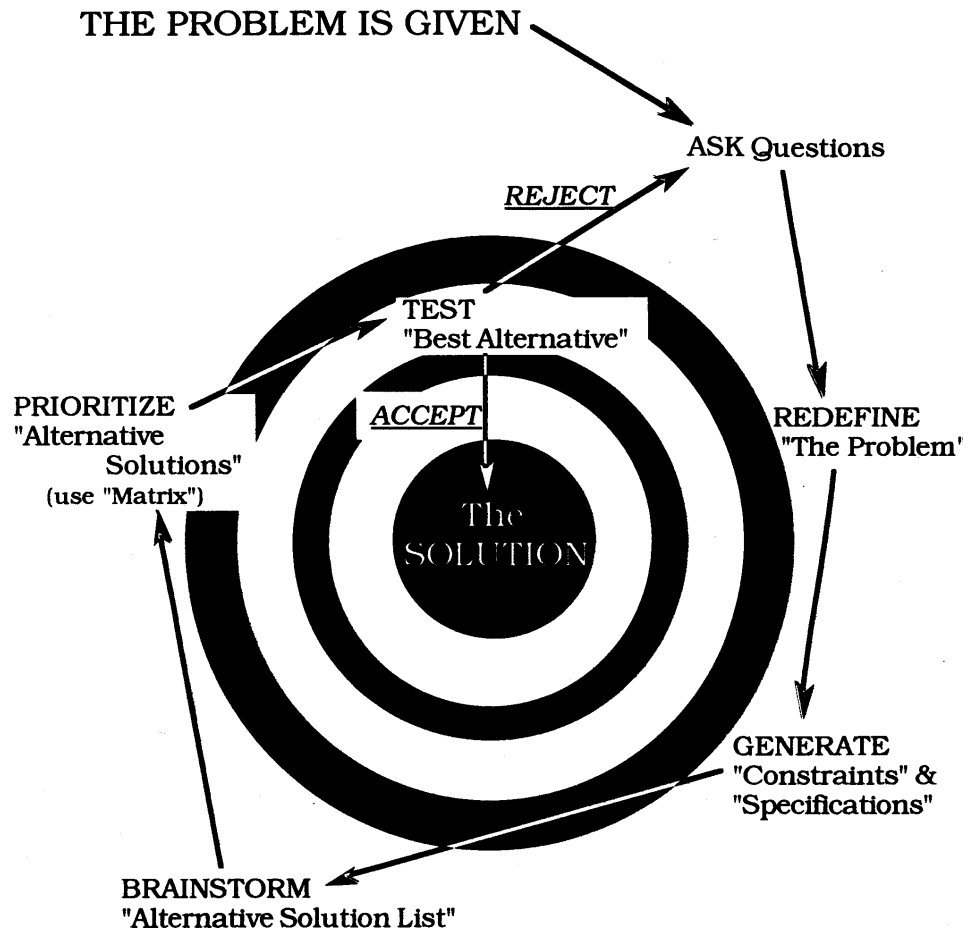


Figure 1. The Problem-Solving Cycle as conceived by Carl Mehrbach, Science Coordinator at Hanover High School, Hanover, New Hampshire.

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Engineering and Problem Solving

Engineers see opportunity where others see problems.
—John Collier, Myron Tribus Professor of Engineering
Thayer School of Engineering

How do you solve a problem?

One way is to think for a minute and then start working with the first idea that comes to mind. If nothing comes to mind, then surely the problem is unsolvable.

If you are working with people who know how to brainstorm, you'll perhaps make a list of ideas, pick the one that appears most feasible, and go to work. But what do you do when your most likely solution pulled from brainstorming seems to lead to a dead end? Do you go back and brainstorm again?

For engineers, the approach to problem solving is more orderly. Engineers—particularly engineers trained at Thayer School—solve problems by proceeding through a problem-solving cycle, step by carefully documented step. If they run into a wall, they don't need to go back to square one. They examine their paper trail and move back only as far as they need, perhaps only a single step. When they have gone the full round of the problem-solving cycle, they look at the original problem and decide whether their solution is specific enough to solve it or whether they need to iterate the cycle.

Each step of the engineer's problem-solving cycle is clear:

- look at the problem carefully
- redefine it to eliminate bias
- identify constraints and set specifications for solutions
- brainstorm alternative solutions
- analyze the alternatives
- select the best potential solution and test it
- look at the original problem statement and decided whether or not you have solved the problem

The problem can involve any kind of decision making, from a social problem such as "Students are taking too long to get into the lunchroom" to a complex one such as developing a device to sort *Drosophila* fruit flies.

Whatever the problem, the engineering team approaches it with interrogating minds. Team members clarify every word in the original problem statement and, if necessary, redefine the problem to make it more precise. They determine constraints that might apply. From constraints they develop specifications that any proposed solution must meet.

Setting specifications aside for a moment, the team plunges into a session of free-for-all brainstorming. "Anything goes" is the rule. A good engineer knows that even an apparently silly idea is nonetheless a valid contribution to the process, that a totally impractical suggestion may indeed trigger the idea that *does* lead to the best solution.

With specifications and a list of alternative solutions, engineers have a method for analyzing every idea before it is either rejected or selected for further development. This method is the matrix.

The Problem-Solving Matrix

The process of homing in on the best possible solution is framed by a series of problem-solving matrices. The columns of a matrix are headed by the specifications, the rows by the ideas for alternative solutions.

Alternatives can be ranked on a simple scale of good, bad, and neutral (+, 0 and -) or a more sophisticated scale that gives additional weight to the most important specifications. The best solution is the one that garners the most points by satisfying the most specifications. For example, an engineering team working on a town's parking and traffic problems might brainstorm the idea for banning cars from the downtown area. This idea would score well for reliability but not for practicality. The best solution will score well for all specifications.

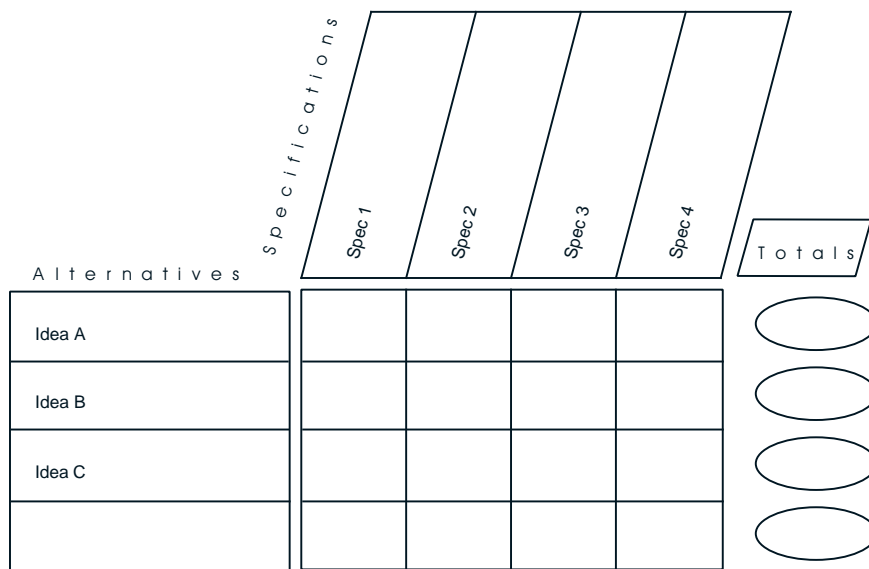


Figure 2. Problem-solving matrix

Iterating the Problem-Solving Cycle

The first round of the problem-solving cycle narrows the focus of the original problem. Then it's time to start another round.

- Redefine the problem to develop a more specific solution.
- Generate tighter specifications.
- Brainstorm more focused alternatives.
- Analyze the alternatives and use the matrix to select the one that best narrows the focus of the problem.
- Reiterate this process until the problem is solved, using a new matrix for each major decision.

For a complex problem, a team may go through the problem-solving cycle a number of times. The first matrix answers the question, "How do we go about...?" The second matrix answers the question, "How will we implement...?" Further matrices answer such questions as "How will we test...?" or "How can we evaluate...?"

As the team iterates the problem-solving cycle, they research and experiment with every aspect of the potential solution. With each cycle, the problem becomes clearer, the constraints more focused, the alternatives closer to solving the original problem.

Iterative problem-solving is "messy." The process involves investigating resources, gathering data, experimentation, and analyzing test results. Any one of these activities may require further investigation, gathering, experimenting, and analysis. With every task carefully documented, at times the paper trail may threaten to spill out of its folder, the project seems out of control. A good team keeps going, knowing that however messy the process, it is also thorough. As shown in the next sections, which follow a team solving an environmental problem, the matrix helps both to narrow the focus and to serve as documentation. The iterations of the cycle assure the team that the best possible solution will be found.

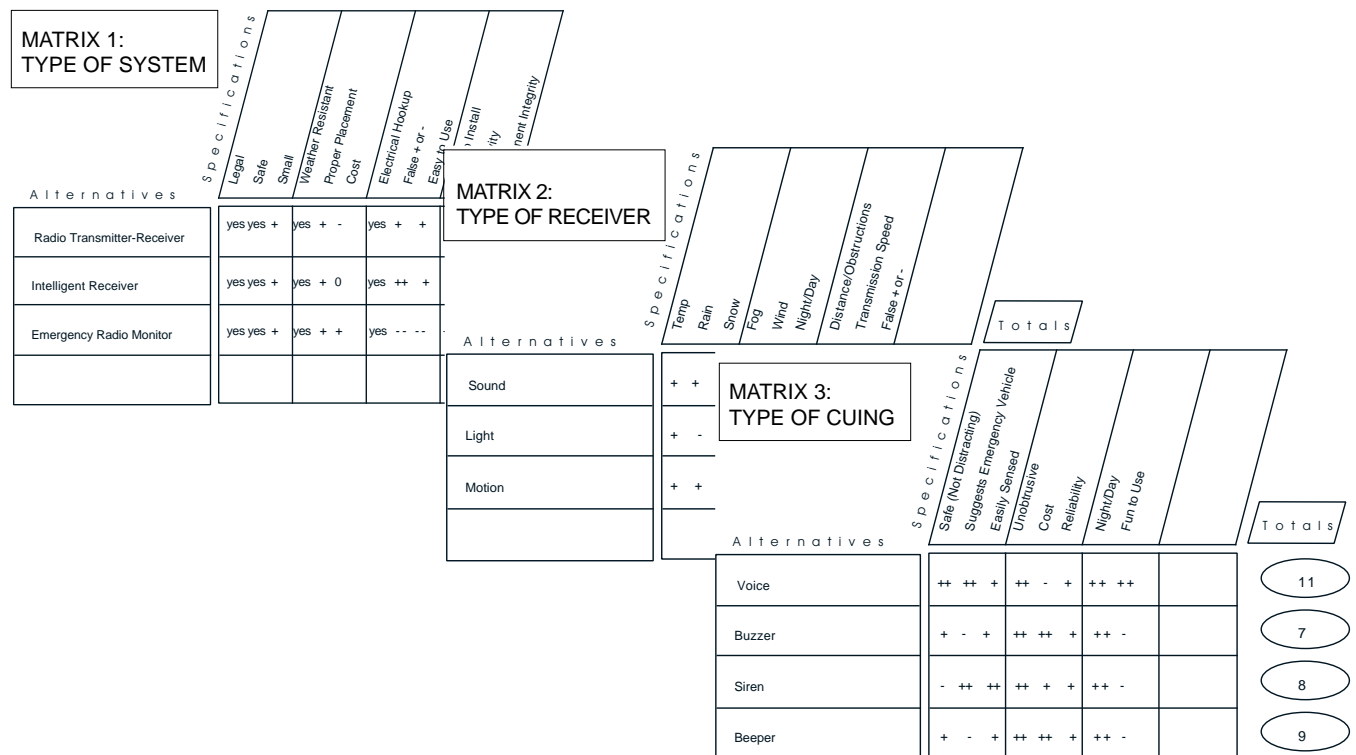


Figure 3. A workshop team's iteration of the problem-solving cycle for an emergency vehicle warning system.

What's the Problem?

The first step in the engineering problem-solving cycle requires a problem statement, one that focuses on a content area of the course or a concern taken from the real world. A problem statement can be

- an open-ended question
- an existing condition in need of change
- a challenge to look ahead for problematic conditions of the future
- a kit of materials provided to design and build something
- a research proposal for a student project

A physics teacher might present students with materials and a narrowly defined problem in aerodynamics, as Jennifer Groppe, of Washington, D.C., did:

You will be given two sets of identical “parts” with which to make two objects. One object is to be as aerodynamic as possible, one to be as air-resistant as possible.

Another physics teacher might present students with an open-ended proposal that requires the use of electronics:

Design an electronic device to aid in the prevention of crime.

A third might, as did Tom Woosnam of Hillsborough, California, take a local problem—such as a dangerous road on which students drive every day—and create an RFP from a fictitious funding organization:

The Triple B Auto Association has published a survey stating that the number of accidents on Route 92 between Half Moon Bay and Crystal Springs Reservoir varies during the different months of the year. CSU Engineering Foundation is interested in developing devices that will prevent the greatest number of accidents.

Each of these problems requires the application of some principles of physics. For a narrowly defined problem, the application is specific. For an open-ended question, the link between textbook physics and the actual problem may seem less clear to students. Such a problem reminds them that the world beyond the classroom is not neatly divided into chapters with questions at the end.

Many teachers begin their problem-solving ventures with a demonstration problem, moving the entire class as a team through one or two rounds of the problem-solving cycle. The problem statement for such problems does not need to be related to the subject matter of the course. The objective is to have the students experience—and discuss as they experience—the steps of the cycle.

In one of the summer workshops for high school teachers, Professor John Collier demonstrated the problem-solving cycle using an energy conservation problem:

An ecologically concerned client wants to change her home heating system from electricity to gas in order to reduce her high heating costs.

It's a good model problem to work through the problem-solving cycle.

What's the Real Problem?

Good problem solvers, according to Professor Collier, assume that the initial problem statement reflects both the customer's bias and a preconceived notion of the desired solution. There is always more to a problem statement than first meets the eye. An engineering team that simply accepts a problem statement may be bewildered by the client's hostility to a proposed solution. If the team begins by understanding the client's implied solution, there will be fewer surprises at presentation time.

Here, again, is the problem.

An ecologically concerned client wants to change her home heating system from electricity to gas in order to reduce her high heating costs.

Look at it closely. There are really two problems.

- The cost of heating her house is too high.
- Heating with electricity is both expensive and ecologically unsound.

The team starts by examining key phrases.

- *ecologically concerned*: How great is her concern? How much is she willing to pay for it?
- *change from electricity to gas*: Is gas always cheaper than electricity? How much does "change" cost?
- *high heating costs*: How do her heating costs compare to comparable homes in the area?

What, then, is the client's bias?

- Heating with gas is less expensive than heating with electricity—if you don't count the change-over cost.
- Heating with gas is ecologically sound, because reduced cost equals reduced energy.

What is the client's implied solution? Clearly she believes that changing from electric to gas heat would both reduce the cost of heat and have least impact on the environment. But is that solution right? That's the question the consulting team wants to answer using the problem-solving cycle. They redefine the problem:

What is the most cost-effective change the client can make to reduce her energy costs?

What Are the Constraints?

With a clearer understanding of the problem, the team sets about generating a list of constraints. What conditions must the solution meet in order to satisfy the client? Research is in order. The team needs to know more about the client than that she is concerned about protecting the environment. For a problem taken from outside the classroom, students will do on-site research; for a theoretical problem, they may use role-playing. Lisa Torres, of Lebanon, New Hampshire, has her students conduct a planned interview with herself or another person acting as the client (complete with costumes and mannerisms).

For the home heating problem, Collier asked all the workshop participants to imagine an in-depth interview and a thorough inspection of the client's home. Their imaginary client, they decided, was

an engineer who lives alone in a mid-Atlantic state in a sprawling brick ranch heated by an electric baseboard system. Her windows are single-pane crank-outs with aluminum frames. She has installed some energy-saving devices, but her costs are still above average for the area.

What then are the constraints?

In the workshop, Collier pointed out that general constraints, such as feasibility, practicality, or reliability, are those that apply to any problem's solution. Specific constraints, such as cost or environmental impact, apply only to the problem at hand. With a good list of constraints, the team can develop the specifications to which each potential solution must conform.

- feasible
- reliable
- economical
- aesthetic
- legal
- moral
- safe
- environmentally sound
- practical
- ethical
- efficient
- timely

From Constraints to Specifications

Engineers never assume that a word is just a word. What does “feasible” mean? What is “practical?” Before a specification is included on the list, it is defined, quantified and justified in order to ensure consensus. Take the specification “economical.” The team decides that economical is

- *defined as:* the greatest savings, considering both capital cost and operating costs, when compared with current costs
- *quantified as:* capital cost, operating costs, and savings
- *justified as:* reducing costs as quickly and efficiently as possible

After taking each suggested specification through the define-quantify-justify process, the list of constraints might be refined into sets of specifications, such as:

feasible: technologically feasible, can be accomplished in less than six weeks

safe: safe for user (trained or casual), safe for installer, safe for bystander

economical: capital cost, potential savings, operating cost

environmentally sound: production and use do not harm environment

At this point, some teachers might ask their teams to record the specifications along the top of the problem-solving matrix. Others prefer to have the students brainstorm before making up the matrix, in order to prevent any negative mental criticism that suggests ideas don't fit the specs.

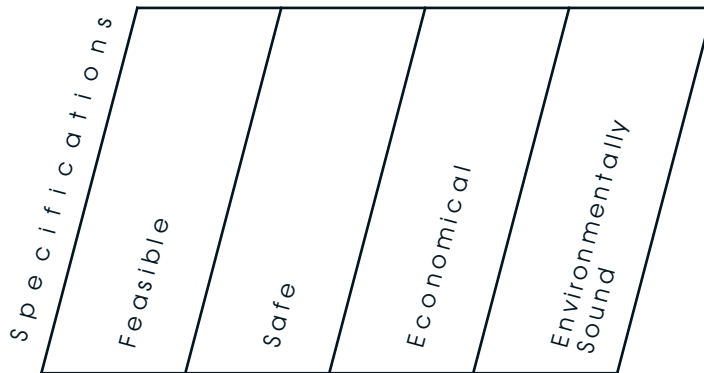


Figure 4. Specifications on the matrix

What Are the Alternatives?

Finding alternative solutions begins with brainstorming. A good brainstorm triggers creative juices. Every suggestion is taken seriously, even ones thrown out for laughs. A recorder makes a list, and every possible alternative goes on it. A long list assures problem solvers that, should a first choice fail, another solution can be worked on.

The high-heating-bill problem generated a lot of ideas.

- Install gas heating system.
- Add wood stove.
- Burn coal.
- Bury the house in an earth berm.
- Add insulation.
- Put a dome over the house.
- Fit windows with drapes.
- Add shutters to windows.
- Install high-efficiency heat pump.
- Plant trees to block the wind.
- Brick in existing windows.
- Install programmable thermostat.

When the brainstorm subsides and giggles taper off, the team is ready to work with the matrix. Some teachers run the matrix analysis with all possibilities, while others ask their students to organize the suggestions into categories, reasoning that a long list on the problem-solving matrix makes the process tedious and unproductive. The disadvantage of the categories is that although a particular idea may be good, it may belong to a category that, as a whole, does not score well.

Organized into categories, the home-heating ideas are placed to the left of the matrix.

A l t e r n a t i v e s
Install new heating system
Lower energy losses
Increase efficiency of current system

Figure 5. Alternatives on the matrix.

Which Is the Best Idea?

In the analysis, the team weighs the advantages and disadvantages of each alternative. Here the matrix comes to life.

In order to analyze the matrix, problem solvers may need to experiment. They certainly need to get out into the field.

Market research tells them what's available. Technical research tells them what is feasible. In the library, they scan technical references and journals. They use the telephone or the Internet to reach other resources, such as companies and trade associations. They conduct patent searches to learn about new energy-saving devices being developed. By the time they are ready to rank the alternatives, they know a lot about heating systems, energy, and efficiency.

A l t e r n a t i v e s	S p e c i f i c a t i o n s				T o t a l s
	Feasible	Safe	Economical	Environmentally sound	
Install new heating system					<input type="text"/>
Lower energy losses					<input type="text"/>
Increase efficiency of current system					<input type="text"/>

Figure 6. Setting up the matrix for analysis

Choosing the Best Alternative

The matrix provides a visual means for weighing the alternatives. Each alternative is ranked for each specification, using a scale everyone agrees on. A simple relative scale is "good, bad, neutral." Quantitatively,

- + Better than the other alternatives
- Worse than the other alternatives
- 0 No appreciable difference

If Ideas A and B are both relatively safe while Idea C is a little risky, then A and B are assigned "0" in the Safe column while Idea C is assigned "-." Another scale might quantify the rankings on this matrix as

- + Having a beneficial impact
- Having a detrimental impact
- 0 Having a neutral impact

A third kind of scale uses positive numbers ranging from 1 to 3 or the popular 1 to 10. Teachers have reported success with the 1-to-3 scale, especially for interdisciplinary projects with non-science colleagues uncomfortable with negative numbers. Most teachers have found the 1-to-10 scale too broad, leading to careless quantification without real differentiation between, say, a 6 and a 7.

