CHAPTER 5

PROBLEM SOLVING AND CREATIVITY

Engineering education focuses heavily on problem solving, but many professors teach content and then expect students to solve problems automatically without being shown the process involved. Our position is that an explicit discussion of problem-solving methods and problem-solving hints should be included in every engineering class. A problem-solving taxonomy was briefly discussed in Section 4.2.4.

Most engineering schools are very good at teaching routines, and most engineering students become very proficient at them. And since diagnosis is required for many problems, particularly in upper-division courses, most students become reasonably proficient at it also. Students in general are not proficient at strategy, interpretation, and generation. These three areas of the problem-solving taxonomy will be discussed throughout this chapter.

In this chapter we will first briefly discuss some of the basic ideas about problem solving and compare the differences between novices and experts. Then a strategy for problem solving which works well for well-understood problems will be presented, and methods (heuristics) for getting unstuck will be discussed. The teaching of problem solving will be covered with a number of hints that can be used in class. Finally, creativity will be discussed.

5.1. PROBLEM SOLVING—AN OVERVIEW

Extensive studies have shown that problem solving is a complicated process. The concept map shown in Figure 5-1 gives some idea of the interactions and complexities involved (this figure is modified from the one in Chorneyko et al., 1979). An entire book would be required to explain the information on this map fully. Readers who feel a need to understand parts of this map which are not explained in this chapter are referred to the extensive list of references at the end of the chapter.

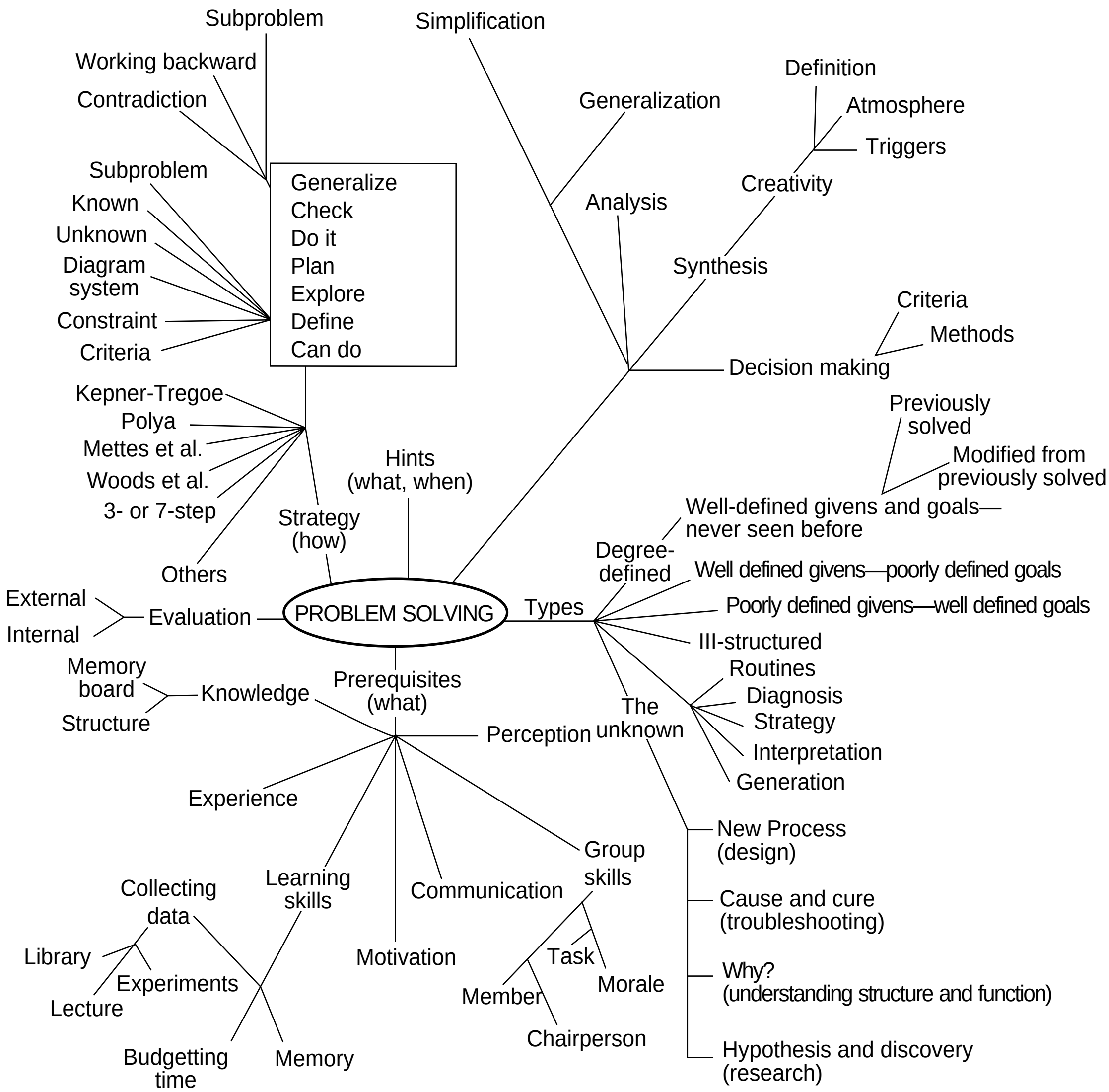

FIGURE 5-1 CONCEPT MAP OF PROBLEM SOLVING. Reprinted with permission of *CEE, 13*, 132, (1979).

Cognitive psychologists are in general agreement that there are generalizable problem-solving skills, but that problem solving is also very dependent upon the knowledge required to solve the problem [see Chapter 14 and Kurfiss (1988) for a review]. Of the prerequisites shown in Figure 5-1, knowledge and motivation are the most important.

Problem solving can be classified by the type of problem which must be solved. Three different classification schemes are shown in Figure 5-1. A scheme based on the degree of definition of the problem (Cox, 1987) is useful since it ties in closely with the strategy required.

