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 CO_2 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 Lo.

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

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 i*n 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
desire
safety
cost
fun
political support
legality

skills
equipment
resources
ergonomics
individual or group
liability

feasibility
environmental
impact
size/weight
aesthetics
ethical

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 dophins?"

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.