CHAPTER 5

PROBLEM SOLVING AND CREATIVITY

An explicit discussion of problem-solving methods and problem-solving hints should be included in every engineering class. Heywood (2005) agrees, although he notes that the position can be debated. A problem-solving taxonomy was briefly discussed in Section 4.2.4. Most engineering schools are very good at teaching the lowest levels—routines and diagnosis—and most engineering students become very proficient at them. But students in general are not proficient at strategy, interpretation, and generation—three areas of the problem-solving taxonomy to be discussed throughout this chapter.

We will first briefly discuss some of the basic ideas about problem solving and compare the differences between novices and experts. Then present a strategy for problem solving which works well for well-understood problems, and discuss methods (heuristics) for getting unstuck. 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. SUMMARY AND OBJECTIVES

After reading this chapter, you should be able to:

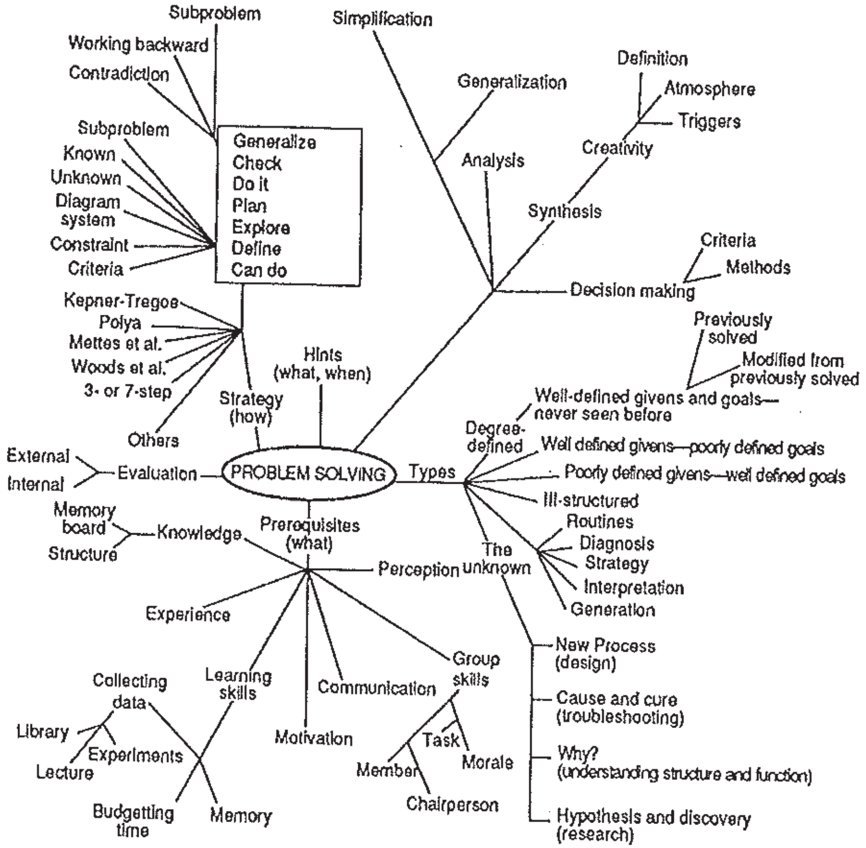
- Discuss and modify Figure 5-1 to fit your understanding of problem solving.
- Delineate the differences between novices and experts. Use these differences to outline how to teach novices to be better problem solvers.
- Discuss the steps in a problem-solving strategy (one different from the one discussed 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.

5.2. PROBLEM SOLVING: AN OVERVIEW

The concept map shown in Figure 5-1 gives some idea of the interactions and complexities involved in problem solving (this figure is modified from 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.

Cognitive psychologists agree 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.

Figure 5-1. Concept Map of Problem Solving (Chorneyko et al., 1979. Reprinted with permission from *Chemical Engineering Education*.)