Relatively structured strategies are most useful for well-defined problems (Mettes et al., 1981). Ill-structured and less well-defined problems need an approach which focuses on determining what the problem and goals are (Kepner and Tregoe, 1965; Fogler, 1983).

Various multistep strategies are often appropriate for problems with intermediate degrees of definition (see Section 5.3). The classification based on the unknown is discussed by Chorneyko et al. (1979).

The various elements of problem solving in Figure 5-1 show how it interacts with other cognitive activities. Analysis and synthesis are part of Bloom's taxonomy while generalization is a seldom taught part of the problem-solving taxonomy. Simplification is a procedure that many experts use to get a rapid fix on the solution (see Section 5.2.). Creativity is an extensively studied, but not really well understood, adjunct to problem solving. Creativity can be enhanced in individuals with proper coaching (see section 5.6). Finally, decision making is often a part of problem solving which connects it to the Myers-Briggs analysis (see Chapter 13) and is a major part of the Kepner and Tregoe (1965) approach.

5.2. NOVICE AND EXPERT PROBLEM SOLVERS

Experts have about 50,000 "chunks" of specialized knowledge and patterns stored in their brains in a readily accessible fashion (Simon, 1979). The expert has the knowledge linked in some form and does not store disconnected facts. Exercises which require students to develop trees or networks can help them form appropriate linkages (Staiger, 1984). Accumulation of this linked knowledge requires about ten years. Since it is not feasible to accumulate this much information in four or five years, producing experts is not a realistic goal for engineering education. However, it is reasonable to mold proficient problem solvers who have the potential to become experts after more seasoning in industry.

How do the novices who start college differ from experts? This has been the topic of many studies (Dansereau, 1986; Fogler, 1983; Hankins, 1986; Larkin et al., 1980; Lochhead and Whimbey, 1987; Mayer, 1992; Smith, 1986, 1987; Whimbey and Lochhead, 1982; Woods, 1980, 1983; Woods et al., 1979; Yokomoto and Ware, 1990). A number of observations on how novice problem solvers differ from experts are listed in Table 5-1. Read through it briefly before proceeding. The table is arranged in roughly the sequence in which one solves problems.

The differences between novices and experts show some areas that engineering educators can work on to improve the problem-solving ability of students. In the category of prerequisites, students should be encouraged to learn the fundamentals and do deep processing. Knowledge should be structured so that patterns, instead of single facts, can be recalled. Motivation and confidence are important, so professors should encourage students and serve as models of persistence in solving problems.

In working problems, students need to practice defining problems and drawing sketches. The differences between a student's sketch and that of an expert should be delineated, and the student should be required to redraw the sketch. Students also need to practice paraphrasing the problem statement and looking at different ways to interpret the problem. A distinct

TABLE 5-1 COMPARISON OF NOVICE AND EXPERT PROBLEM SOLVERS

Characteristic	Novices	Experts
Memory	Small pieces Few items	"Chunks" or pattern ~ 50,000 items
Attitude	Try once and then give up Anxious	Can-do if persist Confident
Categorize	Superficial details	Fundamentals
Problem statement	Difficulty redescribing Slow and inaccurate Jump to conclusion	Many techniques to redescribe Fast and accurate Take time defining tentative problem May redefine several times
Simple well-defined problems	Slow Work backward	~ 4 times faster Work forwards with known procedures
Strategy	Trial and error	Use a strategy
Information	Don't know what is relevant Cannot draw inferences from incomplete data	Recognize relevant information Can draw inferences
Parts (harder problems)	Do NOT analyze into parts	Analyze parts Proceed in steps Look for patterns
First step done (harder problems)	Try to calculate (Do It step)	Define and draw Sketch Explore
Sketching	Often not done	Considerable time Abstract principles Show motion

strategy should be used (see the next section). Students should also practice analyzing problems to break the problem into parts, and they need to be encouraged to perform the explore step. A chug-and-plug mentality should be discouraged, and students should be encouraged to return to the fundamentals.

Once students know a strategy, they should be encouraged to monitor their progress. Methods for getting unstuck should be taught (see Section 5.4). Then once the problem has been completed, students should be required to check their results and evaluate them versus internal and external criteria. After the problems have been graded, some mechanism for ensuring that students learn from their mistakes is required. Throughout the process students should be encouraged to be accurate and active. Specifics of methods for teaching problem solving are discussed in more detail in Section 5.5.

TABLE 5-1(CONT) COMPARISON OF NOVICE AND EXPERT PROBLEM SOLVERS

Characteristic	**Novices**	**Experts**
Limits	Do not calculate	May calculate to get quick fix on solution
Equations	Memorize or look up detailed equations for each circumstance	Use fundamental relations to derive needed result
Solution procedures	"Uncompiled" Decide how to solve after writing equation	"Compiled" procedures Equation and solution method are single procedure
Monitoring solution progress	Do not do	Keep track Check off versus strategy
If stuck	Guess Quit	Use Heuristics Persevere Brainstorm
Accuracy	Not concerned DO NOT Check	Very accurate Check and recheck
Evaluation of result	Do not do	Do from broad experience
Mistakes or failure to solve problems	Ignore it	Learn what should have done Develop new problem solving methods
Actions	Sit and think Inactive Quiet	Use paper and pencil Very active Sketch, write questions, flow paths.Subvocalize (talk to selves)
Decisions	Do NOT understand process No clear criterion	Understand decision process Clear criterion

5.3. PROBLEM-SOLVING STRATEGIES

Many experts have difficulty verbalizing the problem-solving strategy they are using since the strategy has become automatic. When an expert does verbalize how he or she solves a problem, it is clear that a distinct strategy has been used. Novices have a strategy also—it is a trial-and-error strategy. It is not very effective and does not help the novice become a better problem solver.