Whatever the scale, the rank for each alternative is totaled by assigning numbers:

- + = 1
- 0 = 0
- = -1

The best solution is the one with the highest total.

For the client with the high heating costs, the following matrix uses the beneficial-detrimental-neutral scale, which indicates that the most viable solution is lowering heat losses. It's time to reiterate the problem-solving cycle.

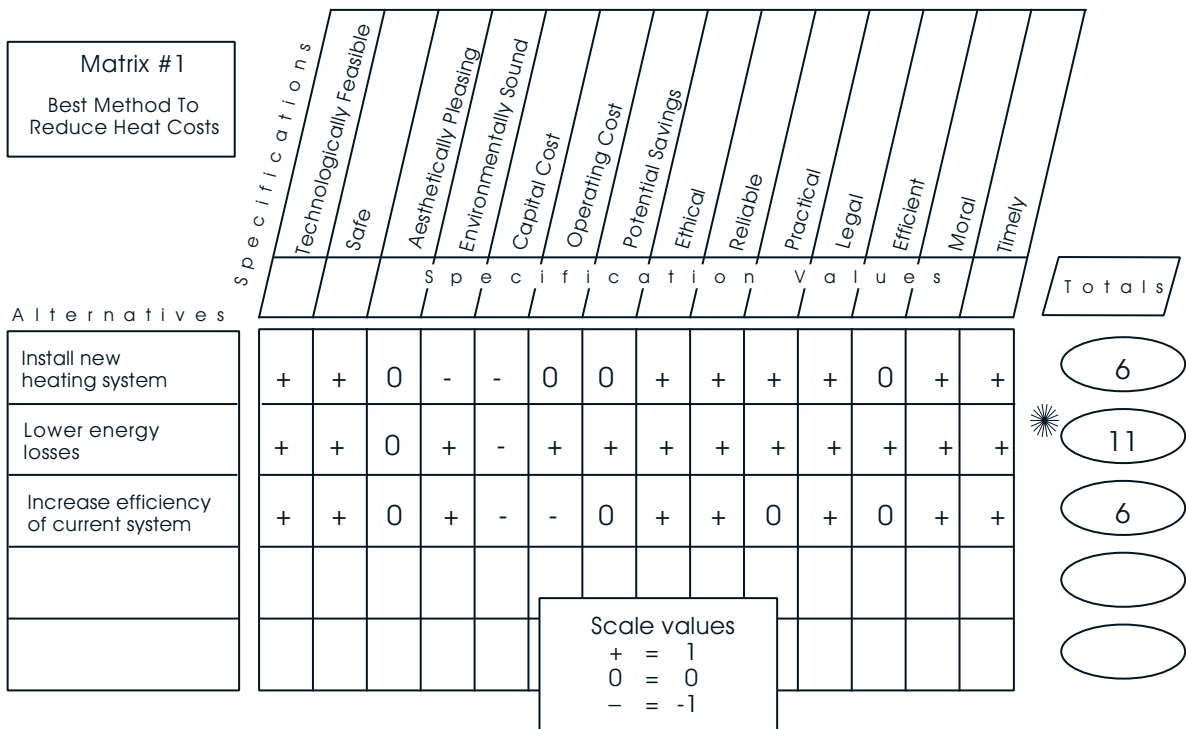


Figure 7. Matrix 1: Best method to reduce heat costs

Another Round, Another Matrix

Now that the team knows the general solution—lower energy loss—they can look for a specific solution. They start by redefining the problem:

What is the best way to reduce heat loss?

The specifications are similar to those developed for the first round, because the first matrix analyzed categories, rather than specific ideas. More general specifications—legal, moral, ethical—can be dropped because the top-ranked category rated well in those; or the second matrix can simply repeat the specifications of the first round.

The team extracts from its original brainstorm list the three serious ways to reduce heat loss:

- Add shutters.
- Add insulation.
- Fit windows with new drapes.

Together, the team members form a new matrix and embark on another round of research. They rank each alternative, and begin the cycle again.

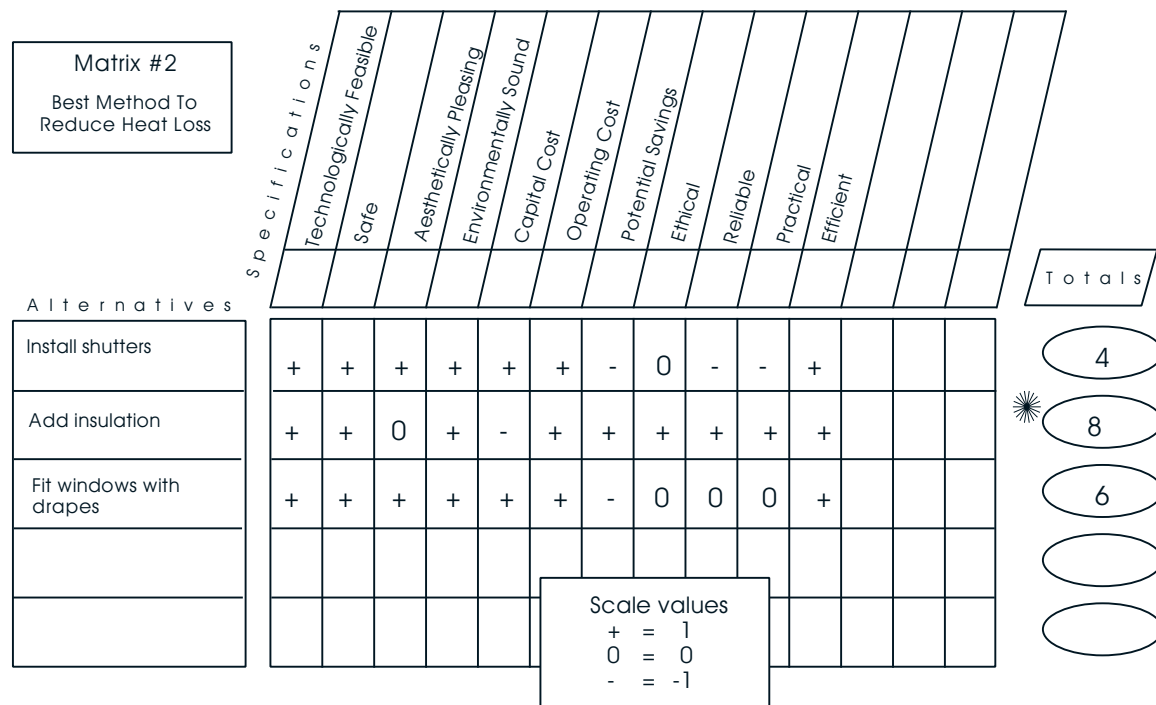


Figure 8. Matrix 2: Best method to reduce heat loss

Round 3, Matrix 3

Selecting the alternative with the highest score from Matrix 2, the team redefines the problem as:

Where in the home would added insulation be most effective?

For this round, the team redefines earlier specifications more narrowly:

non-toxic, non-carcinogenic
 having a real impact on heat loss
 having a reasonable installation cost
 not detracting from the home's appearance

Another round of brainstorming generates potential insulation locations.

windows walls
 attic doors
 floors

Another round of research brings in information on insulation ratings, installation costs, and environmental impact.

As the team reiterates the problem-solving cycle, it evolves a more sophisticated ranking scale for the matrix. Team members decide on the relative value of each specification and weights it on a scale of, say, 1-to-5. For example, Matrix 3 weights each of three specifications—"installation costs," "impact on heating loss," and "non-toxic, non-carcinogenic"—as "5," since these three are all very important in solving the problem. The fourth specification, "must not detract from appearance of home," less important to the ecologically concerned client, is weighted at "3."

Under a weighted system, each alternative is given a rating or "perceived effectiveness" value, again perhaps on a 1-to-5 scale. The actual score for any alternative for any specification would be the product of the specification weight and the rating or estimated effectiveness for that alternative. For example, the estimated effectiveness of insulating the doors is 2 (on a 1-to-5 scale). Since "must not detract from appearance" is weighted at 3, the actual score for insulating the doors, insofar as detracting from appearance, is 6.

Matrix #3 Best Location For Insulation		Specifications				Specification Values				Totals	
		Installation Costs 5=Low Cost, 0=High Cost	Impact On Heat Loss 5=Greatest, 0=Least	Non-Toxic, Non-Carcinogenic 5=True, 0=False	Must Not Detract From Appearance of Home 5=Does Not, 0=Does	5	5	5	3		
Alternatives		2	3	4	2	10	15	20	6		51
Insulate Doors		3	1	2	2	15	5	10	6		36
Insulate Walls		5	5	5	3	25	25	25	9		84
Insulate Attic		5	5	5	5	25	25	25	15		90
Insulate Windows		2	1	5	5	10	5	25	15		55
Insulate Floors											

Weighted importance in relation to other listed specifications. Scale: 1-5.

Product of specification weight and perceived effectiveness.

Perceived effectiveness Scale: 0-5

Figure 9. Matrix 3: Best location for insulation

Round 4, Matrix 4

With insulation for windows ranking highest on Matrix 3, the problem is redefined as:

What is the best way to insulate windows?

The team can look back at previous matrices to find the appropriate specifications. With an improved understanding of the problem, team members may want to refine the specifications or consider one or two more.

capital cost
 non-toxic, non-carcinogenic
 longevity (7 to 10 years)
 operating cost
 potential saving
 does not detract from appearance of home

By now, the team members' brainstorming is not only focused, it is also informed by a good deal of research. The list of alternatives is thorough.

plastic film over the windows
 shutters on outside of windows
 storm windows
 fiberglass on outside of windows

Placing alternatives and specifications on another matrix, assigning specification values, determining estimated effectiveness, calculating the rankings—team members are sure of their solution.

The homeowner should retrofit her house with Thermopane windows.

They are prepared to justify the retrofitting even though the capital cost is higher than for the other alternatives.

In their presentation to the client (or to a review board of teachers, administrators, and members of local business and professional communities), the team can back up every decision with solid research. The solution, with the accumulated documentation, is convincing:

Glass is better than gas!

Alternatives	Specifications							Totals
	Capital Cost 5=Low Cost, 0=High Cost	Operating Cost 5=Low, 0=High	Potential Savings 5=Low, 0=High	Non-Toxic, Non-Carcinogenic 5=True, 0=False	Must Not Detract From Appearance of Home 5=Does Not, 0=Does	Longevity (7-10 years) 5=High, 0=Low	Participation of Owner 5=No, 0=Yes	
Plastic Film Over Windows	5 25	0	1 5	5 25	0	0	0	55
Install Storm Windows	2 10	0	4 20	5 25	3 9	5 15	1 3	82
Shutters On Outside of Windows	4 20	0	0	5 25	4 12	5 15	1 3	75
Fiberglass On Outside of Windows	3 15	0	2 10	5 25	0	1 3	0	53
Install Thermopane Windows	1 5	0	5 25	5 25	5 15	5 15	5 15	100

Figure 10. Matrix 4: Best method for insulating windows

Chapter 2

Getting Ready

Making It Work

The engineering framework for problem solving challenges students to take responsibility for their own learning. It also demands a strong commitment on the part of the teacher.

The teacher's primary tasks are to help students pose questions they can successfully pursue and to interpret the results of the students' work in terms of the appropriate discipline. Full implementation of the engineering problem-solving cycle, though, is more than helping students pose questions and discover solutions. The teacher is called on to develop resources—human resources, paper resources, technical resources—not readily available in standard textbooks. The teacher becomes a mediator of a process that may take students outside the teacher's own area of expertise. When the time comes for assessment, the teacher must oversee a review process that demands much more energy than is required for scoring short-answer quizzes or multiple-choice tests.

Bridging the Gap

Physics teacher Jeffrey Lange poses the question, "How can schools bridge the gap from theoretical on-paper work to the full process—patent research, building a physical model, review panel—especially for other than Advanced Placement or highly motivated students?"

Every school has its own constraints—the flexibility of the curriculum, the structure of the school day, the technology available—and every teacher has ideas for potential implementations. The best scenario is an interdisciplinary team approach with strong support from the administration and the local community. A teacher who feels isolated in the classroom needs to build alliances by offering peer training, inviting colleagues to sit on a review panel, and initiating joint projects with colleagues. Teachers with access to the Internet may use e-mail to communicate with like-minded reformers; those without e-mail can work through professional organizations.

Even in the most supportive environment, implementing change is a long-term process. Some teachers begin by introducing project work above and beyond the ordinary expectations for their course. Others augment their curriculum by adding some, but not all, aspects of the engineering approach to problem solving. Still others integrate problem-solving methods into their current curriculum by displacing traditional course content. Teachers need to assess their particular situations and find the best match. The integrative method works best for most students and teachers, but any implementation places a teacher at the frontier of reform in science and mathematics education.

Supplementing the Curriculum

Some teachers report that even in a course rigidly content-driven, opportunities arise to use the problem-solving cycle. When physics teacher Tony Komon began implementing engineering problem solving in his classes, he remained obligated to provide the content to prepare his students for the New York State Regents Examination. Reasoning that in the typical forty-minute period, the first ten minutes are generally used to take attendance and for other management tasks, he turned those minutes instead into project work: ten minutes a day of formal attention to the problem-solving cycle—the rest of the project work comes out of student energy and a teacher willing to be available to his teams during lunch and after-school hours.¹

Problem Solving in the Lab

Teachers can incorporate engineering design into laboratory work. When biology Gene Hampton brings students into his lab, he gives them a traditional experiment, for example:

When yeast is fed different amounts of food, what is the effect on its gas production?

Then he challenges them to design an experiment. The students work in groups to redefine the problem and establish parameters for the experiment. What could have been a simple cookbook exercise becomes instead a unique venture into research design, a mini-project that extends over several lab periods.

Lisa Torres has her chemistry students design their own experiments, and expects them to define both dependent and independent variables. For example, with the class working on gasses, she may set experiment parameters as:

What is the effect of A on B?

To redefine the problem, each team must decide which gas will be the subject of its experiment and which variables to manipulate. Once two teams have signed up for, say, the effect of volume on temperature in air, that topic is closed.²

Torres creates an environment which pushes students to design their own equipment. She purposely keeps only two pressure gauges on hand; if both are in use when a team needs to measure the air pressure of a deflating balloon, the team is encouraged to invent a gauge that will give them the data they need.

Independent Projects

Teachers who encourage students to enter national competitions, such as the Duracell Contest or the Seiko Youth Challenge, find that many of these are open only to individual projects. Teachers, especially those working with students whose social skills are limited, sometimes encourage independent work: “Certain students,” says Gene Hampton, “especially the introverted ones, just work better alone.”

The engineering approach, although it emphasizes teamwork, contains many elements that can be exploited by the single student. Even brainstorming, clearly a group activity, can be simulated when an individual discusses ideas with other students, friends, relatives, or mentors. Other elements of engineering problem solving—constraints, matrix work, iterating—provide valuable structures for an individual project.

1. See “Project Work on Ten Minutes a Day,” p. 88.
2. See “Designing Chemistry Labs,” p. 107.

Integrative Problem Solving

Teachers who choose to integrate engineering problem solving into their courses face the question, "Can I do project work and still teach all the course content?" The answer to this question is probably, "No, not without sacrificing my sanity!"

Taking the integrative approach means being committed to the vision of scientific literacy defined by AAAS' Project 2061. To assert that memorizing the symbols of the elements is less important than being able to ask intelligent questions and find reasonable answers about those elements may mean going out on a limb, but that is a risk teachers may be increasingly willing to take as reformers redefine the terms of twenty-first century mathematics and science education.

Just what content might be jettisoned to make room for engineering problem solving, teachers and administrators will need to decide for themselves. When physics teachers Tom Woosnam and Jim Housley discussed this issue, they concluded that every student of physics must study mechanics; beyond that topic, they suggest, physics teachers can generally define the course of study.

Woosnam presents the problem-solving cycle on the first day of class; so far as his students know, physics *is* problem solving. For his honors physics course, the first semester involves problem solving around the topics of light and optics followed by a thorough grounding in mechanics. In the second semester, students solve problems in relativity, particles and interactions, and electricity and magnetism. Gone are solids and fluids, fluids in motion, and thermodynamics, not because these areas are less important, but because this is Woosnam's choice. Students who need to learn areas of excluded content in order to take the Advanced Placement Physics examination work with him before school and during activity times.

Interdisciplinary Problem Solving

Mathematics teacher Nancy Borchers has drawn a number of her colleagues into project work by initiating interdisciplinary teamwork. Students from the art department worked with her geometry students, as have students from American history, computer science, physics, and Spanish classes. She has also involved several elementary schools in her district by having her pre-algebra students design math games and then teach them to both third graders and their teachers.³

Carla Huffman and Laura Rabe team-teach several integrated mathematics-science projects each year. In 1996, their cellular biology and pre-calculus students probed the question:

Which type of bacteria is best for a spectrum of research?

Environmental science and algebra students took on acid rain; chemistry and advanced algebra students investigated gas laws.

A number of teachers have called on their school technology teachers for expertise and supervision of prototype construction. In Hanover, New Hampshire, for example, science coordinator Carl Mehrbach team-teaches his course with technology instructor David Johnson.⁴

Other teachers have introduced the approach to teachers outside the mathematics and science departments. New York Wayne Snyder reports that colleagues in the Social Studies department have adapted engineering problem solving for their Participation in Government course and that the technology teacher is excited about its potential in his classes. "We envision this method becoming a standard format that students will encounter throughout their high school experience."

3. See "Interdisciplinary Geometry," p. 90.

4. See "Engineering Concepts for Advanced Students," p. 96.

An Entire Course of Problem Solving

Having sold their schools on the tremendous potential of engineering problem solving, several teachers have developed semester or year-long electives that integrate science, mathematics, and technology into a single framework. Karen Falkenberg, formerly a mathematics and science teacher, offered a year-long elective called “Engineering Concepts” that took students through short- and long-term projects. Science teacher Carl Mehrbach has created an engineering class for seniors who have already completed the chemistry and physics curriculum or who have completed one course and are enrolled in the other. Both curricula begin with short-term, narrowly defined problems and gradually work with their students toward a substantial final, open-ended project that moves each team through the problem-solving cycle to patent searches to professional review boards.⁵

“Front-Loading” the Course

However teachers choose to implement Thayer-style project work, they know implementation depends on detailed work before the project starts. “Front-loading” the course, as John Collier puts it, means that teachers put in many summertime hours making sure the structure is in place. Course goals, potential problem statements, timelines, review criteria—all need to be carefully thought out before the first day of class. Potential human resources—colleagues, administrators, guidance counselors, librarians, mentors, review board members—must be contacted and given information on the teacher’s expectations. Preparation is indispensable for all teaching, but getting ready for engineering project work requires more than lesson planning. The teacher is the hub of a large network, and managing the network calls for skills above and beyond in-depth knowledge of subject matter and how to teach it.

The rewards are great. Guiding students into the kind of scientific inquiry that mimics the work of the professional engineer, scientist, or mathematician—this is the stuff of real teaching. Students who define their own problems and take responsibility for their own project direction never ask, “Why are we doing this?” They know why they are working so hard, staying after school or meeting during lunch hours. Teachers often report that students, after project work is over, wonder why they can’t learn this way every week.

Reckoning the Cost

Designing a device is paperwork; constructing it requires materials, and materials cost money. How do teachers, with tight school budgets, pay for project work?

Grants are one way, of course, although grant writing is tedious and time-consuming. Reform in teaching science and mathematics is high on the priority list of many funders, so a proposal can be worth the effort. Even when grant money is available, teachers still are wise to limit the amount any team may spend for a single project.

Scavenging is another route. Companies are often happy to donate equipment to students who approach them with a clear explanation of their project and their needs. Louise Bennicoff notes that her students, most from low-income families, managed to scavenge a discarded radar system from the California Department of Transportation and an ultrasonic range finder from a local agriculture business. “I just blindly gave assignments,” she says, “and the kids found creative ways to get what they needed.” For a final exam, she asked students to build a race car propelled by the energy of a falling brick; one car rolled along its appointed course on wheels borrowed from the superintendent’s barbecue grill! In more affluent communities, teachers sometimes assume that their students’ parents will help purchase necessary materials or equipment, yet “I do stress that the project is not to cost a lot of money,” says physics teacher Tom Woosnam.

5. See “A Whole Year of Inventions,” p. 94.

Course Goals

Traditionally, the goal of a course is the mastery of a specific body of knowledge considered central to that discipline. Although the AAAS calls for reversing the “accretion of memorized material,” teachers are caught in the disparity between the goals of Project 2061 and their classrooms today. Yet, even in content-driven courses, teachers can redefine their goals so that engaging students in active learning is primary.

General Goals

Professor John Collier tells students on their first day of class that his course will

- be interesting, even exciting
- build confidence
- show problems as opportunities
- allow the use of creative energy
- show why engineering is exciting
- permit them to create something novel, do something never done before

As if inviting his students to intrigue, Collier announces that there will be no quizzes, no exams, no homework. Nevertheless, he promises that they will work very hard indeed and will have opportunities to present their ideas for evaluation before a professional review board.