Problem solving can be classified by the type of problem being solved. A classification scheme based on the degree of definition of the problem is useful since it ties in closely with a scheme based on the strategy required (Figure 5-1). 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 et al., 2013). Various multistep strategies are often appropriate for problems with intermediate degrees of definition (see Section 5.4). 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 and of the strategy used in Section 5.4. Many experts use simplification to get a rapid fix on the solution (see Section 5.3). Creativity is an extensively studied, but not really well understood, adjunct to problem solving. Creativity can be enhanced with proper coaching (see Section 5.7). 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 approach (Kepner and Tregoe, 1965; Fogler et al., 2013; Table 4-2).

5.3. NOVICE AND EXPERT PROBLEM SOLVERS

The vast majority of new engineering students in the US are novice problem solvers. How do the novices who start college differ from experts? A number of observations on how novice problem solvers differ from experts are listed in Table 5-1. The table is arranged in roughly the sequence in which one solves problems. It is useful to point out to students the differences between novices and experts. Explain that experts were initially novices. The students' engineering education is designed to help them along the path from novice to expert.

Table 5-1. Comparison of Novice and Expert Problem Solvers (Bransford et al., 2000; Fogler et al., 2013; Larkin et al., 1980; Lochhead and Whimbey, 1987; Mayer, 1992; Smith, 1987; Whimbey and Lochhead, 1982; Woods, 1980; Woods et al., 1979; Yokomoto and Ware, 1990)

Characteristic	Novices	Experts
Memory	Small pieces	"Chunks" or pattern
	Few items	~ 50,000 items
Attitude	Try once and then give up	Can-do if persist
	Anxious	Confident
Categorize	Superficial details	Fundamentals
Problem statement	Difficulty redescribing	Many techniques to redescribe
	Slow and inaccurate	Fast and accurate
	Jump to conclusion	Define tentative problem
		May redefine several times

Table 5-1. (Cont.)

Characteristics	Novices	Experts
Simple well-defined problems	Slow Work backward	~ 4 times faster Work forward known procedures
Strategy	Trial and error	Use a strategy
Information	Don't know what is relevant Stymied by incomplete data	Recognize relevant information Can draw inferences
Parts (hard problems)	Do NOT analyze into parts	Analyze parts & proceed in steps Look for patterns
First step done (hard problems)	Try to calculate (Do it step)	Define and sketch Explore
Sketching	Often not done	Considerable time spent Abstract principles Show motion
Limits	Do not calculate	Calculate for quick fix on solution
Equations	Memorize or look up detailed equations for each circumstance	Derive result from fundamentals except empirical correlations
Solution procedures	"Uncompiled" Decide how to solve after writing equation	"Compiled" procedures Equation and solution method are single procedure
Monitoring 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/ Failure to solve	Ignore it	Learn what should have done Develop new method
Actions	Sit and think Inactive Quiet	Use paper and pencil Very active Sketch, write questions, flow paths. Subvocalize (talk to selves)
Decisions	Process not understood No clear criterion	Understand decision process Clear criterion

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 that require students to develop trees or networks can help them form appropriate linkages (Staiger, 1984). Accumulation of this linked knowledge requires about ten years or 10,000 hours. 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 to start them on the road to mastery.

People can typically store seven (plus or minus two) items in short-term (working memory). Since experts store chunked items, they appear to store a lot more than nine individual items. Students can also learn to chunk items by recognizing patterns. Experts chunk based on core concepts and guiding principles, and they store the rules for when the knowledge is useful (*conditionalize* the knowledge). Students tend to classify by surface similarities (e.g., systems with pulleys would be classified together) (Bransford et al., 2000). In addition to learning to pattern, students need to learn to conditionalize their knowledge. Professors can help by giving occasional review problems and not specifying the method to use.