A distinct problem-solving strategy should be demonstrated and then required from students. The exact strategy used is not important; what is important is that the strategy be used consistently and that students be required to use it. Woods et al. (1979) suggest that the strategy have between four and fifteen steps. If shorter than four steps the strategy is probably too short and not detailed enough to be useful; if longer than fifteen steps it is too long to remember and use.

The strategy that we have used is based on the work of Don Woods and his coworkers at McMaster University (Woods et al., 1975, 1977, 1979, 1984; Woods, 1977, 1983, 1987; Leibold et al., 1976). Through the years their strategy has changed slightly. We have settled on a strategy with six operational steps and a prestep which focuses on motivation:

0 I can.
1 Define.
2 Explore.
3 Plan.
4 Do it.
5 Check.
6 Generalize.

Step 0 is a motivation step. Since anxiety can be a major detriment to problem solving, it is useful to work on the student's self-confidence (Scarl, 1990; Richardson and Noble, 1983). The professor may want to avoid being subtle when first working on this step. It is also useful to teach students a few simple relaxation exercises (Richardson and Noble, 1983; also, see Section 2.7 on handling stress).

Step 1, the define step, is often given very little attention by novices. They need to list the knowns and the unknowns, draw a figure, and perhaps draw an abstract figure which shows the fundamental relationships (remember that most people prefer visual learning). The figures are critical since an incorrect figure almost guarantees an incorrect solution. The constraints and the criteria for a solution should be clearly identified.

Step 2 is the explore step. This step was originally missing from the strategy but was added when its importance to expert problem solvers became clear (Woods et al., 1979). This step can also be called "Think about it," or "Ponder." During this step the expert asks questions and explores all dimensions of the problem. Is it a routine problem? If so, the expert will solve the problem quickly in a forward direction. If it is not routine, what parts are present? Which of these parts are routine? What unavailable data are likely to be required? What basis is most likely to be convenient? What are the alternative solution methods and which is likely to be most convenient and accurate? What control envelope should be used? Does this problem really need to be solved, or is it a smoke screen for a more important problem? Many experts determine limiting solutions to see if a more detailed solution is really needed. Since novices are often unaware of this step, they need encouragement to add it to their repertoire.

In the plan step, formal logic is used to set up the steps of the problem. For long problems a flowchart of the steps may be useful. The appropriate equations can be written and solved without numbers. This is extremely difficult for students in Piaget's concrete operational stage. This step is easier for global thinkers and intuitives, which means that serial thinkers and sensing individuals need more practice.

Do it, step 4, involves actually putting in values and calculating an answer. This is the step which novices want to do first. Even fairly skilled problem solvers often want to combine steps 3 and 4 and not develop a solution in symbolic form. The separation of the plan and do it stages makes for better problem solvers in the long run. Separating these stages makes it easier to check the results and to generalize them since putting in new values is easier. Sensing students tend to be better at doing the actual calculations.

Checking the results should be an automatic part of the problem-solving strategy. Checking requires internal checks for errors in both mathematical manipulations and number crunching, and it involves evaluation with external criteria. A very useful ploy of expert problem solvers is to compare the answer to the limits determined in the explore step. The answer should also be compared to "common sense." This step requires evaluation and many students will not be adept at it.

The last step, generalize, is almost never done by novices unless they are explicitly told to do it. What has been learned about the content? How could the problem be solved much more efficiently in the future? For example, was one term very small so that in the future it can be safely ignored? Were trends linear so that in the future very few points need to be calculated? If the problem was not solved correctly, what should have been done? Students need to be strongly encouraged to study feedback and then resolve incorrect problems.

Note that problem solvers who use this strategy consistently will use all levels of both the Bloom and the problem-solving taxonomies. However, students will rebel against using this or any other structured approach to solving problems. The method is unfamiliar and will feel awkward at first. Since many aspects of problem solving are automatic, making them conscious is uncomfortable at first and may inhibit the student for a period. An analogy is the self-taught golfer or tennis player who starts taking lessons. Thinking about the swing so that it can be improved makes it difficult to swing effortlessly. However, in the long run the person with training will become a better golfer or problem solver. (Note that an expert golfer will also be an expert problem solver in this narrow domain.)

Many other problem-solving strategies can be used. Polya (1971) originated a four step approach which is a predecessor of the approach shown here. Since Woods (1977) has published an extensive review of problem-solving strategies, these older papers will not be reviewed here. Scarl (1990) also describes a procedure very similar to that presented here, and in addition he is very directive of what students should do when. Mettes et al. (1981) describe a systematic flow sheet approach that is quite different from the method illustrated here. Their structured approach was developed specifically for solving thermodynamics problems and may not be generalizable. Smith (1986, 1987) discusses expert system models for problem solving. Kepner and Tregoe (1965) developed procedures that are most applicable to determining what the problem is (troubleshooting) and for decision making. Guided design is a method for guiding groups of students through a structured problem-solving procedure (Wales and Stager, 1977; Wales et al., 1986). This method will be discussed further in Chapter 9. In a book used to teach problem solving, Rubenstein (1975) discusses five models of problem solving.

5.4. GETTING STARTED OR GETTING UNSTUCK

A problem-solving strategy is not much help if you just cannot get started on a problem or are completely stuck. What do you do then? Novice problem solvers tend to give up or make wild guesses, whereas experts persist, recycle back through the define step, and use heuristics.

The first step for a professor is to encourage students. Remember those high school football slogans, "When the going gets tough, the tough get going," and "Winners never quit, and quitters never win," and so forth? A short pep talk is not out of order, particularly for students who have the prerequisites to be successful. Nothing makes a student more confident in her or his ability to solve problems than successfully solving difficult problems.

The second step is to encourage the student to recycle in whatever problem-solving strategy the class is using. Ask, "Have you reread the problem statement to be sure you are solving the right problem?" "Have you rechecked your figures for accuracy?" "Have you thought about whether your plan of attack still seems reasonable? Novices want to apply a strategy once through, while experts apply a strategy in a series of loops. One advantage of having an explicit strategy is that you can easily refer the student to a particular stage of the process, and both of you will have a common language.