Mathematics teacher Mary Lou Derwent wants her students to:

- explore divergent as well as convergent thinking through brainstorming
- be exposed to the interaction between the agendas of technology and society where there are mutual restraints and tradeoffs
- acquire both a thought process and a tool that is a life-skill

In peer-training workshops, Derwent emphasizes that the goals of project work are to increase students’ interest, encourage development of multiple solutions, encourage creativity, expand interdisciplinary work, expand learning into unexplored areas, and foster the students’ personal expertise. Project work reduces the teacher’s power. “The teacher,” Derwent tells her colleagues, “is the coach with the students only dependent on the teacher’s knowledge to move them along.”

Lynn Stallings, from the University of Georgia, sees a number of critical factors for a course framed by engineering problem solving:

- relevance
- work on project / problem of broad scope
- production of a final product that is valued by those inside and outside the school
- “real-world” working conditions, such as autonomy, teamwork, resourcefulness
- integration of a variety of student skills from different disciplines, such as mathematics, physics, engineering, writing

Integrating Project Goals with Content Goals

Adding these goals to a course already crammed with specific content goals asks a lot of both teachers and students. Teachers who guide engineering electives acknowledge that they have the advantage of not having to worry about whether the course prepares students for a more advanced level of science or mathematics. When the problems are open-ended, they know, not everyone is guaranteed to “learn” the same concepts. For required courses that feed into other courses, the challenge is clearly greater.

As teachers revamp courses, they may want to involve their students in the process, as John Van Ackerman did in when he challenged his physics students to solve the problem of how best to learn physics.⁶

Setting goals, whether with students in a single class or by involving the entire faculty and administration, calls for an assessment of the immediate situation. No one expects the goals of Project 2061 or the standards of the professional science and mathematics organizations to be realized overnight. Teachers do well to set themselves both long-range goals (wish lists for restructuring) and short-term goals (what can be accomplished now).

Support Networks

The most successful project work is a collaboration with other adults involved as mentors to students and as support for teachers.

Mentors for Students

Traditionally, students with questions go to the teacher for help. Students who choose their own problems to solve often find themselves exploring areas outside the domain of their teacher's expertise. An outside mentor—a professional scientist, technician, engineer or business person—can provide the technical support they need, acting as a consultant and providing feedback at crucial points in the project. Mentoring by adults outside the classroom offers students first-hand experience of how scientists, for example, function in their jobs. Although business and professional people lead busy lives, many are pleased to be informally involved with student projects.

For a mentoring system to work well, the teacher must locate—before the project begins—people willing and able, with expertise in some aspect of the problem area. Colleagues, administrators, school board members, college professors, public officials, hobbyists, as well as business and professional people from the community all are possible contacts. Interested teachers within the school can also be helpful as mentors. Case managers or resource-room teachers can be enlisted to work with students on Individual Education Programs (IEPs), as editors for written work or checkers for math calculations or simply as intelligent “nonprofessional” readers of reports.

Formal Mentoring Programs

Teachers who have established formal mentoring programs have trained mentors in the engineering approach to problem solving. Some train mentors for local science fair projects, knowing that as the approach spreads, it will benefit everyone involved in guiding young scientists.

Science Pioneers, Inc., a group sponsored by The Greater Kansas City [Missouri] Science and Mathematics Alliance, holds an annual “Meet the Mentor Day” when parents, teachers, and students can meet scientists, technologists, engineers, and master teachers on their mentor roster. Science Pioneers offers high school students the opportunity to be science mentors to elementary and middle school pupils, to help them develop ideas for science projects, to advise them along the way, and to show them how mentoring works. Although Science Pioneers was founded to assist in science fair competitions, it enthusiastically endorses the use of its services for high school classes undertaking project work.

Approaching Mentors

Students often need assistance with telephone manners and writing business letters. For Lisa Torres “it is important to monitor letter writing and sometimes to teach phone skills and rehearse these with students. Some are easily frightened and discouraged by switchboards! Writing a script for phone questions helps kids use the phone appropriately.”

Students may also need help formulating e-mail requests for help. Kathleen Conn tells of a student who left a message on the America OnLine LabNet bulletin board asking for “help in choosing a science project.” “This highly inappropriate request received a sole very appropriate reply,” Conn said, “Please be more specific.”

More mature students can be responsible for finding mentors. They may already know people in their field of interest—relatives, family friends, neighbors, former students. Seeking out their own mentors can be part of the learning experience. Jim Housley asked his seniors to locate potential mentors in the science departments of the colleges to which they were applying and to work with them via e-mail. Although he edited their initial letters to make sure the requests were appropriate, the students were responsible for tracking down potential mentors.

Housley’s first experience with this approach confirmed his sense that he doesn’t need to be an expert for students to benefit. “When I started having kids use e-mail,” he says, “I didn’t know how to use it myself. When the letters [from potential mentors] came back, I nudged certain students to visit the computer teacher who had a university account with access to the Internet, and to try their hand at it. A few had parents who used e-mail. Kids asked one another for help. So it grows.”

Once mentors have volunteered their time and energy to a project, it’s important to acknowledge their work with at least a thank-you note. Everyone who helps students of Mark Temons receives a letter of gratitude from him as well as letters from his principal and his superintendent and an official public thank-you from the school board at a board meeting.

Keeping Track of Mentors

With a good support system—student mentors, potential guest speakers, review board members, e-mail support—a filing system is essential, preferably one that can maintain information on each person’s availability, usefulness to particular parts of project work, and, perhaps most important, time the person has given to the program. Common sense says that someone who has just put in a hundred hours on a first-semester project may not be interested in signing up for the second semester. Where more than one teacher in a community is overseeing project work, a master file may insure that the best support people don’t burn out and that teachers do not wear out their welcome in the community.

Support for the Teacher

Without support, teachers become isolated in their separate classrooms, talking to no one but their students or random colleagues on break in the faculty lounge. Teachers need to develop support systems within their departments, across disciplines, and outside the school. A well-run project requires moral, logistical, and financial support, along with expertise from outside sources. Outside support won't lighten the teaching load, but it will make the work more fun as others are drawn into the excitement of student inventions.

In the ideal environment, several teachers from different disciplines work together, guiding the process with enthusiastic support from their colleagues, the school librarian, school board members, the administration, and support staff. Although the teacher is ultimately responsible for the course, many details of the process—students' use of telephones, budgeting, arranging field trips, hiring substitutes to free other teachers to act as consultants and review board members—are best handled by the school's administration and support staff. The school library or media center is where students will begin their research. School librarians can direct their use of other library facilities, either in the community or at a local college or university. If the media center is connected to the Internet, library staff can show students how to find resources across the country. They may also be available to assist students with written and oral presentations and participate further by acting as consultants and review board members.

Outside the school, teachers can look to the community librarian, parents, business and professional people, instructors from the local college or university who may be willing to speak to a class, provide a field trip, act as consultants, or serve on a review board.

One way a teacher can build a successful support network is to offer workshops and presentations to colleagues in their school districts and at regional or national teachers' conferences. Sharing information about the engineering approach to problem solving will help build an enlarged support system as well as help a teacher solidify concepts and techniques.

Support on the Internet

Many teachers keep in touch on the Internet. Dartmouth has set up an e-mail "reflector," so that graduates of the Engineering Concepts workshop can post queries and share classroom experiences. This exchange of ideas and excitement is invaluable, especially for teachers surrounded by traditional teaching who otherwise lack such support.

"Labnet," a teacher-mediated network for science teachers, is a member-only Keyword group available (for a fee) to subscribers to America OnLine (AOL). Each subject area has a folder to which teachers contribute ideas about teaching methods, opportunities for grants, and information on workshops or long-term projects. Because contributors are encouraged to create their own folders, New York teacher Nancy Moreau, for example, created one for Engineering Concepts in the High School Classroom in which she posts information about the Thayer School summer workshop and re-posts items from the Dartmouth reflector.

A number of other ramps to the information highway are available to teachers. In some states, public universities offer free Internet access to teachers, who are asked to fill out an application and describe how the Internet would enhance their students' learning. In other states, departments of education are working to get Internet accounts for teachers with nodes where teachers can have access via local calls. Larger school districts maintain Internet nodes that supply all interested teachers with free accounts. For teachers new to the information highway, the best bet is to contact the state department of education or the state university's Education Department to find out what is available.

Chapter 3

Creating an Environment for Problem Solving

Teamwork

Early in their school careers, students learn that cooperation on a test is called cheating. How can they move from an environment where unassisted individual work is valued to one where the work of the individual is subsumed into the team effort? How do they prepare themselves for the world outside the classroom where performing jobs often depends on an ability to work cooperatively?

Selecting Team Members

In a work situation, management may assign small groups of two or three people or large groups of a dozen or more. In the classroom, a teacher can choose either to assign teams, let the students self-select, or use some combination of these selection methods. Most teachers find groups of three to six students optimal for effective teamwork.

Louise Bennicoff, who directed the “Fogbusters” project in the San Joaquin Valley of central California,⁷ introduced her students to the problem-solving process by asking:

What is the best method for choosing a group for the project?

Her whole class, working together, developed specifications for a “good group” and evaluated their alternative solutions on a matrix. They concluded that groups ought not to reflect friendships but, rather, a balance of skills as well as access to simultaneous study halls. When Bennicoff asked them to apply this solution to form groups for the Fogbusters project, they ignored their conclusions and separated entirely along friendship lines. Bennicoff decided not to override their decisions until it became clear that some groups were not functioning, at which point she regrouped them. She says that were she to do it over, she would have held them to their own conclusions.

Harry Stuckey’s students also ignored their own specifications for a “good group,” but Stuckey neither overrode their decision nor let it stand. “I told them that if that was how they wanted to choose groups, the specifications would have to be rewritten. Most students understood what I was saying. I was not forbidding them from doing it, merely pointing out that it did not meet their own specifications. One student commented that the leading proponent of free choice had already selected a group of friends and was attempting to steer the class his way. It did not work. The original specifications stood and were followed by all.”

Teachers preparing for project teamwork need to weigh the advantages and disadvantages of different team-selection processes.

- When the teacher assigns team members, group size and a balance of skills and abilities can be assured. Other criteria may include students’ common free time or home proximity for out-of-class work. The main disadvantage is student resistance to being separated from their friends.
- When students choose their own teams, the main advantage is student enthusiasm. The disadvantage is that the groups will be formed according to friendships that ignore balancing or having mutual free time. Teachers should be prepared to intervene if selection of groups by the students leads to teams that cannot get the work done.
- A compromise lets the teacher solicit student input and take preferences into account, to create groups that balance compatibility, motivation, intellect, and gender.

7. See “Fog Navigation,” p. 85.

Balance

Physics teacher Debra Hill has used a variety of strategies for team selection, including matching students by using a formal learning-style test and balancing academic achievement (at least one “A” student per group). “I find that identifying students in terms of these styles and providing training to the whole class on the strengths and challenges of each of these styles has reduced conflict in teams tremendously. Also, by placing a variety of styles in each team, productivity has gone way up.”

Dale Faughn also selects balanced teams himself but often does not let his students know the criteria. Occasionally, he chooses group leaders, gives them the class roster, and asks them to choose their own teams privately.

Some teachers believe in random selection, even picking cards to group students. “Differences among groups and differences among students in a group reflect student personality differences,” notes Kathleen Conn. “Occasionally shy or reserved students became more outgoing during the project process, but strong, outgoing students never became weaker or less vocal than they were in ‘ordinary’ classroom or lab situations.”

Gender Considerations

“A conscious effort to ‘balance’ the groups based on gender,” points out Linda Hayek, “makes the statement that gender makes a difference. Is this true? Is this important? In my experience, I see students placing themselves in all-girl, all-boy, and mixed groups. I see no detectable difference in the product.”

Tony Komon’s experience is different. He sees girls on all-girl teams as “less inhibited and more able to express themselves openly in their presentations than girls in mixed-gender groups.” All-male groups, on the other hand, tend to get right to the invention, he says, building the device and improving on it while paying less attention to the process. He agrees with Kathleen Conn that personality is the key. “The right mix may well be personality balance. Gender consideration as the only criterion is a bad idea if the personalities clash.”

Maturity is as important as gender, says Jeffrey Lange. “Balanced teams probably stay more on-task, with less discussion about friendship or school activities,” he says. Mark Temons agrees: “For me, age seems to be the primary consideration. With younger groups—ninth and tenth graders—having same-sex teams seems to work much better. As the students’ maturity level increases, this consideration is not so important. A consistent factor, regardless of age, is that same-sex teams seem to ‘compete’ with one another and that seems an additional motivating factor.”

While Wayne Snyder observed boys and girls working alongside each other with model building and sharing equally, Harry Stuckey’s observations, led him to the opposite conclusion. “No matter how bright the girls,” says Stuckey, “they tend to defer to boys even when they know the boys are wrong.” He sees boys dominating mixed-gender groupings, regardless of job assignments, with girls ending up doing a disproportionate share of the work. All-girl groups, he believes, seem to work together better and be more productive than either mixed-gender groups or all-boy groups.

Encouraging Girls

If one of the objectives of engineering problem solving is to prepare students for situations beyond the classroom, then girls must learn to work in mixed-gender groups without deferring to boys or letting themselves get stuck with the grunt work. Stuckey thinks all-girl groups may help girls practice risk-taking behavior. "Some of this is subjective," he admits, "but some is supported by on-going research."

Teachers may disagree on gender issues in team selection, but they know that it is important to encourage girls, especially girls who appear deferential. Teachers may need to intervene when boys dominate a group. If boys significantly outnumber girls in the whole class, teachers should ask themselves why girls are avoiding the course. Research on gender issues is available; teachers who want to review the latest findings can check with their school or local librarian.

Structure of the Groups

Each member of a team has a vital function; all are expected to be active participants. The team, as a unit, determines what to do and how to do it. Structure is essential.

Professor John Collier leaves the structure of the group to the teams, but he cautions students that a democratic, egalitarian approach to group dynamics may not be the most efficient way to accomplish a job. In teaching undergraduates in engineering, he suggests that each team consider itself a company and assign traditional corporate roles.

- The PRESIDENT directs the group effort, fosters consensus building, facilitates meetings, and acts as the tiebreaker when two ideas are equally championed.
- The SECRETARY tracks the scheduling, keeps the team log, determines who prepares oral and written reports, acts as the liaison in contacts with business and professional people.
- The TREASURER is responsible for the budget and for cost analyses.
- The ENGINEER is responsible for testing of the device the team designs and analyzing results.
- The "RADAR" (from the "gofer" character in *M*A*S*H*) facilitates materials acquisition, often using the telephone to beg, borrow, or barter what cannot be purchased within budget.

Other roles can be devised as needed for the project. Some teachers assign roles; others give students the responsibility to do so. With small groups, each team member may wear two hats so that while waiting for one job, he or she can work on another. In long-term projects, students can rotate roles so everyone comes to understand what being a leader or a good gofer means.

Group Dynamics

When teamwork is part of the problem-solving process, students learn some valuable lessons about group dynamics, among them:

- that one single uncooperative member hurts the entire group and the project
- that listening to others is as important as communicating one's own ideas
- that each team member has to understand the point of view of every other member

Taking time to formalize some rules of the game can head off some problems. Professor Collier's students are expected to:

- attend team meetings
- listen to others
- have respect for others
- try to understand other points of view
- not tell others what they should think
- contribute ideas but also understand the ideas of others

Chemistry teacher Lisa Torres call her approach "KISSES." She tells her students:

- **K** Keep your group together
- **I** Include all
- **S** Share ideas
- **S** Stay on task
- **E** Encourage others
- **S** Soft voices

She uses a "group-skills" matrix on a clipboard—columns headed by the skills she deems important and rows headed by students' names—to help her rate team skills as part of her evaluation process.

Before a project begins, Deb Hill takes time to involve students in activities intended to develop group skills. As a whole-class exercise, they discuss ingredients for a successful team; when the students form their teams, they focus on each ingredient and decide which actions are essential for each ingredient. Hill uses a Team Evaluation form to score each team, and asks team members to monitor themselves both as a team and as individual members of the team.

Nancy Moreau also believes in group processing. "Reflect regularly," she tells her students. "Effective projects are influenced by whether or not groups reflect on how well they are functioning." She gives her teams in-class time for assessing their progress, asking them to list three things the group is doing well and one area where it could improve. "At the high school level, students need to be reminded of cooperative behavior on a regular basis. This also reduces the potential for conflict later in the process."

Some difficult group dynamics can be beyond students' ability to resolve. A teacher may need to pull a team member aside, step in and facilitate a meeting, or even, as Louise Bennicoff did, regroup teams which are not performing well. An outside person—the assistant principal or guidance counselor—can be appointed to mediate major disputes.

Like any skill, teamwork comes with practice. Just as students build science skills by doing experiments over and over, they develop group skills by fumbling, taking wrong turns, analyzing what went wrong and trying again. Teamwork skills are essential to doing good science or engineering work.

Teamwork With Socially Limited Students

Some students simply do not work well in groups. Lisa Torres often teaches classes in which there are large numbers of students with limited social skills. With such a class, she allows students a lot of input for group selection, at least at first. "When I begin choosing groups," she says, "I ask each student to tell me *in confidence* the name of one or two others with whom she or he cannot work, and I respect this." She has students work in teacher-assigned pairs for very short (one- or two-day) projects, then gradually increases both the project length and the group size. "I still find *three* to be the *maximum* size for students with limited social skills."

Some teachers go further than Torres and allow students with limited social skills to work individually. Biology teacher Gene Hampton says that he sometimes finds a tension between group projects and individual interest. Some students, he says, particularly "intellectual introverts," do better when they develop their own projects. Hampton walks such students through the engineering model individually and matches them with mentors. Louise Bennicoff also allows students to work individually. "One of the advantages of a small school," she says, "is that you generally know all students' personalities before you get them in physics. One year I had a few personalities who could not cope with group work at all, so I offered an individual option, which was to enter the 'Design a Duracell' contest."

Absent Team Members

Some teachers make sure team members have one another's phone numbers so an absent member can be called and given a "homework assignment." From the beginning teams understand that they are in charge of working out problems such as absenteeism; part of teamwork is having a plan they all agree on to keep absentees responsible. "When team members are absent," says Mark Temons, "the rest of the team attempts to build a list of tasks the home-bound or vacationing student can complete at home, tasks such as research, reading articles, phone calls, etc."

When team members are absent from a review, the problem is acute. If a student can plan in advance of a coming absence, he or she might prepare a videotape. A number of teachers have their teams videotape presentations prior to the final review. Teams then know that if one member is absent, they can play back that person's segment during the final presentation. If an absence occurs unexpectedly, teammates are on the spot, although Tony Komon says his students have come up with a variety of solutions, including dragging a team member out of a sick bed or bringing in a teddy bear and using ventriloquism to cover for the absentee.

Project Timelines

No particular set amount of time is best for project work. For some problems, such as Tony Komon's problem of the library exhaust fumes,⁸ one week is sufficient. For other problems, half or a whole marking period allows the project to fall within the existing school schedule. Karen Falkenberg scheduled projects in her year-long course according to each problem's complexity, with some projects taking four weeks, others eight or ten. Teachers have tried scheduling a single project over an entire school year, but most find a shorter length of time allows students to maintain the intensity necessary for success.

It's important for students to have a detailed schedule in hand before they start working on their projects. If they are to learn to manage time effectively, they need to understand that reports will be due or that a review will be coming up in order to follow their own schedules and plans of action. Some teachers set aside specific class time for teams to check in with one another and make sure a project is on track. Kathleen Conn had her team secretaries hand in a log summary every Friday, thus ensuring that each team kept its daily log up to date. Lisa Torres keeps student paper trails in the classroom so she can spot-check as frequently as she thinks necessary.

One rule most teachers agree on is a rigid end time. Progress reports, final reports, oral presentations—all are due when they are due. No exceptions, no excuses. In a course that simulates the workplace, students learn that deadlines are deadlines. The news doesn't wait for a reporter down with flu.

Chapter 4

Guiding Students Through the Problem-Solving Cycle

What Makes a Good Problem?

A good problem both challenges students and kindles their interest. Within a given discipline, teachers look for problems that are not so advanced that students become bogged down in frustration but that are complex enough to elicit a number of potential solutions. “Make the original statement constructively ambiguous!” says mathematics teacher Mary Lou Derwent who believes ambiguity is a key to creativity.

A good problem must be relevant both to the topic at hand and, in the view of the problem solvers, to their own lives. Given a good problem, students will throw themselves into the process of finding the solution. “If you want people to learn,” says Thayer School’s John Collier, “have them work on something that interests them, something that they can become totally immersed in.”

Model Problem Statements

Teachers often introduce the problem-solving cycle by posing a model problem statement that is more relevant to the students’ daily lives than to the subject matter of the course. Teachers pull problems out of the daily newspaper, such as a subway crash or an airport being closed due to communication failure. “Anything that leads to a lot of discussion of potential solutions is a good model problem,” says Mark Temons. The goal is to bring students to recognize the cycle as valid and essential.

Some teachers elicit a problem from their students, such as a problem about school life:

The pep rallies are not promoting school spirit.

It takes too long to get students into the auditorium.

When Conestoga Senior High School in Media, Pennsylvania, expanded from grades 10-12 to include grade 9, Kathleen Conn began the discussion of problem solving by writing on the board:

9th graders are coming!

“We discussed that this was a statement, not a problem statement,” she said, “and went on to define several problems—for example, overcrowded hallways, juvenile attitudes taking over, etc. Then we chose one student concern to begin working through the problem-solving cycle.”