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. Because motivation and confidence are important, professors should encourage students and model persistence in solving problems. Students need to practice defining problems and drawing sketches. The differences between a student's sketch and that of an expert should be made clear, and the student should be required to redraw the sketch. Students need to practice paraphrasing a problem statement and looking at different ways to interpret the problem. A distinct strategy should be used (see the next section). Students should also practice breaking a problem into parts, and they need to be encouraged to do 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, encourage them to monitor their progress. Teach methods for getting unstuck (see Section 5.5). Then have them 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 encourage them to be accurate and active. Specifics of methods for teaching problem solving are discussed in more detail in Section 5.6.

5.4. PROBLEM-SOLVING STRATEGIES

When an expert verbalizes how he or she solves a problem, it is clear that a distinct strategy has been used for routine problems, problems where the expert knows what to do. Novices have a strategy also: it is a trial-and-error or guess-and-check strategy even for routine problems. The novice strategy is not very effective and does not help one become a better problem solver. For novel problems where the expert does not know what to do, even experts use trial-and-error, but they are more persistent and check results thoroughly.

5.4.1. Problem-Solving Strategy for Routine Problems

A distinct problem-solving strategy for routine problems should be demonstrated and then be required. Develop a handout with the steps of the strategy spelled out. Give the handout to students at the beginning of the semester and refer to the strategy often. The exact strategy used is not important, but the strategy should be used consistently and students should be required to use it. Woods (2000) collected over 150 published strategies and noted that most are quite similar. Most have between two and seven stages including an awareness of the problem stage, a definition stage and a verification stage. Earlier, Woods et al. (1979) had recommended that fewer than four stages is probably too short and not detailed enough to be useful.

Our strategy for routines is based on the work of Don Woods and his coworkers at McMaster University (Woods et al., 1979; Woods, 1987, 2000). Through the years their strategy has changed slightly. We have settled on a strategy with six operational steps and a pre-step that 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, 2003; Richardson and Noble, 1983). Don't be subtle when first working on this step. Also, teach students a few simple relaxation exercises (Richardson and Noble, 1983; Section 2.7).

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, the **explore** step, was originally missing from the strategy but was added when its importance to expert problem solvers became clear (Woods et al., 1979). It 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? Can we quickly set limits for the answer (e.g., concentrations and electrical resistances cannot be negative). 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 (see Chapter 14). This step is easier for students who think globally and are intuitive, which means that students who prefer to think serially and sensing individuals (these terms are discussed in Chapters 13 and 15) need more practice.

Do it, step 4, involves actually putting in values and calculating an answer. This is the step 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 (see Section 13.3.1) 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, the highest level in Bloom's taxonomy, 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 solve incorrect problems again.

In the *transition* between stages the problem solver should monitor progress (Woods, 2000). Have I made progress? What should I do next? If this approach is a dead end, are any parts useful?

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 problems they are asked to solve with a structured approach are not yet routine. If the problems are simple, a structured approach is not needed and if the problems are difficult many students doubt the approach is useful. Since many aspects of problem solving are automatic, making them conscious is uncomfortable and may inhibit the student for a period. An analogy is the self-taught golfer 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 is an expert problem solver in this narrow domain.) Student resistance can be overcome by consistently using the structured approach in examples and consistently requiring that students use the structured approach.

Many other problem-solving strategies can be used for routine problems. Polya (1971) originated a four-step approach which is a predecessor of the approach shown here. Since Woods (1977; 2000) has published extensive reviews of problem-solving strategies, these strategies will not be reviewed in detail here. Scarl (2003) also describes a procedure very similar to that presented here, and in addition he is very directive of what students should do. Mettes et al. (1981) describe a systematic flow sheet approach for solving thermodynamics problems that is quite different from the method illustrated here. Smith (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 that can be taught to engineering students (Fogler et al., 2013). Guided design is a method for guiding groups of students through a structured problem-solving procedure (Wales and Stager, 1977; Wales et al., 1986) (see Section 9.2.5).