If recycling through the strategy does not work, suggest that the student identify his or her difficulty with the problem (Woods, 1983). Where is the student stuck? What is the obstacle? Where does the student want to be? Are there alternatives that can be used? Sometimes this process will lead the student to a productive path.

If still stuck, it is now time for the problem solver to use heuristics. Heuristics are methods which might, but are not guaranteed to, work. A large number of heuristic methods have been suggested to aid a problem solver who is stuck (Adams, 1978; Cox, 1987; Koen, 1984, 1985; Polya, 1971; Rubenstein and Firstenberg, 1987; Scarl, 1990; Smith, 1986, 1987; Starfield et al., 1990; Wankat, 1982; Woods et al., 1979). A very large number of heuristics can be listed; however, it probably does not matter which ones students are taught as long as they use them. For any given obstacle many different heuristics will work, since what the heuristic does is to get the problem solver thinking productively on a new path. (Students need to realize this also—and it can be called another heuristic.) Readers interested in the use of heuristics for problem-solving should consult the short book by Starfield et al. (1990).

The second and third suggestions in this section (recycle and find the obstacle) can be considered either heuristics or parts of the problem-solving strategy. We will list a variety of other heuristics. Select from these the ones that you will teach to the students, remembering that they will need to practice using the heuristics and will need feedback. Particularly with novices, it is preferable to keep the list short so that they can remember and use the heuristics.

1 Simplify the problem and solve limiting cases.

This is a procedure often used by experts. Another closely related heuristic involves solving special cases.

2 Check to see that the problem is not under- or overspecified.

Problems that are under- or overspecified need interpretation before they can be solved.

3 Relate the problem to a similar problem which you know how to solve.

Solutions to similar problems can give a useful outline of how to solve the current problem. A closely related technique uses analogies to give hints about the problem solution.

4 Generalize the problem.

Sometimes the problem is easier to understand and solve in a very general form.

5 Try substituting in numbers.

Sometimes the problem will be clearer with numbers inserted because it will appear more concrete.

6 Try solving for ratios.

Often a problem can be solved for ratios, but not for individual numbers.

7 Get the facts and be sure there actually is a problem.

Another way to say this is, "If it's not broke, don't fix it." This heuristic can be taught and reinforced in the laboratory.

8 Change the representation of the problem.

If the first representation of the problem is too difficult, change it. This is often called education or advertising.

9 Ask questions about the problem.

Specifications are often set arbitrarily but may make the problem extremely difficult to solve. Question them. Does the purity really have to be so high? Do the tolerances really have to be so tight?

10 Concentrate on the parts of the problem that can be solved.

Very often parts that seem unsolvable become solvable when other parts of the problem have been solved. This is partly a confidence factor.

11 In groups, be a good listener and maintain group harmony.

Groups can be synergistic in solving problems, but only if people listen and there is some group harmony.

12 Use a plus-minus-interesting (PMI) approach when presented with possible solutions (deBono, 1985; Gleeson, 1980).

The plus helps the morale of the person suggesting the solution. Minuses are why the solution is not yet complete. Interesting are the ideas that can be adapted.

13 Use a mixed scanning strategy (Rubenstein and Firstenberg, 1987).

A mixed scanning strategy alternates a broad look at the entire problem with in-depth looks at small parts of the problem.

14 Alternate working forward and backward.

Although experts work forward on simple problems, they alternate working forward and backward on difficult problems.

15 Take a break.

This is not quitting but is a break allowing you to do something else before returning to the problem with a fresh view.

16 Ask what the hidden assumptions are or what you have forgotten to use.

Novice problem solvers often limit their solutions by assuming constraints which are not part of the problem.

17 Apply a control strategy.

Experts keep track of where they are in solving a problem with a metacognitive control strategy.

Schoenfield (1985) suggests that you ask yourself three questions: What are you doing? (Be exact in the description.) Why are you doing it? How will it help you solve the problem?

18 Refocus on the fundamentals.

Sometimes asking what is fundamental will break the log jam.

19 Guess the solution and then check the answer.

Yes, guessing is a novice approach. However, sometimes when we are stuck, we have strong hunches. If we guess the answer, it may be easy to prove whether it is correct or incorrect. The differences between novice and expert behavior here are that the expert makes her or his guess after working on the problem for a period and always checks the guess.

20 Ask for a little help.

Even experts ask for help. The key is to get only a little help and not to let the helper solve the problem for you.

To close this section it may be useful to consider the six categories of blocks which Adams (1978) has identified. *Perceptual blocks* are difficulties in seeing various aspects or ramifications of the problem. *Cultural blocks* lead to inadvertent assumptions about the solution method or the solution path. In particular, in engineering there is a cultural bias toward convergent (logical) thinking and away from divergent (lateral or creative) thinking. *Environmental blocks* are due to the problem solver's surroundings, including people. For students this means the professor and other students. A lack of acceptance of novel ideas can be a major environmental block. *Emotional blocks* such as anxiety or fear of failure can make problem solvers much less effective. *Intellectual blocks* can include a lack of knowledge or trying to use inappropriate knowledge. The use of unannounced review questions on homework can help overcome this block. *Expressive blocks* involve the use of inappropriate problem-solving languages or inappropriate paths. For example, trying to solve a problem without an appropriately drawn figure can be an expressive block. An additional heuristic is: Determine the blocks which are preventing you from solving the problem.

5.5. TEACHING PROBLEM SOLVING

Many excellent papers and books have been written on how to improve the problem-solving abilities of students. In this section we have distilled many of these ideas. Readers interested in more ideas and applications are referred to the literature (Goodson, 1981; Greenfield, 1987; Kurfiss, 1988; Lochhead and Whimbey, 1987; Plants, 1986; Scarl, 1990; Starfield et al., 1990; Stice, 1987; Wales and Stager, 1977; Wales et al., 1986; Whimbey and Lochhead, 1982; Woods, 1983, 1987; Woods et al., 1975; Yokomoto, 1988). With a little creativity you can adapt the ideas in this chapter and invent new methods to improve your teaching of problem solving.