Physics teacher Harry Stuckey used a dynamic before-and-after demonstration. He asked his students to:

Measure the volume of a section of the hallway in 15 minutes using only 30-cm rulers.

“I let the students try this on their own,” he said. “After several unsuccessful attempts, we took the problem through the problem-solving cycle. Then they tried again—with much better results.”

The goal is to have the students experience the essence of problem solving. A simple but relevant problem allows them to focus on the process as a whole, so that they can make meaning of it from their experience.

A List of Model Problems

The following list suggests the range of model problems successfully used. Some are in the form of questions (How can I...?), others in the form of instructional commands (Design a...), while others are simply statements of a situation that needs to be changed.

Design a new lunch schedule to accommodate four seatings instead of three.

Design a method to solve the problem of overcrowding in the senior parking lot.

How can blind persons be sure of the denomination of paper currency used to pay for a purchase and of correct change?

How can you determine the depth of a well?

How should we deal with dead leaves on the lawn?

It takes too long to get students into the auditorium.

Not enough students want second-period lunch.

Redesign the fire exits in school after the upcoming room changes, additions, and other renovations have taken place.

Students need to get to class on time.

Problem Statements Within a Discipline

Once students have experienced the problem-solving cycle as a whole-class exercise, teachers look for problems of emerging relevance within their disciplines. For some, the problem will focus on a specific piece of content. Gene Hampton asks his biology students to use the problem-solving cycle in their labwork.

What effect does feeding various concentrations of molasses to yeast have on its CO₂ production?

Students have to determine the constraints of the problem and brainstorm alternative experimental designs before they can conduct experiments. Jim Housley set his physics students to:

Design a speed reducer to couple one of a variety of motors to the axle of a representative vehicle.

The key is to redirect the typical laboratory experiment from a recipe students are to follow step by step—often without understanding the why of any particular step—into an exercise that offers them an opportunity to figure out for themselves exactly what they are going to test or construct...and why!

Good problems can be found in textbooks or laboratory manuals, but often such problems are narrowly focused and lead to only one course of action. The teacher's task is to open them up so that, instead of a single textbook solution, the problem provides a number of directions to be explored. Then each team's redefinition of the problem statement will determine a different range of potential solutions.

List of Discipline-Specific Problems

Biology

Assess the feasibility of using *Pseudomonas* bacteria for toxic waste biodegradation.

Can boa constrictors be maintained on a diet of live bull frogs?

Design a device to test the effect of *thigmic* stress on plant development.

Examine the role of *plasmids* in antibiotic resistance of *E. coli*.

Chemistry

Can you produce aspirin from a plant source, such as willow bark or birchsap?

Develop a student lab exercise that involves reacting two elements and making measurements to find the formula of the compound formed.

Design an experiment to find the heat of fusion for ice.

Which brand of antacid is the best buy?

Physics

Construct a device that will lift 20 grams through a vertical distance of 10 cm in the least possible time using heat as the primary source of energy.

Design a pair of glasses that enable the wearer to see 360° without turning the head.

Focus a laser light through a filled aquarium on a dime outside the tank, using a minimum of three optical devices from different sides of the tank.

Move a 2-kilogram cart from one end of the table to the other in exactly 10 seconds without human intervention.

Mathematics

Design a popcorn container using solids of revolution.

Design an experiment which will allow you to quantify projectile motion.

Does height and/or weight effect the success of a football player?

Is there a relationship between drug use and extra-curricular activities?

Open-Ended Problems

Open-ended problems are those for which students develop their own problem statements out of a given area of study. With an open-ended question, a team can steer the project into an area of strong interest, allowing team members to use skills they already have. When students take responsibility for finding and solving problems they themselves have defined, solving the problem becomes urgent, not for the grade at the end of the project, but because the commitment to the project has grown out of genuine interest.

Open-ended problems can be risky, for both teachers and students. Teachers face the possibility that students may pursue a problem for which the teacher does not readily know a solution. Teachers may also find that, as a class moves from teacher-directed exercises to student-directed problem solving, some students are too used to passive learning to be comfortable defining their own goals or pursuing them effectively. The key is practice. The more students engage in active learning, the better able they are to define problems and devise solutions.

Some open-ended problems can be tied directly to coursework. Chemistry teacher Christine Tyrie asked her students to

Develop a product whose reason for being is fragrance.

Physics teacher Deb Hill knows that teaching is one of the best ways to learn; she challenges her students to

Develop a lesson that describes a motion in the real world.

Gene Hampton's biology students are given a project mission, dubbed Lo-Down Critter, that turns them into NASA astronauts:

Design and construct a model of a life form found by astronauts on Jupiter's moon known as Io.

List of Open-Ended Problems

Acid rain: what can we do about it?
Can Muncy Creek be developed into a naturally producing trout stream?
Design a toy or game that can be used to teach mathematics to third-grade students.
Design an aerodynamically efficient football.
Design an attraction for a theme park.
Design and solve a problem in the area of optimization.
Develop a packet of instructions for a topic or topics from the extended areas of the New York State Regents Physics syllabus.
Develop an electronic device to aid in the prevention of crime.
Invent a device that will draw room dust into it, thus eliminating the need to dust.
Redesign something in the school to make it more accessible to the elderly and the handicapped.
Research the topic of welfare and propose a change in the current welfare system that would be a mathematically supportable improvement.
The Keebler Baking Company is looking for new cookie designs.
Using physical models, determine which type of tree, coniferous or deciduous, provides better shade and wind protection for a residence.

Request for Proposal (RFP)

A popular form for the open-ended problem is the Request for Proposal or RFP. The teacher begins simply with a broad area of concern, such as highway safety, improvements for the environment, aids for the elderly, or devices for handicapped children. Students are given an RFP that defines the concern and lays out the general constraints of the project, including the time commitment, monetary allotment, the requirements for written and oral reports, the expectations of the review board, and the grading criteria. Each team's first round in the problem-solving cycle is directed to finding a problem that it wants to solve and that it thinks can be solved within the time scheduled for the project.

Harry Stuckey asked his students to focus on the physics of movement.

Movement of matter in all its aspects is a worthwhile area of study. Design Advancement for Real Needs (DARN) is searching for new ideas to market. DARN is a large foundation with interests that extend from mass transit to manufacturing processes, recycling, fluid transport, teleportation, irrigation, etc. At this time, DARN is soliciting proposals from groups interested in providing original, marketable ideas in the area of movement.

Wayne Snyder created a scenario focused on amusement park rides.

A new amusement park is being built in your town. Your company has been invited to submit a proposal for a park ride.

Snyder's physics teams used the first matrix to decide on the type of ride—roller coaster, freefall, spinning, etc.—and the second matrix to define the specifics of the ride. At the final review, Snyder was pleased to hear a team explain why a roller coaster could not physically make it up the next hill, an explanation, he says, that “was a more efficient lesson on conservation of energy than any I could have given.”

Teachers can turn a standard textbook problem into an effective RFP. Consider the familiar “volume vs. surface area function” found in many mathematics textbooks. A mathematics team at one of the Thayer School workshops reworked that one into this RFP:

The Ski Club wants to build the World's Perfect Soft Drink Holder to market for a fund raiser.

The objective was to give students an opportunity to integrate mathematic skills with language and art skills by designing a three-dimensional product with a useful function.

Teachers working within the RFP format need to be mindful that projects that engage students affectively, such as devices to aid handicapped children or the elderly, may make defining a problem easier for students new to engineering problem solving. When they interview children and caretakers in a local facility for the handicapped or senior citizens in their own neighborhoods, students uncover solvable problems that engage them because of the human connection.

List of RFPS

Accessibility for the handicapped	Improved crutches
Aircraft design	Improvement of the environment
Crime detection	Mass transit
Crime prevention	Games for teaching elementary students
Destruction of habitat	Nuclear waste
Destruction of resources	Peripherals for wheelchairs
Devices for arthritics	Production of electricity
Devices for handicapped children	Tool safety
Energy consumption	Toys for first graders
Energy sources	School safety
Environmental concerns	Safety in the home
Extending the growing season	Sports devices for stroke victims
Fossil fuel production	Wildlife conservation
Highway safety	

Redefining the Problem

When engineers are called in to solve a problem, they know that those who called them often have their own solution in mind, one which they want the engineers to confirm. Given a problem statement, the first task of a student team is to analyze the problem statement, word by word. Is there a hidden bias? Is there an implied solution? “The beauty of this approach,” says Wayne Snyder, “lies in analysis of bias.” He reports one class’s experience with the model problem:

How can smoking in the bathrooms be controlled?

After examining the question for bias, the students discovered that their concern was not so much smoking as that the bathrooms were locked except when a teacher was present. Locked bathrooms were a major inconvenience for students who didn’t even smoke. “They were impressed,” says Snyder, “that problem statements can bias both the process and the outcome.”

Professor John Collier remembers a problem he passed on to his Dartmouth students, one given to him by the Town Manager of Hanover, New Hampshire, where the Thayer School and Dartmouth College are located.

Hanover is losing viability due to traffic and parking problems.

“What’s the bias?” was his first question. He advised his students to question every key word in the statement to find out.

viability: What is viability? Whose definition is to be used?

losing: What did Hanover have that it lost?

traffic: Car traffic or people traffic? Animals, bicycles, trucks, volleyball teams? Is traffic really a problem?

Hanover: Hanover the town or Hanover the home of the Dartmouth campus? Or the historic village of Hanover? Was Hanover ever viable?

due to: Implies a direct cause and effect; the implied solution would be to change the traffic flow.

problem: Who thinks it is a problem? residents? store managers? students? faculty? commuters? The problem was defined by the Town Manager, who is accountable to the Chamber of Commerce and the Town Council.

is: Is the problem immediate or some time in the future?

Discussing every key word gave the students a sense of the implied solution:

If traffic and parking are fixed, Hanover will stop losing viability.

With that in mind, they could go on to redefine the problem according to their own research, knowing that if they came up with a solution different from the implied one, they would also be ready for resistance from the original problem giver, the Town Manager.

Redefinition by Consensus

In 1994, Collier used this problem to demonstrate the redefining step of the problem-solving cycle to high school teachers at the Engineering Concepts summer workshop. In redefining the problem, he told them, it's important to look for consensus. Instead of brainstorming ideas for redefinition, he wrote on the board the first redefinition a participant offered, then asked the whole group to accept it, dismiss it, or modify it. The teacher, he says, must keep in mind that the focus of discussion is the *process* of redefining the problem, not the actual selection of words. Collier guided workshop participants through discussions of four redefinitions before they achieved consensus on a problem statement clearly enough defined and without bias.

First suggested redefinition: Investigate "viability" of Hanover.

Second suggested redefinition: Investigate change in economic growth due to changing traffic and parking conditions.

Third suggested redefinition: Investigate relationship between economic growth and traffic and parking.

Fourth suggested redefinition: Investigate traffic and parking and economic growth separately.

Final redefinition: Generate baseline data for traffic and parking and economic growth. Investigate "viability" through interviews.

The final redefinition, the group decided, was something they could work with. Without knowing current traffic and parking conditions, they reasoned, they could not determine whether conditions were generally worse or better than in the past. They could, however, count the number of cars entering Hanover at different times of day to determine baseline traffic density. *Viability*, they decided, was a subjective quality but could be clarified by gathering data through informal interviews of town residents, merchants, commuters, college students, faculty, and college employees. By examining the original problem carefully and redefining it in terms that could be determined from data gathering, the workshop participants narrowed their focus into a problem that could be solved through concrete investigation.

Even with a narrowly defined problem, such as a specific design for a national competition, redefinition remains an important step. Physics students of Dennis Federico used the problem-solving cycle for an entry for such a competition. He reports that the original question, "How to build a mechanical hand or claw," led the team to a solution that did not work well. When they went back and redefined their problem as "How to pick up objects," the resulting brainstorming session offered many new alternatives.

Constraints and Specifications

Constraints define an arena of inquiry. From the general constraints embedded in a problem, specifications for the first matrix emerge. Certain general constraints apply, regardless of the particular problem.

General Constraints

Collier stresses that any solution to any problem must be safe, timely, feasible, and ethical. During the introduction to the problem-solving cycle, teachers may suggest these constraints if students don't come up with them on their own. Discussions of "timely" and "feasible" are particularly important. An attempt to devise a solution that cannot be accomplished with the equipment available or the skills of the group or within the timeframe of the project offers an exercise in frustration; and although frustration is not always bad for students to experience during the problem-solving process, the successful completion of a project is naturally the overall goal.

General constraints need to be incorporated into specifications only for the first several rounds of the problem-solving cycle. When the chosen alternative clearly fits the initial specifications, new constraints specific to the narrower focus will be generated.

Specific Constraints

Some constraints are specific to the problem posed and to the discipline within which the students are working.

- A physics team might have a general constraint that compels the design to use the principles of motion or to fit an invention into a cubic foot.
- A chemistry team might need to make its lab tests *in vitro* rather than *in vivo*.
- A geometry problem might require a minimized surface area and a maximized volume.
- A pre-calculus class might be asked to fit data to several types of function models in order to predict trends.

Demonstrating Constraints

Teachers spend time in helping students understand the concept of constraints and specifications. In a whole-class exercise, constraints can be listed on the board as students suggest them, without editing or categorizing them. Giving students time to generate a large number of constraints is important: without good specifications, the matrix will not do its work. The following constraints were generated by teachers attending the 1994 Engineering Concepts workshop, where the problem was to devise a solution to losing pens.

time	skills	feasibility
desire	equipment	environmental
safety	resources	impact
cost	ergonomics	size/weight
fun	individual or group	aesthetics
political support	liability	ethical
legality		

Fun as a Specification

When students are asked to come up with their own problem in a given area of concern, "fun" may be an important specification for the initial matrix. Team members are more willing to put in the extra time to make a project successful if they are enjoying themselves. Also, as physics teacher Jim Housley says, "If personal feelings aren't openly taken into account, they will likely be considered subconsciously in ways that complicate the decision-making process."

Brainstorming Alternative Solutions

The center of the problem-solving cycle is the point at which students generate ideas for possible solutions. Managed well, this step can lead to creative and innovative solutions. It can be the most vividly remembered part of the process.

Successful brainstorming depends on an environment that ensures a free flow of ideas. Students need to know that in generating alternative solutions to a problem they can suggest any idea that comes into their heads. Every idea, no matter how off-the-wall, takes its place alongside others for evaluation. Brainstorming is important, not only for the number of ideas that come out but also for the unconscious ways in which the ideas work in everyone's mind. Experienced problem solvers know that an idea that appears totally unworkable often contains a nugget of inspiration that will lead to ideas that *are* feasible.

Without restrictions, will the class clown dominate the brainstorming session? Skillful classroom management allows an unfettered flow of ideas while keeping the brainstorming session productive. Without the free flow, brainstorming becomes a hollow exercise in which the students practice guessing what the teacher already has in mind.

Lisa Torres reports that she learned not to censor even ideas contributed only to titillate, such as “paper condom” as a possible paper product. “I realized that listing even mildly obscene suggestions without comment was a powerful way to support the brainstorming process. Students were so shocked that I continued to *follow the rules of brainstorming* that they quickly came back to task.”

The teacher is assisted by the structure of the engineering problem-solving cycle which prevents useless meandering down blind alleys. Brainstorming merely generates alternatives; the matrix analyzing the alternatives assures an orderly process of finding the best and most practical solution. Joke ideas, placed on a matrix, generate few laughs.

Basic brainstorming guidelines include:

- the more ideas, the better
- valuing all ideas
- no analysis of—or even comment on—an idea
- no penalty for redundancy or even for craziness

With reluctant classes, teachers sometimes ask students to write two or three ideas and then have each student contribute one of those ideas to the group brainstorming. With exuberant classes, the teacher's task is to ensure an environment that encourages everyone to express at least one idea and also does not allow any one student or group of students to dominate.

While brainstorming can be introduced to an entire class, the optimum group size for brainstorming is 5 to 10 people—large enough to generate a range of ideas, but small enough for everyone's idea to be heard.

Good brainstorming often leads shy students to contribute; it always leads to the proposal of a variety of creative solutions to problems. The process can be amazing—and downright fun.

Analyzing Alternatives

Understanding comes about when new information makes a person rethink previous ideas, but the process that takes one from an older position to a newer, more informed view is not always clear. Learning can be nonlinear, and nonlinear endeavors can be untidy. Solving problems can take many attempts and may include trips down blind alleys.

The engineering approach to problem solving offers a technique for systematically evaluating the alternative solutions generated by brainstorming. By ranking each alternative against each specification, the best solution for that round can be pursued. This works for problems from the most general—"What shall we do for a project?"—to the most specific—"How can we determine that the infrared sensor is sensitive enough to detect very small motions?"

A tool for organizing the decision-making process, the matrix also documents the process so that if a potential solution proves unworkable, the team has merely to return to the previous matrix to take up a different idea. For the long view, the use of a matrix for decision-making demonstrates that scientific success is the result of original, systematic work.

Iteration

Iteration is the real key to engineering problem solving. Rarely are problems solved in one cycle. The matrix is a tool students use again and again as they move through a project. If the first round of problem solving is used to find a problem within an area of concern, the second round narrows the focus of inquiry. Progressively tighter redefinitions of the problem bring new specifications, new alternative solutions, new rounds of research and matrix analyses.

A team might begin with the problem of how to prevent accidentally netting dolphins while fishing for tuna, as one group did in Cold Spring Harbor High School, Long Island, New York, and proceed to iterate a more closely defined problem, such as "Could we emit a sound to scare off dolphins?"

Sometimes an idea developed by a team is too fascinating to drop at the final review. A team from Hanover High School in Hanover, New Hampshire, designed an automatic cigarette lighter for automobiles. The students performed a preliminary patent search and constructed a working prototype for their first-semester project. In the second semester, they iterated the process for a new project, refining their design and filing an official application for a patent.⁹ Similarly, investigations of color led a Fogbusters team, in Corcoran, California, to design colored foglights; in the following year, another team built on the research and developed stick-on/peel-off filters.¹⁰

Teachers can assist the students' iterative process by specifying the objectives of several matrices. Nancy Borchers, for example, instructed her geometry students to use the first matrix to determine the type of attraction they would design for their theme-park project, the second to select its specific features.

Iteration teaches students that problems are never simple, that they require both precision and perseverance, and that good solutions can evolve.

9. See "Engineering Concepts for Advanced Students," p. 96.

10. See "Fog Navigation," p. 85.

Chapter 5

Research, Documentation, and Testing

Starting a Search

The matrix cannot work its magic alone. A group of ideas cannot be ranked against project specifications until something is known about each of idea. Although identifying constraints and generating alternative solutions are group efforts, research—reading the literature, gathering data by telephone and direct contact—requires team members to work individually or in pairs and to report their findings back to the group. Many research questions can be answered by students who are absent from school for reasons but not incapacitated by illness.

When supervising student research, three broad questions are essential to keep in mind:

What is the current state of the art for any given idea? Who manufactures similar products? For a solution to be innovative, teams must know whether an idea is already on the market, and, if it is, how well it solves the defined problem.

Who is the target user of this product? Who would be willing to pay for it? Whether a team is redesigning a traffic intersection or building a device to aid stroke victims, someone or some agency is the customer. If a team wants its solution to be practical, the ideas can't be ranked until the market is understood.

How would this product work? How can this device be tested? Whatever the field of inquiry, a team must know exactly how to make sure its ideas are feasible. An idea can't be ranked until team members know how it works and how it can be tested.

Thus, before any idea can be effectively ranked on the matrix, the team must gather sufficient data to identify

- the current state of the art
- the market potential
- procedures for testing

This phase of the research is extremely important. Many students come to the matrix predisposed toward a particular idea—sometimes consciously, sometimes unconsciously. Without the team carefully researching all ideas, a dominant personality can sway others to a “pet” idea. Often teams are so eager to get to the actual construction phase, they don't want to consider a lot of options. An exceptional group of students may slight this phase and still produce an exciting solution, but for the process to work for all students, careful consideration of each idea will assure each team member that the solution the whole team chooses is, after all, the best one possible.

First Round of Research

When students establish personal contacts through mentoring, they put themselves in a position to obtain superior assistance in the research process. Students need to know that business and professional people, however much they might want to be helpful, do not want to—and often will not—spend time answering trivial questions. Before contacting a mentor, students will need to do the “book work” and “leg work” that make questions posed to their mentors intelligent.

The first stop for research, as suggested earlier, is the school library. A librarian trained to field naive questions can direct inquirers to resource materials for beginning the data-gathering process. An up-to-date general encyclopedia may be a good first stop. Even better, there are scientific encyclopedias, such as the McGraw-Hill *Encyclopedia of Science and Technology* or the Kirk-Othmer *Encyclopedia of Chemical Technology*. All encyclopedias have bibliographies, which students can use to find other reference works and textbooks in the field. Periodicals—technical reports, conference proceedings, journals and magazines—may offer the latest information in any field of science or technology. A librarian can assist a student in sorting through the different periodical indices, such as Reader’s Guide, Applied Science and Technology Index, Physics Abstracts, Electrical and Electronics Abstracts, or Engineering Index, and finding those appropriate to the student’s level and research need.

Students in high schools with access to the Internet may be able to use college or university online catalogs, compact disc products, or remote databases. If the school is not online, teachers may be able to negotiate with a college library to allow selected students to use the college’s network. With good access to the Internet, students can post inquiries on a variety of bulletin boards or browse information in the multitude of databases that inhabit the World Wide Web.

A Yellow Pages Directory and a telephone can be powerful tools for finding out what local companies exist in the field of inquiry and what products they make. To identify manufacturers and suppliers nationwide, students can consult the Thomas Register, which is organized by products and services, and company profiles, with a catalog file for specifications, illustrations, and the performance data of products.

Federal or state government agencies, such as the Departments of Energy, Forestry, Fish and Waterways, or Transportation, can be contacted either by e-mail or telephone. NASA, for example, offers information materials for use in schools. The offices of legislative representatives, especially those representing the district in which a school is located, can assist students in opening doors.

As students move from resource books through telephone and e-mail conversations to questioning mentors, they become increasingly expert in their field of inquiry. They not only become conversant in details of a field, they also come to feel the power of knowing what they are talking about.

Patent Searches

A patent grants to an inventor the exclusive right to market an innovative device or process. It applies to the United States and its territories and possessions. To acquire a patent, an invention must meet three criteria:

- novelty
- usefulness, that is, it must function
- non-obviousness, that is it must improve upon the state of the art

Patents are granted for processes, machines, manufactured items, compositions of matter, varieties of plants, and ornamental designs, among other things. A functional patent is good for 17 years, a design patent for 14.

The U.S. Patent and Trademark Office (U.S.P.T.O.) issues an *Official Gazette* that lists all new pending patents. Students with access to this publication can look up devices similar to those they are proposing by checking under the device's function. For example, a team designing a new thermometer would check for similar instruments under "temperature-measuring device."

There are a number of avenues for doing patent searches. Every state has at least one Depository Library, which maintains a microfilm collection of all issued patents, the *Classification Manual* which explains the Patent and Trademark Classification System, and a computer supplied with the classification system program. Although the microfilm may not list patents earlier than 1973, it is a good place to start understanding the subject area.

Some libraries can access commercial computer databases, such as Dialog or LEXIS, which students can also use for patent searches. At Dartmouth's Feldberg Library, a computer CD-ROM allows searches by key words, inventors' names, companies to which patents have been issued, or words in the title of the patent abstract. Some business firms have the same capacity. Again, teachers need to negotiate permission for students to gain access to such resources.

The Internet has several locations where students can search patents. The U.S.P.T.O. is online at

<http://www.uspto.gov>

An IBM-created database offers access to patents, both descriptions and images, and allows searchers to move backward or forward through the database to search the history of a particular patent.

<http://patent.womplex.ibm.com>

Teachers whose students are designing novel devices may want to enlist a patent attorney to serve on the review board and perhaps offer to advise students as to whether their invention is patentable. Students of Lynn Godshall gathered information from attorneys listed in the section in *Popular Mechanics* called "For Inventors." Godshall cautions that some patent attorneys may ask students to send them their ideas. To protect students, he makes sure they understand the process of "witness and understanding," which verifies that an idea is their own and which can be executed at their oral presentation, provided the log or project notebook contains the idea and its date of inception. The oral presentation is equivalent to a public disclosure of the students' idea; they have one year from the date of the presentation to apply for a patent.

A free publication, "Basic Facts About Patents," is available from the U.S.P.T.O.; a more complete booklet, "General Information Concerning Patents" is available at cost from the U.S. Government Printing Office.

Market Research

Some market research can be done in a library. For example, the government issues a *Statistical Abstracts of the United States* which contains data relating to American society from demographic, economic, and cultural perspectives. Most market research means going out into the field and talking to people. Nancy Borchers' geometry students, in Cincinnati, Ohio, designed surveys to determine both the shape of the cookies they wanted to design and the ingredients.¹¹ Tony Komon's physics students, in Niskayuna, New York, talked to arthritic neighbors and residents of nursing homes before designing devices for the elderly; a team that invented an arm-bike interviewed a paraplegic and her neurologist.¹² When students interact with community people, they see ways in which the world of the classroom is connected to the world outside. Before sending students into the field, though, teachers may want to conduct marketing exercises to help them understand what they are seeking.

It surprises students to realize that markets *do* exist. Who would be interested, for example, in an energy-efficient dog door? Through market research, a group of Dartmouth students found that several groups were, including pet store managers and builders of energy-efficient homes.

Market Segmentation

When determining the market for a product, the question,

Who is the customer?

may seem too vague to answer. Segmentation lets students move from the amorphous to the definite. A classroom exercise in market segmentation allows students to imagine an ideal customer. Questions about the target customer might include the following:

How old is this person?

Which gender?

What economic status?

What kinds of magazines does the person read?

What kind of job?

Where does she or he shop for clothes or groceries?

The goal of the exercise is to make the description of the ideal customer so specific that students would recognize this person on the street. From the particular, the students can expand to define a whole group which is their marketing target.

Harry Stuckey, of East Rockaway, New York, likes to start off his physics students with an exercise in market segmentation. After eliciting a number of opposites, he asks the class to create the ideal customer by choosing one of each pair of antonyms. For example, the list might begin with these pairs:

tall/short

female/male

old/young

educated/not educated

urban/rural

employed/unemployed

newspaper reader/newspaper non-reader

computer user/computer non-user

A target customer then might be defined as:

A young, tall, married female who was educated at Dartmouth. She is employed, jogs, goes to church, lives in the country, and reads the *New York Times* and *Wall Street Journal*. She works on a computer but has carpal tunnel syndrome.

Stuckey continues the exercise by eliciting ideas for this client's typical Saturday morning. Once the class had decided that the target customer likes to "jump into the hot tub, read the paper, and eat breakfast while listening to National Public Radio," they are primed to identify a problem their hypothetical person might have which they themselves could solve.

11. See "Interdisciplinary Geometry," p. 90.

12. See "Project Work on Ten Minutes a Day," p. 88.

Surveys and Interviews

As teams go to work on projects, members take responsibility for contacting potential customers. If the team is inventing something for arthritics, the market researchers interview people with arthritis, as well as medical personnel who work with arthritic patients. If the project is designing toys for first graders, a trip to a first-grade classroom is in order. If students are redesigning a traffic intersection, visits to the township office or the state department of transportation can yield data on automobile accidents, traffic density, and about drivers and others who use the intersections. A “trial run” of a survey or questionnaire, using a dozen or so respondents, can help students recognize overly broad or unclear questions which they will need to refine before taking the survey public.

Just as students need to be informed about their subject and to have specific questions when they contact mentors, they need similar preparation for interviewing potential customers. They also need to be both patient and persistent. In the world beyond the classroom, information is not always attainable at a moment’s notice. When they find themselves obstructed at one point, young people can learn how to move politely around the obstacles to get the information they need.

As teams iterate the problem-solving cycle, they may find themselves returning again and again to their potential customers. A first round of interviews helps the team narrow the field of alternative ideas; a second round helps it to focus on desired features that then become design specifications. As the team gets closer to its final product, students will know their customers well enough to design an effective advertisement to use as a final review prop.

Talking with the people for whom a solution is being designed engages a student’s affective intelligence. The team finds out in a very direct way how its solution can make a difference. Talking to potential customers may prevent students from pursuing solutions for which no problem exists. Further, potential customers who have been consulted may be more likely to adopt a solution or new device when they feel they have been included in the design process.

Test Protocol

Scientists and engineers initiating new processes or designing new devices need to know whether their ideas are workable. They may need to do research on testing devices and find out what equipment is available that meets testing criteria. They may even need to invent a whole new apparatus in order to perform effective evaluations. For an engineer, it is not enough to say, "It works." "It works" must be qualified: under what conditions does it work? How long will it work? The question, "How do you know what you know?" must be answered with measurements and hard data.

The energy-efficient dog door designed by a team of Dartmouth students was not nearly so impressive as the wind tunnel they built to test its effectiveness. They had pursued a number of potential test designs, such as measuring the temperature differential between the outer and inner doors, but could not find an effective method of evaluation. Then, one evening, several students observed that a door cracked open on the ground floor of a house created a considerable draft, enough to lift tissue paper 90 degrees, while a door cracked on an upper floor did not. They began to study the relationships among air flow, air pressure, and heat transfer. Eventually, they designed a test that allowed them to measure the pressure differential, instead of the heat differential, between the two sides of the dog door. By the time they finished constructing a wind chamber to test their prototype along with several manufactured doors, they had come to a deep understanding of the laws of thermodynamics.

Not all testing requires specially designed equipment. Physics teacher Tom Woosnam encourages students to find reasonable methods for testing, whether in a laboratory or in the field. A group designed a bicycle brake that adjusted itself according to weather conditions, using spring scales to test the force exerted on a cable. Another group, after devising a set of bicycle brake-and-turn lights, lent its prototype to friends and to a San Francisco bike messenger for trial runs. A third group modified a wheelchair to prevent patients from getting up without applying the brakes; patients at the local hospital gave the design rave reviews.

Testing is an important part of building a prototype. Even when students design solutions, rather than construct physical devices, they need to think about how their designs can be evaluated in real life.

The Paper Trail

Good problem solvers keep notes. A “paper trail” of the process assures a team that blind alleys are never a waste of time, but, rather, that they can make clear why a particular idea doesn’t work. Documenting ideas that don’t work is as important as documenting those that do. Information from failed attempts builds the knowledge base from which success rises.

Work Logs

A Work Log or Project Notebook documents the decision-making process of the project. It should include details of data gathering, brainstorming lists, matrix analyses and outcomes, who performed which tasks and what problems they encountered. Logs should be clear and detailed enough for someone outside the group to follow the steps which led to the selection of a specific problem, the analysis of alternative solutions and final selection, and the execution of the final design.

Some teachers schedule time during class in which students summarize their log, evaluate their progress, and outline tasks of the coming week. A weekly or daily summary, signed by each team member, can be handed in, so that the teacher can track the team’s progress. The actual Work Log remains with the Team Secretary or in the classroom.

Reviewing the Work Log on a regular basis, teachers can write their comments, questions, and suggestions for the team. These provide a written record of the teacher’s input for the project and let students and teachers check back over earlier questions to see whether the team has effectively addressed them in their latest design. The teacher’s notes also save the teacher valuable time during the review process.

Written Reports

Reports are a way for students to formalize findings and communicate ideas to an audience beyond the teacher. Lengthy projects may require one or more progress reports, as well as a final report that will coincide with the formal review (see page 71). Having students hand in their written reports a few days before the oral presentation gives teachers and review board members a chance to preview the proposed solution and prepare questions. Limiting the number of pages of final reports, even docking points from teams that exceed those limits, prevents the report from becoming interminable and helps students learn to be concise.

Inviting an English-teacher colleague to collaborate in class on report writing can help both teachers and students. Karen Falkenberg brought in colleague and English teacher Jeff Walkington to spend time discussing the art of technical writing. Walkington asked the students to consider their audiences—the executive (or decision-maker), the scientist (or expert), the technician (or operator), the layperson (or consumer). “The primary audience for a student team’s report,” added Falkenberg, “is the teacher (or evaluator), which means that students’ reports often need to include explanations of concepts underlying a project.”

A good progress report includes diagrams of devices or plans and explanations of the concepts or principles used. Some reports include the process—a chronological description of team efforts, the matrices used to analyze different aspects of the problem, the reasoning behind each decision, even test procedures that didn’t work. Other reports, in particular the final ones, are a comprehensive description of the problem and its chosen solution without details of the process.

Final reports are usually divided into three sections: the front matter, the body of the report, and the back matter. The front matter includes:

- the title page
- an abstract of the problem solved
- the table of contents
- a list of illustrations

The body of the report includes:

- a brief description of the problem
- an explanation of the cause of the problem and the reason for seeking a solution
- if the solution is an invention, a brief description of the state of the art
- a list of specifications, with the key specs prominent
- a brief description of alternative solutions not pursued
- an analysis of the alternatives, with justification of the chosen one
- a detailed description of the solution (and prototype)
- a description of the test results and analysis
- discussion and conclusions, with recommendations for the future of the project

The back matter includes:

- a bibliography
- appendices that detail the chronology of the project and its budget

Portfolios

Keeping a portfolio for each group helps document the students' progress. For long-term projects, which require several reports, a portfolio makes informal assessment of team progress easy.

Each page of the Work Log can be used to give immediate (in-class) feedback to students. It also becomes a document in the portfolio that can be used later for assessment. Each report can be matched with the Work Log to make sure the project is on track. At the end of the project, the portfolio is there to explain how any grade is determined. It is also tangible evidence that demonstrates the efficacy of the engineering approach to problem solving—to a school board member, a potential review board member, or colleagues at a professional meeting.

In long-term projects, teachers want to be able to see the progress and to make sure that questions they have noted on one of the project reports are answered in the next one. The key, according to Lisa Torres, of Lebanon, New Hampshire, is not to fall behind: keeping everything—work logs, lab notes, written reports—in the classroom assures that at any time information about a project can be located by either the teacher or the students.

Chapter 6
The Review Process

Engineering Review

Engineers make formal proposals to potential clients. Once awarded the contract for a project, they present progress reports and final reports to the clients. These reports are usually both oral and written. The review of students' work in engineering problem solving is similar. When working with an RFP, students make their first presentation as a proposal for a solution for the problem, followed by progress reports and final reports at specified intervals. Students working on more closely defined problems make only one or two formal presentations, oral or written or both, to a professional review board.

The Review Board

An external review board is a vital part of the problem-solving cycle. It encourages intensity and increases the students' sense of the value of their work. Students face people they don't know well and receive feedback from these professionals on important issues. The review is where a student's reputation works neither for nor against his or her work: straight-As won't help students who try to slide by on their record; a "special education" label won't hinder students who have done their work.

When outsiders review students, teachers become facilitators and mentors rather than the sole source of grades. They also may find themselves introduced to a new slant on a problem or to new information about previously unfamiliar technical ideas.

A good review board has three to six members, each with different expertise. For example, students in Lebanon, New Hampshire, who designed a nature trail presented their work to a panel that included a biology teacher, an elementary teacher whose class was to use the trail, a member of the town's Parks and Recreation Commission, and a naturalist. Before beginning construction, the same students also presented their project to the School Board for approval. Involving the School Board was serendipitous—a year later, according to their teacher, Lisa Torres, that review was a factor in the Board's decision not to sell the parcel of land to the city for a new police station site.¹³

Preparing Review Board Members

Teachers prepare review board members for their job, either informally or through formal training sessions. Review board members evaluate student work effectively when they understand their role as evaluators as well as the problem-solving cycle itself. With low-level students, review board members (and mentors) may need to be briefed about ability levels in the mechanics of report preparation. An engineer who understands that a student is still struggling with percentages is less likely to expect the student to explain relationships using calculus; a business person who knows that a student is dyslexic may be able to look past spelling errors in a report to the thinking process.

A general rule for all review board members is that criticism must tell the students what they need to do to improve their solution. The most important contribution a review board member can make lies in the questions asked after the oral presentations. Teachers remind new review board members that the purpose of questions is to guide the students, either into their next phase of development or into a better understanding of their accomplishments.

13. See "Improving the Environment at School—and at Home," p. 109.

Review Board Questions

The questions that follow were asked at different stages of review of the Thayer School team that designed a portable, spillfree plastic mug and bowl to reduce paper use on the Dartmouth campus. Reading through the review board's questions, it becomes clear that the questions change from concerns about general design to questions about specific constructions. In the final presentation, review board members, knowing that the team intended to move ahead with marketing their Enviromug, focused on test protocol and marketing. For the team, the final review was directed toward being absolutely sure of the product design before they ventured into the world of business.

Progress Report #1

How can you quantify the friendliness of the new design?
Have you considered a collapsible cup?
Is the bowl necessary?
How clean is it for fluids other than coffee?
Where will the student wash the cup after use?
Have you looked at military mess-kit analogs?
Can you get official cooperation? Can you, for example, get the College to mandate the use of the cup with a stiff penalty for use of paper cups?

Progress Report #2

Have you talked to someone in the plastics industry? What is cost/price ratio? What is protocol for determining customer satisfaction?
How do you test for reliability? How will it wear?
Why not a screw top? If you think a screw top is less sanitary, is that feeling or fact? Give us a reference.

Summing Up: You've made good progress, you have good experiment data and an early analysis. Now focus on your key set of specs: cost, durability, precise spec for leakage (is there a tradeoff for cost?); get a precise spec for cool-down. Rank all tests on matrix. Visit GW Plastics. Since this market is already hit, you must make a real improvement.

Final Presentation

Did you go back and show your prototype to your survey's respondents?
Is the cup dishwasher safe? microwaveable?
If you are marketing to schools, can you build in a place for the school logo?
Did you do any testing other than the bicycle test? What about durability testing? How many times can the handle fastener be opened and closed before the handle falls off?
How did you get your market estimate figures?

Summing up: You used some clever ideas. You have a good working model for the way you went about understanding customers. Your performance data (testing) are a little fuzzy, but overall you've made a nice contribution.

These questions both support the student team and direct team members toward further study. They were asked by professionals who have sat on many review boards for Thayer School students. Some of them have worked closely with Professor John Collier over a number of years and are experienced not only in a field of expertise but in the art of questioning students. As teachers develop rapport with their pool of mentors and review board members, they will find the level of questioning rises appreciably every year.

The Teacher's Role on the Review Board

The teacher heads the review board and is responsible both to its members (ensuring that their task does not become unreasonably time-consuming) and to the students (ensuring that review board members support the students' effort). At the review, Collier allows members of the review board to speak first, keeping for himself the task of summing up the general response to the team's progress and directing it to future tasks. High school teachers, as well as summing up board feedback, can help students process criticisms after a review has taken place.

Reviewing Students

Teachers who model project work directly on the Thayer School's Engines 21 course give students four opportunities for review. For the first presentation, a team defines its proposed problem and outlines the direction of its project. Two interim progress reports focus on how well the project is developing. A final report and oral presentation wrap up the project. For some teachers, reports at each step are both written and oral; for others, only the final report is presented orally to a review board.

If four reviews in ten weeks seems daunting, especially when project work is done in more than one course, then the teacher should require fewer formal reviews. When review board members act also as mentors, the students' contact with them can serve as quasi-reviews along with a single interim report and a final review before the whole board. As with other elements of engineering problem solving, the focus is on the *process* of review, rather than the actual number of presentations.

Oral Presentations

Much of a team's success in the problem-solving cycle lies in the way the group presents its project and responds to questions. For students, the presentation is as important as the project. The results of good problem solving are useful only if they can be communicated to others.

Proposals and interim presentations may be offered by only two or three members; for the final one, the entire team shares the responsibility. Each member prepares not only his or her part but also gets ready to field questions on other aspects of the project that are most familiar.

Teachers prepare students for the first oral presentations. If video equipment is available, a session of videotaping gives team members the opportunity to critique themselves before appearing before the Review Board. The teacher will also want to devote some time to discussing tips for good presentations, such as:

- Good visual aids work to explain complex ideas concisely. They should be uncluttered and visible to all members of the audience. Materials should *not* be passed out at the conclusion of the presentation because doing so may distract the audience from the next group's presentation.
- Personal appearance is important. When dressing, students should ask themselves, "Does my appearance add to or detract from the presentation?"
- Presenters should speak slowly, distinctly, and with appropriate volume. Notes are to be used sparingly, only as a framework for the presentation. Chewing gum while speaking or using meaningless phrases such as "you know" or "I mean" work against a professional presentation.
- An ear-catching introduction and a strong conclusion help focus the audience. These should be practiced in advance.
- Students should act confident, show enthusiasm and try to sound authoritative during the presentation, even if they are scared. Good acting can create the confidence it projects.

Time Limits

Time limits for oral presentations are important for both teachers and students. Teachers managing multiple classes need to estimate exactly how long each review session will take. Review board members may not take kindly to a session scheduled for two hours that runs to three. Many teachers place an absolute time limit on presentations, telling students in advance how many points will be docked from the review score for each minute over the set limit. Lisa Torres reports that using an electronic timer is effective: "When the beeper goes off, they know they have one minute to sum up. Then I will stop them!"

Students, too, gain from limiting their presentation. With a lot of information to impart, they have to weigh each piece carefully to decide whether it is a vital part of the presentation and, if it is, how to condense without losing meaning. Knowing that time is limited encourages students to practice, so that they don't lose precious seconds. Smooth presentations are a pleasure for everyone involved.

Assessment

In the world beyond the classroom, engineers make proposals in order to obtain contracts. As they work on a project, their progress reports and final reports are scrutinized by their clients. In the end, any engineering firm with consistently substandard solutions and presentations will not survive.

Reviews of students' project work are modeled on the world of engineers, although the consequences of good or poor work has to be forced into the traditional format of grades. Because engineering problem solving is complex and often nonsequential, assessment is much more difficult than, for example, marking a short-answer quiz. However, if teachers want to measure what's worth learning, instead of what is easy to measure, then their task is to devise methods for assessment that both reflect what the students have learned and are neither unwieldy nor time-consuming.

The *Curriculum and Evaluation Standards* prepared by the National Council for Teachers of Mathematics (NCTM) urges teachers to assess what students know rather than what they do not know, and to do this using various assessment techniques, including written, oral, and demonstration formats. Engineering project work encourages multiple assessment by having students demonstrate their knowledge concretely, by designing a solution to a problem, and verbally, through written and oral reports. The goal in engineering problem solving is not the "correct answer" but rather the justification of a solution. Review board scores should indicate to students where they need to improve rather than only result in a rigid grade to be averaged in with other scores.