Lumsdaine and Lumsdaine (1991) and Rubenstein (1975) recommend a separate course in problem solving. However, specific knowledge in the problem domain is essential for solving problems. Thus, we suggest embedding problem solving into existing engineering courses.

Then, the problem solving and specific knowledge can reinforce each other. It is helpful if the knowledge is organized by students in a hierarchical structure since this is what most expert problem solvers do. Some information at the knowledge level of Bloom's taxonomy is essential, and professors should not hesitate to require memorization of certain crucial numbers. Most problems in lower-level engineering classes require facility with algebraic manipulations. Thus it is essential that students master algebra. Obviously, other mathematical skills are important, but algebra appears to be the lowest common denominator.

Problem solving should be taught throughout the student's college career. This can often be done in the form of little hints or suggestions of a heuristic to try while students are struggling with problems. Ideally, the same strategy would be used in all science and engineering classes and in textbooks. However, since most strategies are similar, students will not be hopelessly confused if the strategy changes. Illustrate the strategy when solving problems in class and in handouts. This includes solutions to homework and test problems. Many students will learn to use a strategy on their own, but students most in need of help in problem solving will not learn without help. Encourage and perhaps even force students to use the strategy on homework and test problems.

Although no student can become an accomplished problem solver merely by watching a professor solve examples, example problems are an important learning device, particularly for sensing students. Unfortunately, most professors inadvertently foster the idea that problem solving is a neat process and thereby do damage to the student's confidence. Using a routine to determine an answer is a neat process once the problem has been interpreted, a strategy chosen, the problem diagnosed, and the routine selected. These other steps are messy but represent the real heart of problem solving. Suppose that solving a problem took fifteen minutes and resulted in two dead ends and a page of scrap paper. Your typical approach may be to clean this up and show it to the students in five minutes with no mistakes and no dead ends. What the students see is a process that they cannot duplicate. Then when they are unable to solve problems in this way, they begin to doubt their abilities. Occasionally show a messy solution. Solve a problem in front of the class that you have not seen before and verbalize as you solve it. This can be done by having students select a problem from the textbook for you to solve. Yes, this is scary since you may fail. However, it does demonstrate the process that one goes through when solving novel problems, including step 0, the motivation or confidence-bolstering step.

Students need to solve problems to learn how to solve problems. Unfortunately, rote learning and drill will at most teach how to do routines which are necessary but not sufficient to becoming a good problem solver. Students need to solve more challenging problems requiring all levels of the problem-solving taxonomy. The good news is that all the professor has to do with the better students is to challenge them with good problems and provide feedback. The bad news is that this classical procedure does not work with the poorer students. Yet, these poorer students have the potential to become excellent engineers. How can one teach problem solving to make it accessible to them?

Particularly for beginning students, requiring a neat regular structure is useful. Tell students to lay out the problem solution in the same format for all homework problems. Require separate labeling of steps in the problem-solving strategy. Make students work down one side of the paper in regular columns. Let, and in fact encourage, students to doodle, try out ideas, and play with the problem on a separate piece of scrap paper. It is important to encourage them to write things down since this external memory is often more effective than trying to store ideas internally. (Paper is much cheaper than time.) Require a sketch even for students who can solve the problem without a sketch. Students should define all symbols even if they are the same ones as in the book. Before plugging in numbers, they should obtain an algebraic solution in symbolic form. Until an individual student has proven that he or she can skip algebraic steps, all algebraic steps should be shown. A separate equation line with all numbers substituted into the equation should be shown before the student calculates the answer. Obviously, students will resist this degree of regimentation. They will truthfully say that they are now slower and poorer problem solvers. In the long run such a procedure will produce better, neater, faster, more accurate problem solvers, and in the short run troubleshooting their solutions will be much easier. Since there is no reason why creative solutions cannot be neat and understandable, this procedure will not deaden creativity as long as the professor grades solutions with an open mind when the solutions are different.

Give a combination of application, analysis, synthesis, and evaluation problems. Be sure that the homework problems bracket the test problems in terms of difficulty, or students will think you are unfair. Be sure that some problems require the simultaneous solution of equations, or students will believe that all problems can be solved sequentially. Some problems should be open-ended, and synthesis should be required. Often students who excel in these problems are not the same students who excel in doing routines. Require students to evaluate solutions.

Separately cover all steps of the problem-solving strategy. For example, for one problem the students might do the define, explore, and plan steps only. Give multipart problems where students first have to define and draw a sketch; then after the entire class has received feedback and has that step correct, they would do the next step, and so on. Require students to completely check their solutions by solving the problem with a completely different method. Then note that the answer is still wrong if incorrect values for physical parameters are used. For another problem a complete solution with all numbers checked and no errors should be required. If accuracy is important for practicing engineers, then students must practice this level of accuracy. For these few problems where accuracy is being stressed, return the problem to the student for a corrected solution if there are any errors.

Try to cover all aspects of the problem-solving taxonomy. Give a few problems which are carefully worded to be ambiguous so that students can practice interpretation. Require students to find or estimate some of the physical constants they need (and be prepared for a variety of solutions). Give them the assignment of making up a problem so that they have practice in defining problems. Give them real cases where a clearly defined problem is not laid out in front of them. These can include troubleshooting or debottlenecking problems.

Students can be made more aware of their problem-solving procedures by verbalizing what they are doing while solving problems. This can be done conveniently in class with the Whimbey-Lochhead pair method (Whimbey and Lochhead, 1982; Lochhead and Whimbey, 1987). The class is divided into pairs, and one member of each pair is designated the problem solver. His or her job is to solve the problem and to say out loud everything he or she is thinking while solving the problem. The other person in the pair is the recorder-encourager whose job is to take notes on what the person is doing and to encourage the problem solver to keep verbalizing. As the the encourager he or she can say things such as, "What are you thinking now," or "Tell me what you're thinking." As the the recorder he or she needs to try to understand every step, diversion, and error made by the problem solver. When the reasons for a step are unclear, the recorder asks what the problem solver is doing and why. The recorder can point out algebraic or numerical errors, but he or she should not be specific as to where the error is. The two cardinal rules for the recorder are to avoid solving the problem and to not lead the solver toward a solution.

After explaining the roles to students, give the problem solver a short written problem statement. Then, as students start to read this to themselves, remind them they have to read out loud. Encourage them to verbalize their anxiety as they read a new problem and encourage them to verbalize self-encouragement. Encourage the problem solver to use a pencil and paper while solving the problem. During the remainder of the solution of the problem, visit various pairs and reinforce the role of each student.

Once the problem has been completed, either correctly or incorrectly, the recorder and the problem solver should discuss what the problem solver did while solving the problem. Remind students that learning how one solves problems is the purpose of the exercise, not correctly solving the problem. Students can then switch roles and solve a new problem.

To be effective, this procedure needs to be used several times during the semester. Note that it can be used in quite large classes. It keeps students active and simultaneously teaches both content (the problems chosen) and problem solving. This type of activity is a nice break from excessive lecturing. Professors can also learn from the Whimbey-Lochhead pair method and verbalize while they solve example problems.

Problem solving can also be taught with discovery methods of instruction (Canelos, 1988). These approaches include simulation, case study, guided design, and discussion. In all these methods students should work on real, or at least realistic, engineering problems. They should help define the problem and then work at developing a solution. Then the professor should push the students to evaluate their solution and look for a better one. When the process is completed, the professor helps the students describe the problem-solving process so that they discover the method. These methods are suitable for either individual or group work. Further details of these methods are given in Chapters 7 through 9.

Student work in groups is particularly conducive to learning problem solving. Being in a group of one's peers can help reduce a student's anxiety if it is clear that no one has all the solutions. Extroverts and field-sensitive individuals will benefit from the group support. The verbalization that occurs in a group is a good way to obtain internal feedback. Groups are excellent for clarifying difficult-to-interpret problems since each group member will look at the problem in a slightly different way. Brainstorming during the explore step is easily done in groups. From the professor's viewpoint it is more efficient to work with groups of three to five students rather than individual students since the number of questions is reduced by a factor of from three to five. Finally, when they graduate, the new engineers will be expected to work in teams in industry. Providing practice in teamwork while they are students will help their transition to industry.

Your goal while working with problem-solving groups or individuals is not to give students what they want. Students want the solution. As a professor you want the students to find a solution essentially on their own and to improve their problem-solving skills in the process.

Encourage them to verbalize and refuse to let them quit prematurely. You can check to see if the students' knowledge base is correct and can help them see the hierarchical structure of the knowledge. You can also focus their activities on problem-solving methods. For example, if they are stuck, you can ask, "What heuristics have you tried?" and "What other heuristics can you try?" If students are stuck on a clearly incorrect approach, show them why they are incorrect but without showing them a correct approach. Guided design suggests that the entire problem and responses be developed in advance so that students are automatically guided through the steps of problem solving (Wales and Stager, 1977; Wales et al., 1986). (See Section 9.1.) Although many professors do not have time for this much detail, it is helpful to have a brief outline or script of how you want to proceed. This will help you to remember to cover all important points.

5.6. CREATIVITY

Creativity is a novel and unexpected way of defining or solving a problem which leads the observer to ask, "How did you think of that?" Creativity can be a part of problem solving, but many successful solutions do not illustrate creativity. Creativity requires divergent thinking and usually appears at the define or explore step in problem solving if it is present. Note that creativity is only part of the entire problem-solving step. The creative idea must be proven to be a valid solution by a logical analysis during the plan, do it, and check steps. The generalize step can be used to further develop the creative idea and to look for other applications. The importance of creativity in engineering is summarized by Florman (1987, p. 75): "Engineering is an art as well as a science, and good engineering depends upon leaps of imagination as well as painstaking care."

Everyone is born with creative abilities. According to Hueter (1990) these abilities increase in elementary school up to an age of about eight and then steadily decrease with further schooling. At about eight years old children become very aware of the opinions of other people. It becomes important for them to fit in and to use objects for "what they are supposed to be used for." The result is a decline of creativity that continues through college. If Hueter is correct, then engineers are in a paradoxical situation. The very education which makes an engineer more capable of solving difficult problems decreases the likelihood that he or she will invent a creative solution. However, creativity can be enhanced in class with a positive attitude and suitable exercises (Christenson, 1988).

The professor's job is to nuture the creative abilities which everyone possesses and to stem any decline in creativity . What can professors do to encourage the latent creativity of every student? We will discuss three things that professors can do in engineering classes.

1 Tell students to be creative.
2 Teach students some creativity methods.
3 Accept the results of creative exercises.

5.6.1. Tell Students to be Creative

People are more creative when they are told to be creative. More creative solutions are generated when people are told to generate many possible solutions. There appears to be a bias, particularly among college students, toward producing a single solution unless they are explicitly told to produce multiple solutions. Thus, the first step professors can take is surprisingly simple. Ask for many solutions. Examples of ways to do this are:

"Develop some creative solutions for this problem."
"Give some different ways to interpret this problem statement."
"List twenty (or fifty) possible solutions to this problem."

Once a large number of possibilities have been generated, you can ask students to further develop two or three of these ideas. For example, in a design class the assignment could be to develop a folding cane. Students are asked to generate twenty different possibilities and then to do detailed designs for two of these ideas. Note that when doing this you need to accept ideas positively even if they probably would not work. The second part of this assignment asks students to do the necessary work and logical analysis to make the creative idea work. A second example which is applicable to any class is to require students to write homework or test questions with answers (Felder, 1987). This is a useful problem-solving exercise, and it becomes a useful creativity exercise also if students are told that grading will depend upon the novelty of their questions. However, remember that this will be quite time-consuming for students. A third exercise is to ask students to identify as many uses for a common object (e.g., a brick or a pencil) as possible (Christenson, 1988).