When to Assess

Because student progress often depends on correction based on feedback from the teacher, teachers assess students' performance at different points in the project—perhaps before the project, to evaluate prior knowledge, interests and skills; at one or two points during the project, to monitor student progress and give feedback; and at the end of the project, as a summary evaluation, with the assistance of a review board.

What to Assess

The written goals and objectives for the project are the best guides for assessment, so the assessment process for the teacher really begins before the first day of class. In drawing up goals and objectives, teachers need to consider how to assess each objective as well as each task required of the student teams. Students have the right to know in advance what they are working for in terms of grades. They may not think that some things they do for a project have value. Teachers need to be clear about grading criteria and share them both with students and with review board members. Teachers should also be specific about their expectations for each task in the project. A written definition of the terms of each report or presentation—what it is to contain, how long it should be—helps students do their work and is useful in any dispute about grades.

How to Assess

Professor John Collier assigns grades based on both oral and written work, with 50% of the grade for the oral presentations, 50% for written work, including reports and team notebooks. He goes over the notebooks carefully, looking for evidence of the team's decision-making process, market research and patent searches, expansion of specifications, brainstorming sessions, analysis, error analysis, and documentation of the construction and analysis phases, especially the testing procedures. He looks at all the matrices a team has used and weighs how well the final solution to their problem satisfies all the criteria for all the matrices. Knowing that some projects, by their nature, require more effort than others, he balances the degree of difficulty of a project with the quality of execution. After he assigns grades, Collier calls each team in to give them his evaluation face to face.

Tom Woosnam also interviews students at the end of each semester and goes over their grades with them. He defines for them, at the beginning of the school year, his expectations for letter grades, using a rubric that clarifies the difference between, for example, an A- and a B+. He says that the majority of students agree with the grade he gives them; when they don't, they have the option of doing additional work to prove to him that they do know the specific content area of the project.

Teachers who total numerical scores over the length of the project usually check those scores against a system such as Woosnam's, to make sure the letter grade a student is given really reflects how he or she is doing.

Many teachers use the evaluation of the review board as part of the final grade. Mary Lou Derwent clearly defines a point system for reviewers and uses an average of review board scores as 50% of a team's final evaluation. Her students agreed that the points of the external review board were important to them, were, in fact, the motivational tool that drove them to do quality work. They did not want to embarrass themselves in front of strangers.

Assessing Teams and Individuals

With the strong focus on teamwork, how do teachers evaluate students individually, especially when much of the work of the project is done outside class, unobserved by the teacher, and all the reports and presentations are group efforts? For many teachers, it makes sense to follow through on the emphasis of cooperative learning by awarding the same final grade to the entire team.

When working with low-level students or students who need considerable structure, Lisa Torres records a daily team grade based on her observation of students' work habits and their records in the Work Log. Using her "KISSES" group behavior standards (see page 42), she moves through the lab, making assessments during class time.

Kathleen Conn recommends a 400-point scale for each four-member team. For her kinematics project,¹⁴ each group was responsible for apportioning the final score among themselves to reflect the actual contribution of each team member. Some teams, she says, simply divided their final score by four to award each member equal points. Other teams, however reluctantly, rewarded team members who shouldered the load with more points and members who "goofed off" with fewer.

Torres also uses a total score to be divided among team members by the students themselves, with the following limits:

- no individual gets more than 100 points or fewer than 60
- the entire team must agree that the point assignments are fair

"Kids hate the process," she says, "because they have to confront openly slackers and folks with inflated egos! But usually it works."

Dale Faughn gives individual grades based on what he observes throughout the project and on the report each team completes detailing each member's contribution. The report is signed by the entire team to show complete agreement on who did what and how much.

John Collier assigns one grade to all team members, telling them that they are free to alter the individual grades to reflect their perception of the work done, but that no one member of the team can have a grade more than a single increment above or below the team grade. Thus, even the slackard member of a B+ team cannot receive less than a B. This system provides an incentive to get every member of the team working. Students learn that it is more important for a hard worker to develop the leadership skills that will get all team members doing their jobs than it is to carry an extra load alone.

Many teachers ask their students for a formal evaluation of both their team as a whole and one another as individual team members. Some teachers ask team members to grade one another and define the grades; others ask each team member to detail what each team member accomplished. "State exactly what you contributed to the development and completion of this project," Mary Lou Derwent asks each student. "Be specific, not modest." This request is followed by, "Evaluate the work done by the three other members of the group. Be specific about each member." Reading through the evaluations of team members, Derwent gains a fairly complete overview not only of each student's contribution to the project, but also of how team members interacted with one another. These perceptions are important when so much of the project is out of the teacher's sight.

Project Evaluations

Teachers new to project work often initiate dialogues with their students so that they can respond to students concerns, even, if necessary, alter timetables or objectives. Mid-way through her first project, Kathleen Conn asked her kinematics students for specific feedback on the printed instructions she had given them, her own involvement in the process, the specific work the students had done, the nature and appropriateness of the assignment, and how they thought their projects would turn out. At the end of the project, she asked them if their project had turned out as they envisioned it, whether the process had helped their understanding of kinematics, and what changes they would propose to make it a better project.

Some of the interim evaluations, she reported, showed the confusion of students new to engineering project work, but by the end of the project, students understood its purpose better. One student wrote, "While in the beginning it seemed like a hellish nightmare, as¹⁵ time went on it didn't seem so bad. Now that it is over and in retrospect, I'd do it again."

15. See "Kinematics at the Traffic Intersection," p. 101.

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 oncoming 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 CO₂ 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.'"

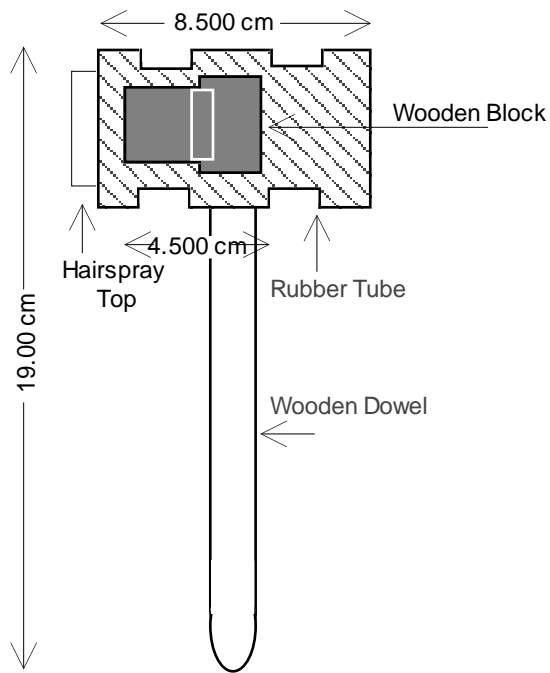
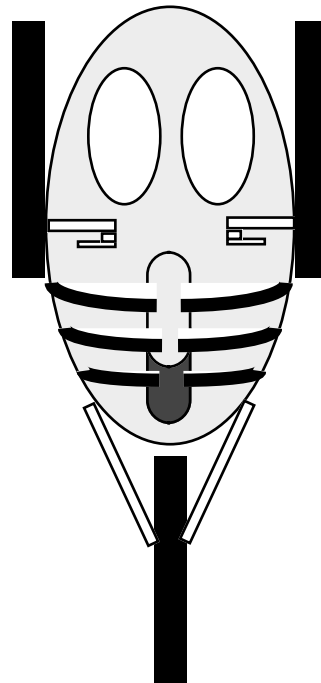


Figure 12. Student CADs: doorknob extender for arthritics and arm-bike for paraplegics



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 tessellating 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 redefinitions, 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.

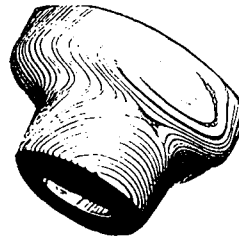
One team researched the area of accidental poisoning of children. The first matrix analysis helped them choose from different categories of child-proof safety devices—sensors, lids, nonphysical and physical deterrents, and security measures; a second matrix weighed different types of safety lids. Their 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 advertisements. 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 accommodate most sizes of containers. So stock Kid-Stoppers, by Protect-A, Inc., and help promote a safer environment for our children.



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.

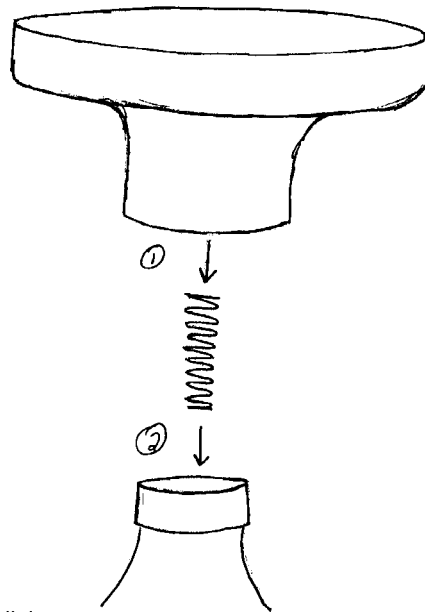


Figure 14. Diagram, ad, and prototype for child safety lid.



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.

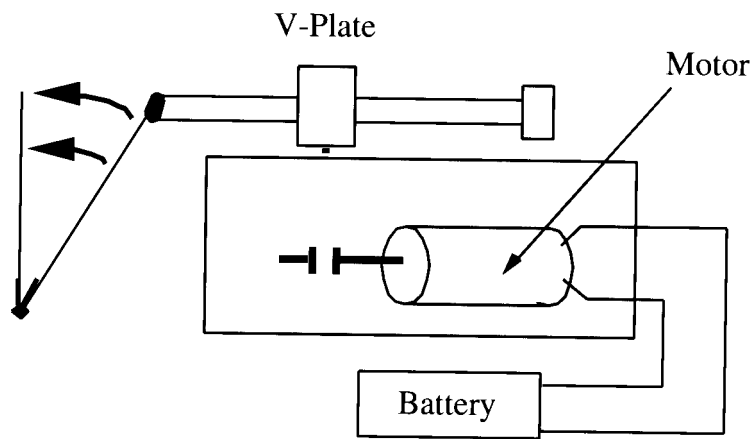


Figure 15. Student CAD of a washcloth wringer for arthritics

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."

Mehrbach 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 performance 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.

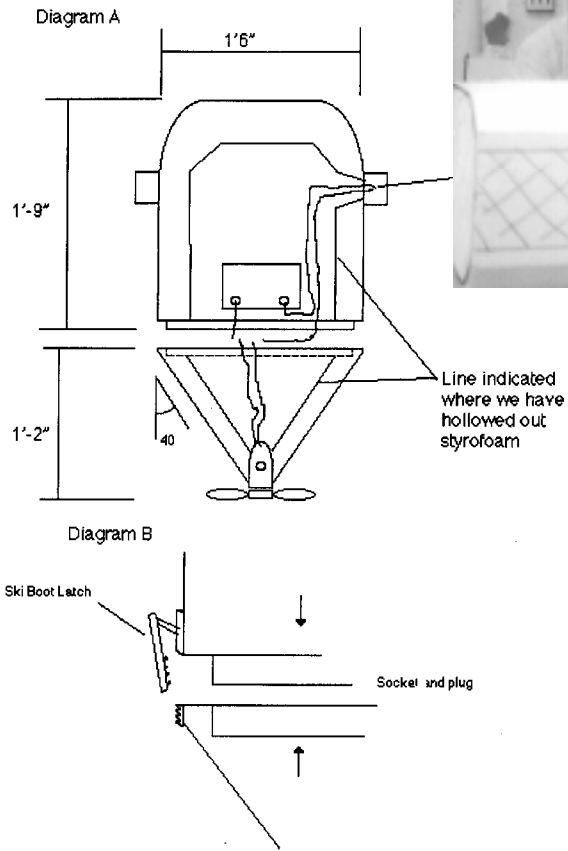


Figure 16. Student sea sled diagram and team in review

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.

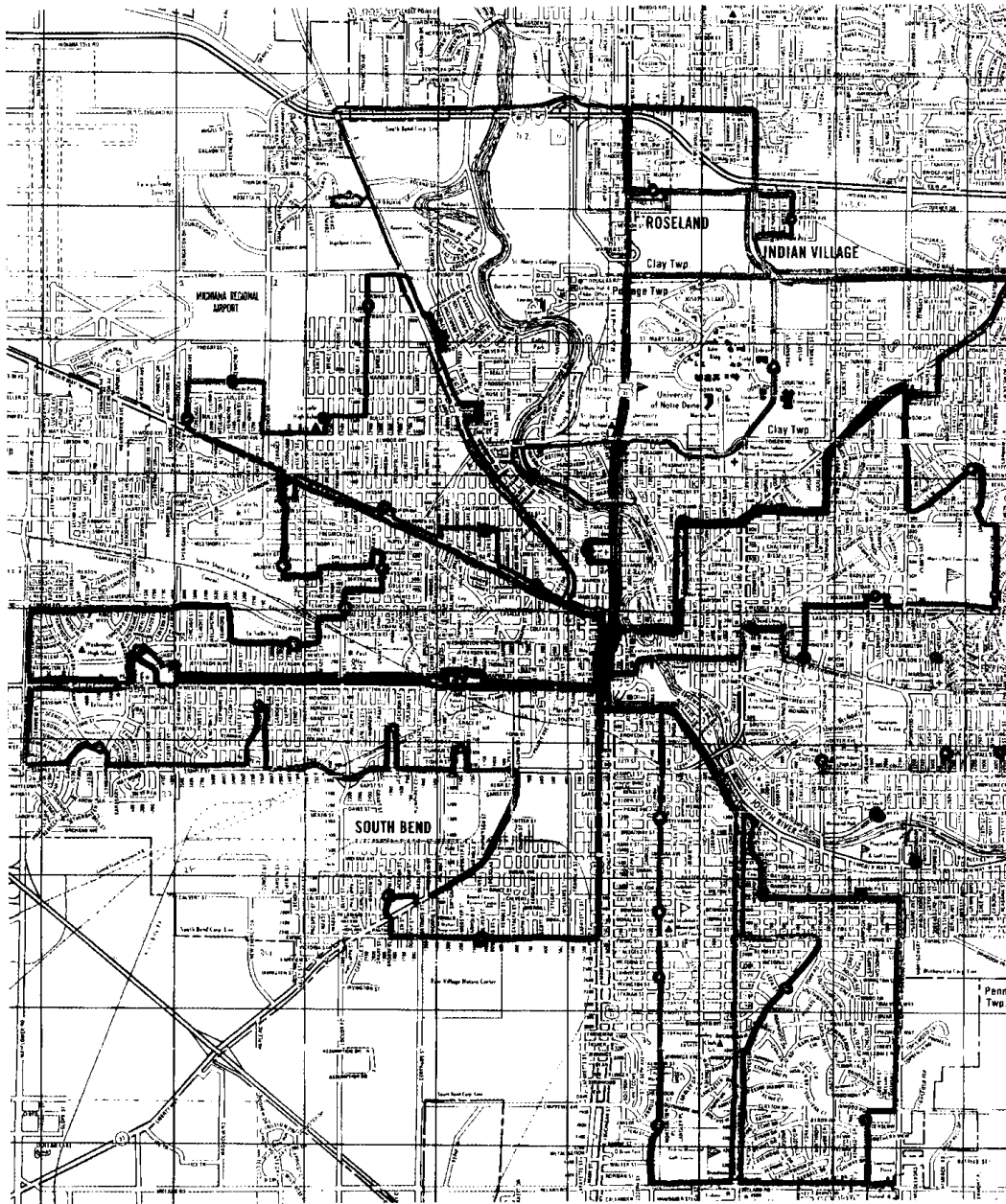


Figure 17. Student redesign of South Bend Public Transportation System

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 set-ups. 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.”

Chapter 9

Problem Solving in the Work World

Defining the Problem

“Defining the problem through marketing is absolutely critical,” says Dean Spatz, founder and CEO of Osmonics, Inc., in Minnetonka, Minnesota. “As engineers, we can make the greatest product in the world, but if it doesn’t meet a human need, then it’s basically worthless. There’s no sense in developing a solution to a problem that doesn’t exist in the first place.”

Engineers at Osmonics apply reverse osmosis to processes as diverse as concentrating sugars for maple syrup processing or purifying water for dialysis machines. The idea for the company began in the early sixties with a jar full of brackish water. Spatz and his Thayer School classmates were given the sample and told to find a way to make it potable. Reverse osmosis was a relatively new concept then, so Spatz and his team worked to apply the process to desalinization. After successfully using membranes to separate the brackish component out of the water, Spatz looked at other applications of the process, such as concentrating sugars. Shortly after finishing his degree at Thayer School, he formed Osmonics and set up a reverse osmosis unit on a friend’s sugar bush—several acres of maple trees devoted to maple syrup production. The fuel savings the first year alone were more than 60%.

Over the years, Osmonics engineers have discovered a variety of markets for the reverse osmosis process, and the company has grown steadily from a small business with a single market focus to a \$150-million company with diverse markets. Spatz attributes at least part of his success to the way he has applied the precepts of engineering problem solving to the inner workings of the company. He says that he often has to teach problem solving to young chemical engineers whose traditional textbook problem solving has not prepared them for defining and redefining a problem.

Spatz believes in problem solving for students at every level. He understands the challenge for teachers. “The instructor has to help students define the project without getting in there and saying, ‘You do this, you do that.’ More like a coach. That’s a tough job for the classically trained teacher. But the whole idea of coaching is preparing someone to do the work. The coach can’t get in there and play. From a business standpoint, it’s no different. That’s what separates good managers from the ones who may have some leadership ability but can’t let others do the job.”

Technical Specifications and Marketing Constraints

Another Thayer School graduate, Cameron Jones, worked with Thayer School instructor Sydney Alonso to transform a different laboratory problem into a business. The original problem was: How can digital electronics improve music instruction? Young electronic composers at Dartmouth College worked on Moog synthesizers, the instrument of the day, but these were unwieldy instruments to set up and, worse, had no memory. Alonso accepted the music department's challenge and built the world's first digital synthesizer; Jones, a musician as well as software expert, programmed it.

"I knew what I wanted the machine to do because I was a musician," remembers Jones. "The computer technology available at that time offered only very, very primitive sounds—triangle waves and pulse waves." Alonso agrees that what they were doing was, in those days, just barely doable. Generating sound for digital processing was hard enough, but taking into account such musical characteristics as harmonics or attack and decay, gave the problem added complexity.

The enthusiasm of Dartmouth music students led Alonso and Jones to think that there might eventually be a market of professional musicians. In 1976, they left Thayer School and founded New England Digital, Inc., makers of the Synclavier Digital Music System. For a number of years, the company remained a technology-driven company. A musician could pose a problem, but the emerging technology could only do what it could do. "Here's this incredibly primitive technology," says Jones, "and the question is, can we do something useful with it and will somebody pay for the product? O.K., let's do that. And then two or three years later it's making feeps and boops, and we ask, are any of these sounds something people would find useful? And so it kind of grew."

Jones reckons it was ten years before the technology was sophisticated enough to make the instrument useful for full-scale music or audio production. "By 1985 there was a wide palette of technologies available," says Jones. "And at that point, you had to apply business constraints as well as engineering constraints to the problem. Instead of, here's the technology, who might be able to use it? it was, which market do we want to go after?"

Through the mid- and late 1980s, the company produced the Rolls Royce of digital music systems and sold it to customers such as Oscar Peterson, Laurie Anderson, Stevie Wonder, Frank Zappa, Michael Jackson, and Sting. As the array of digital audio technologies grew, the customer became an important source of new problems. Pat Metheny, master guitarist, heard the quality of the Synclavier and asked whether a guitar could be the user interface; within a year, sounds of the Synclavier were emerging from Metheny's strings. Pianists who questioned the feel of the non-responsive electronic keyboard pushed the company to develop a keyboard sensitive to both velocity and pressure. Eventually the company branched into digital audio recording, marketing to Lucas Films and other film post-production studios.

As New England Digital became a market-driven company, it became a prime example of how communication between problem solvers and their customers keeps a developing product on the cutting edge. By designing a machine to be used by creative people—musicians, sound technicians, film directors—New England Digital could take advantage of the imaginations of their customers. Customers, using the Synclavier in idiosyncratic ways, told New England Digital engineers what might make the machine work even better. The engineers, of course, continued to look at the existing technology and devise new ways to push it further. The core problem—how to improve the Synclavier—was in a continuous state of redefinition.

Both Alonso and Jones believe problem solving is an essential ingredient of the education process. "Compare the approach that just spends all its time in the classroom working on artificial problems" says Alonso. "If it's not something you're going to use, it can be pretty dry. You get motivated kids and then treat them to a methodology more applicable to ROTC or prison or something, they soon get unmotivated. But set them to real problems and some kind of spark may happen."

Teamwork and Leadership

Leadership, says William Boddie, Chairman of the German division of the Ford Motor Company, is not dictatorship. "You've got to find out how to motivate. You cannot coerce people. Well, you can, but the results may not be what you want. If you've got something you want done in ten minutes, coercion may be the best way, but if you've got something that's going to take three years, you're dead if you try coercion. People who learn that early in their careers are the most successful."