5.6.2. Creativity Techniques

Knowledge is necessary to be creative. An interesting question is, What knowledge? Prausnitz (1985) strongly makes the point that cross-fertilization of knowledge is required. Students should take a variety of courses in many areas and not overspecialize. This should include advanced-level courses in different disciplines. People who hunt or fish know that the edges are by the far the most productive areas. The edges between disciplines are often the most productive areas for creative ideas.

A variety of creativity techniques have been developed and can easily be adopted for use in engineering classes. Brainstorming was invented by Osborn (1948, 1963) and has since become so common that the term is now part of common usage. The technique is easy to use in class. The professor tells the class to think up any possible solution to a specific problem and say it out loud. One or two students who are selected as recorders write the ideas down. The one cardinal rule is there can be no judgment of any of the ideas during the brainstorming session. The professor acts as a facilitator to encourage students to generate more ideas and ensures that there is no criticism of ideas during this stage. Students are encouraged to build on the ideas of others. After the session, the ideas are collected and a list of possible solutions is generated. Then, in a separate session the ideas are criticized and possible workable solutions based on one or a combination of several of the ideas are chosen. In a design class different design teams can then be assigned to further develop these ideas. The principles of brainstorming are easily distilled.

1 Develop a lot of ideas.
2 Build on the ideas of others.
3 Make no criticism during the development phase.
4 Evaluate the ideas afterward.
5 Further develop promising ideas.

These principles can be applied to other creative exercises. For example, individuals can brainstorm by themselves. Groups can brainstorm in a conference telephone call or by electronic mail. In all cases the idea generation and evaluation stages must be separated; otherwise, the evaluation will inhibit idea generation.

Lateral thinking is an approach suggested by de Bono (1971, 1973, 1985). It involves restructuring patterns, changing viewpoints, jumping around, deliberately trying to change things, changing the problem statement, and avoiding logical (vertical thinking) analysis. Lateral thinking, unlike logical analysis, does not have to be sequential, does not have to be correct at each stage, does not have to use relevant information, and is not restricted to the problem as posed. Since lateral thinking is used only in the define and explore stages, it is completely checked by logical analysis in the later stages. Essentially, lateral thinking is more an attitude than a method.

A few examples will help illustrate. The same amount of money can be collected in tolls at less cost and with less disruption of traffic by closing half the toll booths. Stop for a minute and think about how this could be done. If all the toll booths going onto an island are closed, the toll can be doubled for cars leaving the island. This solves the problem.

A process called reversal can be illustrated with the following problem. The occupants of a new office building complained that the elevators were too slow and that the wait for elevators was too long. The straightforward logical solution was to speed up the elevators. What was the reversed problem? Reversal suggested slowing down the people. Mirrors were installed next to the elevators so that people could watch themselves (and others) while waiting for the elevators. Complaints plummeted afterward.

Dieting is a problem for many people. The straightforward solution is to tell people to eat less. A great deal of money has been spent on variations of this straightforward solution. What is the reversal solution? Go ahead and think up some ideas—none of them are wrong. One possible reversal solution is to tell people to eat as much of anything they want, whenever they want but with one simple rule. When they eat, that is all they can do. No television, no conversation, no thinking about problems, no radio, no music, no reading, and so forth. They eat, and while they eat they think about what they are eating (Smith, 1975). One of the authors (PCW) can attest that this wonder diet does work. It apparently works because the body gives a signal that it is full. When people do nothing but eat, they are much less likely to ignore this signal, and in addition, when on this diet there is little worry about going hungry later. However, the diet is not necessarily simple since it requires changing habits, but it is a different solution. Many of the heuristics, challenges to students and exercises discussed in the remainder of this section can be considered part of lateral thinking.

Writing can be a very useful method to get students to think about thinking and to think creatively in engineering (Hoerger and Bean, 1988; Elbow, 1986). Writing in a journal can be a useful method for getting students to think creatively, whether as freewriting or as fast exploratory writing where the student just writes without worrying about grammar or spelling. For example, he or she might write a page about uses for a screwdriver. One can also have students develop an idea map which can be considered a less sophisticated version of a concept map (see Figure 5-1). A journal is also useful for improving the writing skills of students.

Challenging students with creative games, questions, and exercises is a good way to increase their creativity (Felder, 1988). These do not have to be tied to engineering content. For example, have them brainstorm 100 possible uses for a brick. Ask them the meaning of word games such as what is "12safety34," or what is "milonelion"? There are also many mathematical exercises which require creativity to solve rapidly. For example, if there will be a single elimination tennis tournament with 360 players, how many matches need to be held to determine the winner. This can be done laboriously, but a rapid creative solution can be obtained. Since every player except one must lose a match, there must be 359 matches (Gardner, 1978). There are several books which specialize in this type of question and Gardner (1978) is a good source of both problems and references for additional problems. Open-ended creative questions can be invented by the instructor, and it is not necessary to have an answer. For example, Why do bridges freeze before the road surface? How could this be prevented economically? or, What is a good economical use for snow?

Heuristics were discussed extensively in Section 5.4, and many of them are useful for the generation of creative ideas. A few of many possible new heuristics developed specifically for creativity are listed below.

1 Have many ideas. The more ideas, the more likely that one will be good (Christenson, 1988).

2 Reverse the problem.

3 Build on a random stimulus (deBono, 1971). For example, pick a word at random from the dictionary and see if it leads to any possible solutions.

4 Think of something funny about the problem. Make a pun out of the problem. Humor and wit can often lead to original solutions.

5 Think of analogous solutions in nature to similar problems. This is a key part of the synectics approach to creativity (Gordon, 1961).