Ford engineers have traditionally worked on function-based teams. Chassis engineering, for example, might be applied to any car in the company's line. Ford teams are now oriented toward specific customers—Taurus drivers, Escort drivers, or drivers of the F-Series Truck. Each team focuses on the whole product instead of the part. The workers not only understand how their jobs fit into the larger picture, they also have objectives in line with the customer's objectives, making the customer a partner in defining the goals.

Boddie believes that an understanding of group dynamics and interpersonal skills is really the key to leadership. "When you get into a situation with a group of people who are all different, you have to have a way to get every member of the group to want to do the same thing. If you're the leader, you have to make each individual want to do what you want to do. Figuring out how to do that, how to get them to want to do what you want them to do, is the most important skill a leader can have."

The structure of the group, although it may develop out of teamwork, is also the responsibility of the leader. When Boddie first came to Ford, company structure was based on the military. "One of the things that you find in the army is that you have some doers and then you have the watchers and checkers. Because doers tend to rebel against the management style in that type of organization, you have to have watchers and checkers to make sure that they aren't too far out of line. If you're in the army, where you have an infinite number of resources to apply, that's no problem. If you're in a competitive business where other companies don't need watchers and checkers, then you're going to go out of business if you can't figure out how to do your job at the same resource level the other company achieves."

Boddie notes there are times when leaders must make unilateral decisions. The goal is to achieve consensus as best you can, but the leader is ultimately responsible for the team's productivity. "I always try for consensus," says Boddie. "But some decisions could take the group in the wrong direction. It's the leader's job to see that and make the right decision."

Teamwork, then, is a balance of consensus and leadership. "There's no such thing as a highly productive team that doesn't have a good leader." And how does one foster leadership in young people? "I think you learn by doing," he says. "I don't think you learn by being told."

The Customer in the Design Process

Paul Stokstad, like Dean Spatz, is founder and CEO of a company born as a student project. PASCO Scientific, Inc., a company in Roseville, California, designs laboratory kits, computer interfaces, and science accessories for secondary and post-secondary physics courses. The company's first product—a kit to replicate Robert Millikan's 1912 oil-drop experiment—began as a high school physics project; then, while at Dartmouth, Stockstad turned the Millikan experiment into a product to sell. A second project—developing a streamlined version of the unwieldy electrometer of the day—became the second product for what would eventually become PASCO.

Stokstad counts on customers to make the company successful. Some bring ideas and beginning designs for new products. Others test products in the classroom. Stockstad calls teachers "PASCO's conscience." He knows engineers love to put in as many features and gadgets as possible just because they can. When a teacher says, "That's going to confuse the daylights out of my students. I want one knob and I want it to do only this," PASCO listens. Never mind that the other features can be incorporated without adding to the cost. The teacher has the last word on the reality of the classroom.

For example, thanks to feedback from teachers, the low-friction carts that PASCO sells for studying dynamics and motion have spring-loaded wheels. If a student steps on one, it flattens to the floor so the student can't skateboard. "This is what you get from teachers," says Stokstad, "things that an engineer might not think of. But once the teacher says, 'This is what I want, these are my needs,' then you can apply the engineering skills."

Stokstad is in touch with the reform movement in science education and fully supports it. He chuckles about a student intern who was given a piece of equipment which had been the subject of complaints. He was told to read the manual, set it up, and run the experiment ten times. "So the student leaned over," remembers Stokstad, "and he says, 'OK, now what's the number I'm supposed to get?' 'No, Vern, just do the experiment.' He said, 'I know, but what's the correct answer?' And that said something about most of the science courses he took."

Stokstad supports the idea of students starting with experiments instead of lectures. Learning Newton's laws and then proving in the laboratory that Newton was right is not, in his opinion, very effective. "Your mind isn't open, you aren't looking to learn something, you're simply trying to confirm." He believes that the computer is driving us to move beyond the cookbook laboratory. "Computer plots out 200 points, you can see what it is. All right. Now let's do some mathematical curve fitting. What would be a proper mathematical model? So you start with a real-world experiment and work back and find that, well, interesting, Newton had this same conclusion x number of years ago."

Brainstorming in the World of Finance

“A truly innovative solution,” says Peter Fahey, a Thayer School graduate and limited partner at the New York financial firm Goldman Sachs, “is the one that departs the most from the norm. So you have to get crazy before you come back to sanity and reduce something to practical.”

An investment banker advises companies on different financial tasks, such as how to raise money or how to accomplish a merger or acquisition. Problem solving, according to Fahey, is problem solving whether you are inventing a device or facing a financial question. Fahey looks at any situation and asks, how can we improve on the way it has been done previously? “Always seeking the better solution, never being satisfied with traditional solutions—that’s the idea.”

Fahey believes that the key to superior problem solving is the step of brainstorming alternative solutions. He asked colleagues “to suspend logic for a while and generate a number of alternative approaches to a given problem without regard for whether any approach is feasible. It doesn’t matter whether the ideas are even really that good; brainstorming simply serves to generate a wide array of approaches. And it is important to generate them because, although Idea #37 may not make any sense, it will often lead your thought process on a path different from one it might otherwise have followed. Later you are able to make the idea into a feasible solution.” Brainstorming, then, is important not for the number of ideas generated but for the way some of them affect thinking.

Fahey has established a number of formal and informal mechanisms to introduce the engineering approach to problem solving into his firm. In the beginning, colleagues would say, “Oh, that’s a crazy idea!” but Fahey persisted with the point of view that no idea was crazy. Eventually colleagues came to accept the value of identifying a broad array of alternative solutions. Clients, although they may not have known why, found themselves advised to take innovative financial actions. They never knew that a successful idea was the result of the suspension of logic and generation of “crazy” ideas, but, as Fahey says, “Brainstorming is the essential, intuitive part of the process that leads to superior, innovative solutions.”

Communication

Communication is the key to good problem solving, according to Dennis Drapkin, a Thayer School graduate and partner at Jones Day Reavis & Pogue in Dallas, Texas. “The lawyer’s stock and trade are words and language. The ability to communicate is essential. One thing we look for in hiring people is how well they can communicate, how well they can decipher from the world what it is that’s important and then turn around and communicate it to someone else.”

Drapkin believes that legal problem solving is no different from problem solving in any other field. “What’s the process of what I do? It didn’t become completely clear to me for many years, but lawyers, like engineers, are professional problem solvers. I really don’t think there’s much difference in the process.”

Lawyers need to be able to communicate to other specialists in their field and to translate the specifics of a case for those without legal training. “You have to be able to do both,” says Drapkin. “You have to be able to explain technical content to someone who is technically adept and you have to be able to explain it to someone who isn’t but who happens to be your client. Make the complex and arcane parts of the Internal Revenue Code comprehensible to anyone, for example.”

It’s a skill that requires practice: reading and writing critically and analytically, being able to separate the meaningful from the meaningless, communicating orally and in writing. Students who describe their projects clearly and succinctly in writing and before a review board are practicing the skills of a lawyer, skills that will stand them in good stead in any field, from business to medicine to teaching to aviation. Drapkin applauds all efforts that foster good communication skills. “Being able to read and write, being able to comprehend knowledge from a variety of sources and knowing how to find it—these skills are vital to any profession.”

The Interdisciplinary Approach

Charles Queenan, a 1978 graduate of Thayer School, applies engineering problem-solving skills to the world of environmental and energy consultation. As president of Putnam Hayes & Bartlett, an economic and management consulting firm based in Washington, D.C., Queenan underscores four aspects of engineering problem solving that serve him well in his consultation work. First is teamwork. “We do virtually all of our work in teams,” he says, “often with several members of a client’s organization. The trick is to arrange teamwork so that group thinking can go other than in a lot of different directions and still reach good conclusions. It’s an art.”

The second element Queenan believes essential to problem solving is brainstorming, an “exchange of ideas unfettered and unconstrained. And this is a lot harder to achieve in a real-life context.”

Interdisciplinary work is Queenan’s third—and most basic—element. Environmental problems need to be addressed from the perspective of several disciplines—public policy, economics, technical, legal. There are always tradeoffs to consider. Assessing the risks in life sciences, understanding hydrogeology or geology in order to assess the dangers of transporting contaminants, understanding the legal requirements with respect to different solutions that might be applied to a problem—all these issues must be addressed. Bringing different disciplines together in the same team, then, is essential.

Clear and careful analysis from the different perspectives is the fourth element. “Once you have an understanding of why you need to solve this problem or why that technical issue is important, you can do the analysis.”

Teamwork, brainstorming, interdisciplinary grounding, and analysis—these are all brought together each time Queenan takes a client’s case. The mission might be to help the client company evaluate its major potential environmental liabilities, such as hazardous waste sites, and then to help them develop a strategy to solve the problem. The team might include environmental attorneys, engineering consultants, and Queenan himself, with his mix of engineering and business experience. The success of a team comes from what each member brings to the forum and how together they create an atmosphere where they can risk, as Queenan puts it, “the brilliance of dumb ideas.”

Queenan sees a tension between brainstorming—“the freedom to say something stupid”—and the interdisciplinary expertise of the brainstormers. “If any one of us were to say something stupid too often, we wouldn’t be here. You can’t suffer fools too often.” On the other hand, ideas that at first blush appear not to make a lot of sense often help the thinking process. And when ideas are generated in a forum firmly grounded in multidisciplinary expertise, the team needn’t fear going down a blind alley.

“You can have a great exchange of ideas, many of them perhaps stupid, and if you can bring to the issue the right disciplines and the right analysis, the right grounding in theory and in fact, you can really get somewhere.” Each potential solution is tested against constraints articulated out of the expertise of the different team members. Analysis relies on everyone’s perspective. At the end of the day, the best solution may not be the one any single team member might advocate but rather the one all can agree solves the problem with the least harmful impact.

The Physics of Toys or the Toys of Physics*

Copyright © 1996 Dartmouth College. This module was revised by Trina Cannon, Mike Dirks, Marty Peters, and Darnall Stone during the 1996 Engineering Concepts for the High School Classroom workshop from a module originally developed during the 1990 workshop by Jon Davie, Bruce Chappelle, Anthony Nicholson, H. William Davis, and Robert Wolff. This module has not been classroom tested.

A Link Between High School and Elementary School Classrooms (with extensions possible for math and the other sciences)

PROBLEM STATEMENT

Design and build a toy or game which demonstrates a specific physics principle or principles. This toy or game must be suitable for use by elementary school age children and must not presently exist.

PROJECT GOALS AND OBJECTIVES

The goals of this project are twofold: (1) increase the learning of your physics students and (2) create enthusiasm on the part of elementary school students for science in general and physics in particular. Your students will deepen their understanding of physics by analyzing what is needed in their toy or game to effectively convey the concept they have selected as well as through the actual construction process. The implementation with elementary students will both test the validity of their strategy as well as give them practice in communication skills. An added bonus should be stronger links between you and your elementary school colleagues and possibly with other community members.

OTHER CONTEXTS

Just as there is a strong and obvious relationship between the principles of physics and many children's toys, there is a natural connection between many games and basic ideas of mathematics. For that reason this project is easily adapted to a mathematics classroom. Materials needed for implementation might be similar but could be simpler than within the physics context. High school students of biology, chemistry or other areas could likewise create activities to introduce concepts of these disciplines to younger students.

TIME SCHEDULE

You will need to decide how many days of class time are required in your particular situation and how much of the actual design and construction can be done by students outside of class. If this is your first project using the Thayer method, give students adequate time in class to learn the steps of the problem solving cycle. Observe and offer feedback on their use of the method for this project. Also, allocate more time between the design and construction of the toy or game and the final presentation if your students are contacting the elementary school teacher themselves. You may need to provide several weeks or more of implementation time in this case. One possible time frame is provided below:

Day 1: Teach the Thayer problem solving process. This includes the motivation needed to prepare the students, a description of the process and the techniques needed for the process. Include a sample problem so that students can practice problem redefinition, brainstorming alternatives and developing specifications.

Day 2: Finish up your introduction to the process. Assign members to groups and state the problem. Let students begin the problem solving cycle.

Day 3: Today you can observe and offer feedback to ensure that students are actually following the Thayer model.

Day 4: Regular class period. Allow some time to answer questions from the groups. You may want to wait until today to distribute the actual proposal sheet(s) which students will be completing and submitting.

Day 5: Proposals are due. Whatever form your paperwork takes, be sure that students address product design, budget, and where and when their elementary school implementation will take place.

Day 6: Return proposals to students with any appropriate feedback. Contracts can also be used if you are supplying money for project expenses.

Day 8: A written interim report as well as the toy or game is due from each group.

Day X: You may want to allow class time for students to try out their games. Alternatively, you might suggest that they do this outside of class.

Day Y: Project presentations and debriefing with the review committee. Schedule this for the earliest time possible after students have implemented their toy or game with elementary school students.

BUDGET

Unless students are able to rely totally on materials they have available at home or which you supply, some out-of-pocket expenses will be required. Several options for dealing with this are outlined below. Whatever option is selected it is vital that students be properly informed in advance. If funds are made available to students, each group should select a treasurer to handle reimbursement and receipts retained. It is also a good idea to put a limit on the value of salvaged or scrounged materials so that no project appears significantly costlier than the others.

OPTION 1: School funds with a suggested limit of \$10.00/group

OPTION 2: Grant money with a reimbursement as requested by the student group understanding that all groups will not need the same amount of money -

OPTION 3: Grant money with a suggested limit per group as set by the grant guidelines.

OPTION 4: Students fund the project from their own pockets with a suggested limit of not over \$5.00 per student.

OPTION 5: Locate an anonymous benefactor to fund the project.

OPTION 6: Students fund the project from their own pockets with a suggested limit of not over \$5.00 per student and with some monetary limit for scrounged materials.

OPTION 7: Other!!

PRELIMINARY WORK TO BE DONE BY THE TEACHER

Before the teacher starts a project, many things should be done by that teacher. Things, places, and people not left to the discretion of student groups should be decided upon in advance and clearly specified.

1. Obtain permissions for this project from appropriate school administrators. There is nothing worse than a principal blindsided by an angry parent or a disgruntled teacher. Most administrators are eager to support the kind of cooperative learning and community involvement required by this project and need to understand both your process and your goals.
2. Identify the class that will do this project. Because of the resources and space available, a real bottle-neck may occur if you assign this project to several classes at once. Therefore, assigning the project to each class within a different time frame may be desirable.
3. Determine the method of funding and the amount as indicated above. This will be dictated by the school policy and teacher ingenuity.
4. Talk to potential resource people and alert them to the project and its guidelines. A short meeting to show them the plans and to encourage them to be part of a team may ensure their eager participation. You may want to contact potential elementary school teacher participants, but there is value in making that one of the responsibilities of each group. Personal contact is important even if these key people cannot attend a meeting.
 - a. Toy expert
 - b. Shop teacher
 - c. AV person— for video use
 - d. Librarian —School, Community and local college, if available
 - e. Other teachers that might be useful (speech, math, etc.)
5. Find a site with chalkboard for student work. If such a site is not available, furnish each group with a newsprint pad and marker. Portable chalkboards will help to give some group space by serving as temporary walls. A substitute for the portable chalkboard can be made by using an 8'x12' sheet of white Masonite paneling mounted on a support easel. Your classroom and student homes may provide adequate sites.
6. Put relevant books on reserve in the library (ies). Ask the community librarian about book loans from regional libraries if you think this might be helpful.
7. Determine grading procedure for the project and the weight it will carry in the semester grade. All of this should be made clear to the students at the onset of the project to avoid surprises. Having it posted in a visible place in the classroom during the course of the project makes it readily available to the students.
8. Select the deadlines. A consultation with the person who plans the school calendar should be helpful. By notifying fellow faculty members one can avoid picking the same due days as the big English papers or Social Studies project. Kids in stress can cause a major mess!
9. Determine how the groups will be designated and choose them.
10. Line up the review committee for final presentations. Phone calls can be followed by an official letter. Be sure to mention the dates of the project reviews.
 - a. Science Teacher
 - b. Elementary School Teacher
 - c. Administrator
 - d. Toy ExpertCurriculum supervisors and parents also make a good audience for the project presentations.
11. Schedule the auditorium for project presentations. Other teachers may want to bring their classes to see the student work.
12. Prepare the handouts that the students receive sometime during the project.
 - a. Background articles (if available)
 - b. Sample proposal (posted in your room)
 - c. Proposal form (including budget)
 - d. Contract form (if used)
 - e. Presentation guidelines
 - e. Evaluation form
 - f. Sample interim and final reports (posted in your room)

Examples of some of these follow but you may have much better ideas.

13. Prepare a "Thank You Reception" for all review panel members and volunteers that help the students. The extent of the refreshments and the time will be dictated by the money available. Should the student work be funded by a grant, do not forget to put this in the proposal. "Thank you's" are the easiest to give and the easiest to forget to give! Some schools have a fund for receptions.
14. Consider involving the elementary school students in a written feedback exercise. Either you or a member of each group can suggest this to the elementary school teachers involved. You can then display the letters you receive in your classroom.
15. Some of the suggestions provided may seem too elaborate and time consuming. Keep in mind that this whole process needs to be fun for you as well as your students, so modify things to suit your philosophy and your comfort zone. A hands-on, safe experience for your students using the Thayer problem solving method is the one essential element.

PROPOSAL FORM

Date _____

Company Name _____

Company structure: (Group members and their titles)

Physics principles(s) to be the focus of your project:

Specifications of you toy or game:

Materials and estimated budget: (Purchased and salvaged materials)

Preliminary description of your project: A labeled diagram can be included.

Specifications for your elementary school activity:

PRESENTATION

Each group will be provided with 15 minutes in which to present their toy or game to the class and visiting committee. Their presentation should accomplish several objectives:

1. They need to demonstrate that they have produced a functional toy or game.
2. The design and construction of their product is to be described with details on materials used and the method of fabrication.
3. They must be able to use their device to demonstrate a specific principle or principles of physics.
4. They must also show that this is suitable for use by an elementary school child.

Each member of the group is expected to contribute to the formal presentation. It is advisable to limit the prepared talk to a total of ten minutes which will leave five minutes to respond to questions and comments from the audience.

A group is expected to be prepared to make their oral report at their assigned time. This means that their product would be in its final form with no adjustments needed. Any audio-visual equipment required for a group's presentation should be arranged for in advance of the presentation day. They need to have rehearsed their presentation keeping in mind that the quality of the presentation will be a part of their project's overall evaluation.

EVALUATION FORM

ASSIGNMENT: Design and build a toy or game which demonstrates a specific physics principle or principles. This toy or game must be suitable for use by elementary school age children and must not presently exist.

Evaluator's Name _____

Name of Company _____

Student's Names _____

Score the group's performance in each of the following four areas. Use a score from 0 to 5 with 0 representing very poor and 5 being excellent.

1. Clear demonstration of a specific physics principle or principles

- the principle(s) is evident.
- the toy works according to the principle(s).
- the toy really works.

2. Quality of the toy or game

- the toy is suitable for the intended age.
- the toy follows the safety standards.
- the toy is appealing to the intended age.

3. Quality of the presentation

- does not exceed the time limit (15 minutes).
- describes the design and construction of their product with details on the materials and method of fabrication. -demonstrates their device.
- demonstrates that it is suitable for an elementary student.
- each member of the group contributes to the formal presentation.

TOTAL _____

Please add any additional comments, thoughts, or observations about this group's project on the back.

Participation Contract

We hereby agree to exert our best efforts to develop and build a toy or game which demonstrates a specific physics principle or principles. This toy or game must be suitable for use by elementary school age children and must not presently exist. We further agree to arrange and carry out an implementation activity with an elementary school class.

Requirement

Date of Completion

Proposal _____

Interim Report _____

Elementary School Implementation _____

Final Written Report _____

Review Committee Presentation _____

Elementary School and Teacher _____

Group Members _____

Signatures

Date _____

**Contract
between**

Science Department

Name of School

and

Name of Student Company

INTRODUCTION: This contract is effective upon the date of signing between

Name of School

Science Department and

Name of Company

(hereinafter called the "contractor.")

AGREEMENT: The partners agree to the following terms and conditions:

Article 1. Work to be performed:

- A. The contractor shall furnish all personnel, facilities, equipment materials, supplies, and services necessary for the performance of the work generally described as the design and construction of a toy or game suitable for use by an elementary school child.
- B. Specific requirements and due dates are set forth in Appendix A.

Article 2. The Period of Performance:

The performance of the work described in Appendix A including all deliverable items hereof shall be completed by

Due date

Article 3. Consideration and Payment:

- A. In full consideration of the contractor's performance hereunder _____ will reimburse the contractor for costs up to \$10.00.
Name of Department

Expenses to be approved by the contract administrator of

Name of Department

- B. _____ will award academic grades to the contractor's
Name of Department
personnel according to critique sheets completed by the review committee and evaluation of the written report by the contract administrator for

Name of Dept.

Article 4- Applicable Documentation:

In addition to the terms and conditions contained in this schedule, the following documents are attached hereto and made part of this subcontract:

- A. Appendix A, entitled "Statement of Work."
- B. Contractors Proposal dated _____ is hereby incorporated
insert date
herein by reference insofar as it is consistent with appendix A "Statement of Work-"

Article 5. Rights to Proposed Data

Name of Dept _____ shall have the right to use, duplicate, and disclose

for any purpose whatsoever, the technical data contained in the proposal upon which this contract is based.