6 Develop word lists of stimulus words, properties, or key concepts (Staiger, 1984).

7 Use checklists or keywords to trigger different ways of looking at a problem. For example, the word creativity can be used (Sadowski, 1987):

C - combine
R - reverse
E - expand
A - alter
T - tinier
I - instead of
V - viewpoint change
I - in another sequence
T - to other uses
Y - yes! yes! (affirm new ideas)

Most engineers tend to be heavily left-brain-oriented. Their creativity can be enhanced by having them learn how to shut off the left brain and use the right brain. Following the pioneering work of Roger W. Sperry, it is now clear that the left hemisphere of the brain is mainly involved in verbal analytical thinking. The right hemisphere mainly processes visual and perceptual thinking, and its mode of processing involves intuition and leaps of insight. Clearly, engineering education is heavily left-hemisphere oriented.

People can learn how to consciously shut off the left brain and use the right brain. The subdominant right brain can be engaged by giving the whole brain a job which the left brain will refuse to do (Edwards, 1989). One way to practice the shift from left to right brain is to look at perceptual illusion drawings and consciously force yourself to see one part of the illusion and then another. Examples of this type of drawing are the vase that becomes two faces and the many drawings by M. C. Escher. A second exercise is to look at photographs of familiar faces, but with the photographs upside down. This exercise requires a shift in pattern recognition. A third exercise is to draw by using the right side of the brain without using words to name parts. Edwards' (1989) book has detailed exercises for learning how to do this. While doing these exercises you may want to quietly reassure the left brain that you will return to it shortly. In order to be able to shift at will to right-brain thinking, you must monitor the activity so that you know when the shift has occurred. Remember that the purpose of teaching engineering students how to shift to the right brain is to provide them with an alternative way of looking at things since this may produce creative ideas for solutions. Once the ideas are generated, the left brain takes over to prove or disprove the ideas. (A personal note: We find that our most creative ideas often come when we are tired. Apparently being tired relaxes the control of the left brain and the right brain has the chance to generate ideas. This can happen only if the problem has been thoroughly thought about previously.)

How do you incorporate creativity successfully into a class? Flowers (1987) has some useful suggestions based on his experience at MIT. One needs willing students, an enthusiastic instructor, "good" problems, and appropriate feedback. Most students are willing to try something new, and creativity is usually new. Instructors who voluntarily add creativity exercises to their courses will usually be enthusiastic. But picking good problems can be difficult: The instructor needs to know enough about the problem to know that it cries out for a creative solution, but he or she does not want to know the solution. (Instructors who know the solution have a very difficult time not teaching toward that solution.) Since pressure is real in the engineering profession, a project needs deadlines. For motivational purposes it is important to have successes. In the feedback, celebrate the successes which occur in the details. Such things as a clever mechanism, a trick circuit, and a clever coupling of processes need to be celebrated as creative accomplishments. It is these detailed ideas that most often delineate commercial successes since the development of a Xerox machine or the first introduction of a hand calculator occurs rarely. Flowers (1987) suggests individual exercises before group exercises since group exercises introduce a whole new area of group dynamics.

5.6.3. Acceptance of Ideas

A very important part of fostering creativity in students is to accept ideas and help students build on ideas. This acceptance is an inherent part of brainstorming. In working with students both on class projects and as a research advisor, a professor who accepts ideas will foster creativity. But acceptance does not mean stopping the search for more ideas; instead, it means ideas are not turned down.

There are many ways to accept ideas. One way is never to criticize an idea (Hueter, 1990). Instead, suggest to the student that he or she work on it and report back to you on the result. If the idea works, then all is fine and good. If the idea does not work, the student will learn from the evaluation process. Your hope is that in the future he or she will test ideas a little more carefully before talking to you. In either case the student will not be inhibited from generating new ideas.

A second method is to consciously use the PMI approach (deBono, 1985; Gleeson, 1980). First, note the *plus* (P) aspects of the idea. Then note the *minuses* (M) in the idea. Finally, note the *interesting* (I) aspects that can be built on. Encourage the student to build on the idea to retain the pluses while eliminating the minuses.

Building on ideas can be practiced in class. You can outline an interesting, creative idea for the class. Then assign students homework building on this idea. A second approach is to have small groups work on an idea and have each student in turn add to the idea. When this is done, the rules of brainstorming (no criticism) apply.

A third approach is to watch for creative solutions in homework assignments and tests (Felder, 1988). When one occurs, praise the student even if the final result is incorrect. Calling the student into your office and discussing the solution is one way to praise the student and to start building a relationship.

5.7. CHAPTER COMMENTS

This chapter could easily be turned into a book or two. We have tried to keep the information within the bounds of a chapter and at the same time to provide some concrete examples of what a professor can do to foster the creativity of students as well as to help improve their problem-solving skills. A large number of references are included for readers who want more information. If each professor spent five to ten minutes in class about once a week, we believe that students would become both better problem solvers and more creative engineers—certainly two goals worth striving for.

5.8. SUMMARY AND OBJECTIVES

After reading this chapter, you should be able to:

• Discuss and modify Figure 5-1 to fit your understanding of problem solving.
• Delineate the differences between novices and experts. Use these differences to outline how to teach novices to be better problem solvers.
• Discuss the steps in a problem-solving strategy (one different from the one discussed here can be used as a substitute) and use this strategy to help students solve problems.
• List and help students use some of the methods for getting unstuck.
• Develop a plan to incorporate both problem-solving and creativity exercises in an engineering course.
• Explain the three steps which can foster creativity and use some of the techniques.

HOMEWORK

1 Develop several five- to ten-minute problem-solving exercises for an undergraduate engineering course.
2 Develop several five- to ten-minute creativity exercises for an undergraduate engineering course.
3 List thirty open-ended questions which are appropriate for a specific engineering course.
4 For a specific engineering class set up some example problems in the format of the strategy you are using.
5 Write a script for a brainstorming session in an engineering class.

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