Article 6. Contract Administrative Responsibilities:

The contract administrator for _____
Name of Dept

for this contract is _____
Name of Teacher

Article 7. Invoices

Invoices for work accomplished under this contract shall be submitted to:
Name of Teacher

Article 8. Dispute

Any disagreement about the terms of this contract shall be referred to
Science Dept. Head

In witness whereof, the partner hereto have executed this contract as of the date stated below.

Authorized: _____ Accepted: Contractor
Name of Dept.

By: _____ By: _____
Name of Teacher

Title: _____ Title:

Date: _____ Date:

Containers

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Archbishop Ryan High School
Philadelphia, Pennsylvania

Problem

The Raider-Rag-Doll Container Foundation (RRDCF) is looking for proposals in the field of practical containers. The RRDCF has a broad perspective and will consider proposals for containers for any product of given volume. Your job is to design a practical container suitable for holding a specific product, such as popcorn, hot coffee, soda, or cereal, or for transporting a specific item.

The RRDCF has brought together a review board comprising engineers, administrators, guidance counselors, and teachers to assess and evaluate your proposal. Each proposal must include the following considerations:

- At least three different shapes
- The surface area and at least three other criteria, such as cost, usability, aesthetics, liability, and environmental impact
- A justification through matrix form for all decisions made

Assessment

Your group will be evaluated using the following criteria. Did the group—

- function amicably and efficiently and share responsibilities equitably?
- consider at least three different shapes?
- develop appropriate mathematics for surface area, given the volume?
- develop quantifiable decision matrices to justify decisions?
- use a variety of resources effectively?
- show evidence of correct data analysis and the development of logical conclusions based on the data?
- meet all required deadlines?
- submit a typed—the mathematics can be done neatly in pen—report with a maximum of ten pages?
- make a model, or detailed diagrams, of your container? This model does not need to be in the chosen material, since It Is for demonstration purposes.
- articulate clearly, keep to the seven- to ten-minute limit for the oral presentation, and adequately answer all questions posed by the review board?
- submit two or three pictures of your group in action?

Deadlines

- Progress report 1 is due at the end of the first week.
- Progress report 2 is due at the end of the second week.
- The typed report, a maximum of ten pages, is due at the end of the fourth week. Include a copy for each member of the review board.
- The oral presentation—seven-minute presentation followed by three minutes for questions and answer and the model are due on Friday of the fifth week.

Improving the Environment*

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Colerain High School
Cincinnati, Ohio

Course Outline

This year, the Colerain High School Foundation (CHSF) is looking for proposals in the field of improving the environment. The CHSF has a broad perspective and will consider proposals in any area of environmental concerns. Therefore, the environment, in its broadest context, should be considered. Possible areas might include: water quality, air quality, noise pollution, solid waste handling, recycling, packaging, energy efficiency, environmental safety, pest management, acid rain, soil management, solar energy sources, synthetic fuels, etc.

The CHSF is specifically interested in devices/products rather than software, although software may be a portion of the project. Specifically in this proposal you are to:

1. Select a problem in the environmental field;
2. Determine the magnitude of the problem;
3. Determine the specifications associated with a satisfactory solution;
4. Generate a set of potential alternative approaches;
5. Select an approach;

During the project, you will be expected to also:

6. Develop a prototype;
7. Test the prototype;
8. Develop a venture proposal;
9. Present the prototype and venture proposal to the Class/Review Board.

The CHSF will assess and evaluate your efforts. There will be three (3) company presentations during the quarter. The first presentation will be a progress report, the second will be that of your proposal, and the third will be for your final presentations. The tentative schedule for these presentations/assessments are as follows:

Tues. April 30	Written progress report (Thayer process, status of project and bibliography-5 pg max) Oral progress report
Tues. May 13	Written venture proposal (More details later, 10 pg max) Oral presentation of venture proposal
Week of May 12	Product/Device design plans
Week of June 2	Final computer presentation of company solution to their environmental problem (disc) and prototype product/device presentation
Week of June 2	Company portfolio (See Appendix A of contract)

Syllabus

Topic: IMPROVING THE ENVIRONMENT

Instructor: Mrs. Carla Huffman

Week of April 7-11	Goals; Problem-solving activities; Company assignments; Brainstorm ideas; Guest speaker: Joe Maurits, student who has submitted a patent idea
Week of April 14-18	Thayer problem-solving process; segmentation; literature search (library); FPA speaker-Dave Craven; Junior Achievement speaker-Dave Swincher (marketing strategies)
Week of April 21-25	Field trip to Ethicon EndoSurgery, Blue Ash, Ohio; companies will work on progress report (written and oral); Ethicon EndoSurgery speakers- Bill Collins, et.al. (Phase 2)
Week of April 28-May 2	Ethicon EndoSurgery speakers-Bill Collins, et.al. (Phase 3); companies SUBMIT WRITTEN PROGRESS REPORT AND ORAL PRESENTATION; continue brainstorming/ further development of product device ideas/ complete general matrix; introduce venture proposal format
Week of May 5-May 9	Develop and type venture proposal; begin work on PowerPoint presentation of venture proposal
Week of May 12-May 16	Finish Power Point presentation work; SUBMIT WRITTEN VENTURE PROPOSAL AND POWERPOINT PRESENTATION; begin patent searches; begin purchasing materials for prototype and start prototype development; complete specific matrix
Week of May 19-May 23	Continue patent searching; continue prototype development
Week of May 27-30	Finish all work; create budget documentation; begin work on final Company portfolio submission and PowerPoint presentation
Week of June 2-5	SUBMIT FINAL COMPANY PORTFOLIO AND FINAL POWERPOINT PRESENTATION

Company Name _____ Bell _____ Date _____

President _____ Chief Engineer _____

Secretary _____ Treasurer _____

ADVANCED ENVIRONMENTAL SCIENCE WRITTEN COMPANY PROGRESS REPORT

_____/20 Thayer Method of Problem-Solving

- Bias
- Implied Solutions
- Specifications
- Alternatives

_____/26 Description of Company progress

_____/2 Library and other resources, if applicable

_____/2 Bibliography, if applicable

_____ /50 Total

ORAL PRESENTATION

_____/10 Discussion of Specifications / Alternatives for Improving the Environment

_____/10 Discourse of the Company progress, current status, and resources (if applicable)

_____/5 All company members part of conversation

_____ /25 Total

VENTURE PROPOSAL APPLICATION

IDENTIFYING INFORMATION (Please print or type)

Company Name _____

Company Officers: President _____

Secretary _____

Chief Engineer _____

Treasurer _____

Mailing Address _____

I. COMPANY MISSION STATEMENT (your company redefined problem)

II. ABSTRACT (clearly and succinctly explain how the proposal will improve the environment and discuss for possible marketing strategies of the product or device.)

III. DESIGN PLAN (Discuss the steps you will use to execute the development and testing of your prototype. Be sure to indicate resources necessary for the implementation including specific business and community resources, Internet, library, etc. The resource information will be in a list format containing address, telephone number(s), email address, and primary contacts (if applicable.)

Company Name _____ Bell _____ Date _____

President _____ Chief Engineer _____

Secretary _____ Treasurer _____

WRITTEN VENTURE PROPOSAL

_____ / 5	Identifying Information
_____ /10	Company Mission Statement
_____ /20	Abstract <ul style="list-style-type: none">•Explanation of how the proposal will improve the environment•Possible marketing strategies for the product or device
_____ /25	Design Plan <ul style="list-style-type: none">•Steps for development of prototype•Testing plans for the prototype•Resource list
_____ /60	Subtotal

POWERPOINT/ORAL PRESENTATION

_____ /5	Title slide(s) including Company name, officers, and product/ device
_____ /5	Company mission slide
_____ /10	Abstract slide(s)
_____ /10	Design plan slide(s)
_____ 10	Attractive, thorough presentation
_____ /40	Subtotal

_____ /100 Grand Total

COMPANY PORTFOLIO TABLE OF CONTENTS

I Introductory Material

_____	/10	A. One Signed and completely filled out Company Contract
_____	/4	B. Final Syllabus
_____	/10	C. Brainstorming ideas
_____	/10	D. Library / Patent research information
		E. Correspondence (letters, copies of email, fax, etc.), if applicable

II. Thayer Method of Problem-Solving Process

/15	A. General - Thayer Method packet
	1. Problem-Solving Cycle / Thayer Model
	2. Bias-Implied Solutions / Specifications
	3. Matrix
/15	B. Specific - Thayer Method packet
	1. Bias-Implied Solutions / Specifications
	2. Matrix

III. Reflections

_____	/4	A. FOUR on Three problem-solving activities
_____	/4	B. FOUR on Ethicon EndoSurgery field trip

IV. Written Reports

_____	/5	A. Progress report
		1. Evaluation
_____	/5	B. Venture Proposal / Design plans (hard copy and disc)
		1. Evaluation
_____	/5	C. Final Powerpoint presentation (hard copy and disc)
		1. Evaluation

V. Financial Statement

_____	/15	A. Spreadsheet documentation of Expenses
		1. Expense reports

VI. Bibliography

_____	/10	A. Final Bibliographic documentation
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VII Ethicon Folders

_____	/2	A. President
_____	/2	B. Chief Engineer
_____	/2	C. Treasurer
_____	/2	D. Secretary

_____	/120	TOTAL
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Company Name _____ Bell _____ Date _____

President _____ Chief Engineer _____

Secretary _____ Treasurer _____

Final computer presentation of company solution to environmental problem

PROTOTYPE DEMONSTRATION

_____ /50	“Works Like” prototype
_____ /50	“Looks Like” prototype
_____ /100	Subtotal

POWERPOINT/ORAL PRESENTATION

_____ /5	Title slide(s) including Company name and name of product / device
_____ /5	Company Officers slide
_____ /5	Company Mission Statement slide
_____ /15	Prototype Specifications including definitions slide(s)
_____ /30	Technical Concept Demonstration slide(s) (Customer Wants / Needs-How-Tests)
_____ /20	Prototype Development Challenges and Solutions slide(s)
_____ /25	Reflection slide(s) <ul style="list-style-type: none">• Things the Company learned during the Thayer problem-solving process of improving the environment• Strengths and weaknesses of the overall experience• If you were to repeat the project... What would you do the same? What would you do differently? Other reactions or thoughts?
_____ /10	Resource List including all literature and human resources slide(s)
_____ /115	Subtotal
_____ /215	Grand Total

Contract No. ES-10-Y97

Between
Colerain High School Foundation (CHSF-fictitious name)
and

(Group Name)

INTRODUCTION

THIS CONTRACT, is effective upon the execution between CHSF and _____
(Group Name)

(hereinafter called the "Contractor") whose principal offices are located in Cincinnati, Ohio.

AGREEMENT

Now, therefore, the parties agree to the following terms and conditions:

ARTICLE 1 - THE WORK TO BE PERFORMED

- A. The Contractor shall furnish all personnel, facilities, equipment materials, supplies and services (except such as furnished by CHSF) necessary for the performance of the work generally described as the study of _____ (Project) and specifically provided for in Appendix "A" attached hereto and made apart hereof and shall perform the work and report thereon pursuant to the provisions of this contract.
- B. Specific deliverables, quantities, due dates and addresses are set forth in Appendix A hitherto.

ARTICLE 2 - THE PERIOD OF PERFORMANCE

The performance of the work described in Appendix A including all deliverable items hereof shall be completed by _____

ARTICLE 3 - CONSIDERATION AND PAYMENT

- A In full consideration of the Contractor's performance hereunder. CHSF will pay the Contractor up to \$200.00 to cover parts, supplies and other incurred costs.
- B CHSF will award academic grades to the Contractor's personnel, to a degree consistent with the level of performance under this contract.

ARTICLE 4 - APPLICABLE DOCUMENTATION

In addition to the terms and conditions contained in this schedule, the following documents are attached hereto and made a part of this subcontract:

- A Appendix A, entitled "Statement of Work"
- B. Appendix B, entitled "Intellectual Property Provisions"
- C. Contractor's Proposal dated _____ is hereby incorporated herein by reference insofar as it is consistent with Appendix A "Statement of Work."

ARTICLE 5 - RIGHTS TO PROPOSAL DATA

Except for technical data contained in the Contractor’s proposal which are asserted by the Contractor as being proprietary data, it is agreed that as a condition of the award of this contract, and notwithstanding, the provisions of any notice appearing on the proposal, CHSF shall have the right to use, duplicate and disclose and have others do so for any purpose whatsoever, the technical data contained in the proposal upon which this contract is based.

ARTICLE 6 - CONTRACT ADMINISTRATION RESPONSIBILITIES

The Contractor Administrator for CHSF for this contract is Mrs. Carla Huffman.

ARTICLE 7 - INVOICES

Invoices for work accomplished under this contract shall be held by the Contractor and be submitted as an addendum to Appendix A “Statement of Work.”

ARTICLE 8 - DISPUTES AND GRIEVANCES

Disagreements shall be submitted, in writing, to Mrs. Carla Huffman. She shall have the sole authority and responsibility to their resolution.

IN WITNESS WHEREOF, the parties hereto have executed this contract as of the date stated below:

Accepted: CONTRACTOR

Authorized: CHSF

By: _____

By: _____

Title: _____

Date: _____

Date: _____

APPENDIX A STATEMENT OF WORK

The Contractor agrees to exert his/her best efforts to develop a method for

(Project)

The Contractor will deliver to Room 322, Colerain High School, the following items:

1. First written and oral progress reports:
Written and Oral: Week of April 28, 1997
2. Second written, Powerpoint/oral venture proposal which includes product/device design plans:
Written and Oral: Week of May 12, 1997
3. Final computer presentation of company solution to their environmental problem and prototype product/device:
Powerpoint/oral presentation: Week of June 2, 1997
Due: Week of exams
5. Company portfolio will include:
 - a. Complete documentation of progress of work (paper trail)
 - b. Correspondence (i.e., email, letters, phone conversation documentation, etc.)
 - c. Research (i.e., periodical summaries, literature search, patent search, bibliography of all research, marketing research, Internet search, and any other types of research)
 - d. Reflections/progress journaling for each company member
 - e. Thayer Problem-solving process for project and all documentation
 - f. Product/Device design plans
 - g. Written progress reports/venture proposal
 - h. Spreadsheet documentation of budgetDue: Week of exams

APPENDIX B
INTELLECTUAL PROPERTY PROVISIONS
PATENT RIGHTS

A. Definitions:

- 1 "Subject Invention" means any invention or discovery of the Contractor conceived or first actually reduced to practice in the course of or under this contract, and includes any art, method, process, machine, manufacture or composition of matter, or any new and useful improvement thereof, whether patented or unpatented under the Patent Laws of the United States of America or any foreign country.

B. Allocation of Principal Rights:

- 1 Assignments to CHSF: The Contractor agrees to assign to CHSF the entire right, title and interest throughout the work in and to each Subject Invention, except to the extent that rights are retained by the Contractor under paragraph C of this article.

C. Minimum Rights to the Contractor:

- 1 Contractor License: The Contractor reserves a revocable, non-exclusive paid-up license in each patent application filed in any country on a Subject Invention and any resulting patent which CHSF acquires title.

D. Invention Identification. Disclosures and Reports:

The Contractor shall establish and maintain active and effective procedures to ensure that Subject Inventions are promptly identified and have timely disclosure. These procedures shall include the maintenance of laboratory notebooks or equivalent records and any other records that are reasonably necessary to document the conception and/or the first actual reduction to practice of Subject Inventions, and records which show that the procedures for identifying and disclosing the inventions are followed. Upon request, the Contractor shall furnish CHSF with a description of these procedures so that it may evaluate and determine their effectiveness.

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Patent Information

U.S. Patent and Trademark Office

U.S. Department of Commerce
Washington, DC 20231
Automated information line: 703/557-INFO/4636
TTD line: 703/305-7785

Address patent applications to: Commissioner of Patents and Trademarks

"Basic Facts About Patents," available at no cost, includes definitions of patents and brief review of patent law.

No charge for database access from web site; patents can be ordered online for approximately \$3 a patent.

<http://www.uspto.gov/>

Superintendent of Documents, Government Printing Office

Washington, DC 20402
Telephone 202-783-3238

General Information Concerning Patents includes information about applying for patents and granting of patents written in non-technical language. Publication # 003-004-00661-7, \$2.25.

Patent Official Gazette is issued weekly and lists all new pending patents.

Trademark Official Gazette is issued weekly and contains illustrations of trademarks published for opposition, a list of trademarks registered, and Patent Office notices.

Internet Patent Search Machines

Patent Search

A database that searches recent patents by author, keyword, and patent classification. Information includes patent number, author, title, and abstract.

<http://www.patents.cnidr.org:4242/access/access.html>

U. S. Patent Database

A database that accesses 26 years of USPTO patent descriptions and 17 years of patent images. Hyperlinks allow navigation forward and backward from a cited patent.

<http://patent.womplex.ibm.com/>

Patent and Trademark Libraries

Patent and Trademark Depository Libraries (PTDLs) receive patent and trademark information from the U.S. Patent and Trademark Office. Many PTDLs have on file all full-text patents issued since 1790, trademarks published since 1872, and select collections of foreign patents. All PTDLs have both the patent and trademark sections of the *Official Gazette*. Utility and design patents are distributed numerically on 16mm microfilm, plant patents on color microfiche. Patent and trademark search systems are on CD-ROM. All information is available for use by the public free of charge.

In addition, each PTDL offers reference publications which outline and provide access to the patent and trademark classification systems, as well as other documents and publications which supplement the basic search tools. PTDLs provide technical staff assistance in using all materials. Facilities for making paper copies of patent and trademark information are generally provided for a fee.

A list of PTDLs is available from the U.S. Patent and Trademark Office at the address listed above.

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Projectile Motion

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Buena Vista High School
Buena, Arizona

Up until now, you have been studying linear motion. what other types of motion do you observe in the REAL world? Just as an example, pick up an object and toss it to one of your dassmates. How would you describe that type of motion? Is it linear? Is it constant speed or accelerated? By now, you are probably wondering what this is all about. This is your next assignment.

Problem

You will design and construct a repeatable and quantifiable demonstration of projectile motion using lowest materials. Using the Thayer Method, you will select and design a device. You will have approximately three dass periods to design and execute the experiment and to gather the initial data which you will analyze. At the end of the unit, you will hand in a written report

Assessment

You will be assessed on your written report and your group presentation by your teacher / review board.

Written Report

Utilization of Thayer Method

- Define the Problem
- Generate Specifications
- Generative Alternative Solutions
- Test Viability via Matrix
- Selected Best Approach

Execution of Best Approach / Experimental Procedure

- Viable Projectile Motion
- Made Appropriate Measurements
- Record of Data

Data Analysis

- Generated a Graph
- Describe a Curve Mathematically

General Conclusions

- Describe Projectile Motion
- Discuss Error
- Suggestions

Budget Report

Group Presentation

Demonstrate device

Illustrate your use of the Thayer Method including one matrix analysis

Mathematical analysis

Conclusions

Assessment

Design Report

- I. Introduction: (15 pts)
 - Title Page (4pts)
 - Problem Statement (3 pts)
 - Problem Redefined (3 pts)
 - Constraints and Specifications listed and defined (5 pts)
- II. Alternatives (15 pts)
 - Several alternative solutions discussed (5pts)
 - Matrix Analysis illustrated / discussed (10 pts)
- III. Final Solution (15 pts)
 - Clear reason for final choice given (5 pts)
 - Final solution described (5 pts)
 - Clear illustrations used (5 pts)
 - Description of Cost or Prototype and Cost to Market (3 pts)
- IV. Miscellaneous (5 pts)
 - On time with paper trail (deduction only)
 - Neatness of report (5 pts)
- V. Self evaluation: (15 pts)
 - Students worked together in the group (5 pts)
 - Everyone did fair share (5 pts)
 - Solution was the optimal one (5 pts)
- TOTAL (65 pts)

Student Group Evaluation Form

Names of Students in the group—rate them on a scale of 0 to 5 (5=highest) for their effort in making your project a success.

1. _____
2. _____
3. _____
4. _____

If someone scored 3 or less, please explain what you perceive as the problem and why you scored them as you did (on the back of the paper).

1. Did your group function effectively?
2. Did your group work together to share responsibilities equitably?
3. Did your group maintain neat and accurate reports of each phase of your project?
4. Did your group meet all deadlines?
5. Did your group develop logical matrices to assist in redefinition of the problem and to generate ideas for the final product?
6. Did you feel that you did all or most of the work?
7. Did you try to involve all members of the group?
8. What were your specific responsibilities in the group and did you do them?
9. Did your project meet the original problem statement.
10. Overall rating of your Project

Oral Presentation

_____ Group Number/Name

_____ Project

Presentation of Project Results:

1. Clear Statement of Problem 5 pts _____

2. Clear Statement of Constraints 5pts _____

3. Clear Reason Given for Choice of Solution (Matrix) 10 pts ____

4. Clear Description of Device (Verbally and Visually) 10 pts ____

5. Excellent Use of Visual Aids/Props for 1-4 above 10 pts _____

6. Spoke with clarity 5 pts _____

7. All Members of the Group Participated 5 pts _____

8. Answered Questions Clearly and with Intelligence 5 pts ____

TOTAL (55 points max) _____

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