5.4.2. Problem-Solving Strategy for Novel Problems

Problems engineers face at work "are ill-structured and complex because they have conflicting goals, multiple solution methods, non-engineering success standards, non-engineering constraints, unanticipated problems, distributed knowledge, collaborative activity systems, the importance of experience, and multiple forms of problem representation" (Jonassen et al., 2006). When they are confronted with a novel problem, one where the problem solver does not know what to do, even experts resort to a strategy that includes a significant amount of trial-and-error. Bodner (1991) studied the problem solving of chemists when confronted with novel problems. He developed an *anarchistic* model of problem solving. According to Bodner's model, here is a typical transcript of an expert solving a novel problem.

Read The Problem (RTP)
RTP again
Write down what appears to be relevant information
Do whatever may help to understand: Sketch, make a list, write equations, and so forth
Try something such as solving what may be a part of the problem
See if you have made any progress
Draw another sketch, make another list, and write more equations
Try something else
Check if you have made any progress
RTP
Draw another sketch, etc.
Try something else
See where this gets you
Test intermediate results
RTP
Get frustrated
Write down an answer—any answer
Check the answer
If answer is not correct, take a break
Start over and RTP

What makes this the efforts of an expert instead of a novice? The expert writes things down, draws sketches, uses a strategy for subproblems that are familiar, monitors progress and checks answers. As a result, the expert recognizes useful steps quicker than do novices. In addition, the expert expects the problem to eventually make sense, even if it takes years. What is the biggest difference between novices and experts? *The expert never gives up!*

5.5. 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.

When students are stuck, your first step is to encourage them. 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.

Second, encourage the student to recycle or loop in the steps of 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. 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 time to use heuristics. *Heuristics* or *rules of thumb* are methods which might, but are not guaranteed to, work. A large number of heuristic methods have been suggested (Adams, 2001; Koen, 2003; Polya, 1971; Rubenstein and Firstenberg, 1987; Scarl, 2003; Smith, 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 the heuristic gets the problem solver thinking productively on a new path. (Students need to realize this also—and it can be called another heuristic.)

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. 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 procedure is often used by experts. A closely related heuristic is "solve special cases."
2. *Check to see that the problem is not under- or over specified.* Problems that are under- or over-specified 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.

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 ain't 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.
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 have to be so high? Do the tolerances 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* (de Bono, 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. *Alternate a broad look at the entire problem with in-depth looks at small parts of the problem* (Rubenstein and Firstenberg, 1987).
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. A metacognitive control strategy means consciously thinking about the processes we are using while problem solving. Schoenfield (1985) suggests that you ask yourself three questions: What are you doing? (Be exact.) 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 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 (2001) 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 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 that are preventing you from solving the problem.

5.6. TEACHING PROBLEM SOLVING

Many excellent papers and books have been written on how to improve the problem-solving abilities of students. Readers interested in more ideas and applications are referred to the literature (Fogler et al., 2013; Kurfiss, 1988; Lochhead and Whimbey, 1987; Lumsdaine and Lumsdaine, 1994; Plants, 1986; Rubenstein and Firstenberg, 1994; Scarl, 2003; Starfield et al., 1990; Stice, 1987; Wales and Stager, 1977; Wales et al., 1986; Whimbey and Lochhead, 1999; Woods, 1987; Woods et al., 1997).

Lumsdaine and Lumsdaine (1994) and Rubenstein and Firstenberg (1994) recommend a separate course in problem solving. However, specific knowledge in the problem domain is essential for solving problems. 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 and comprehension levels 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. The most extensive application of this is probably the McMaster University Problem Solving Program (Woods et al., 1997). Few schools have been willing to make this extensive a commitment to problem solving. However, problem solving throughout the curriculum 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 use a strategy unless required to. Encourage and perhaps even require students to use the strategy.

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 takes fifteen minutes and results in two dead ends and a page of scrap paper. A professor's typical approach is 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. Have students select a problem from the textbook for you to solve. 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. At most, rote learning and drill will teach how to do routines, which is 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. All you have to do with the better students is to challenge them with good problems and provide feedback. But, this classical procedure does not work with the poorer students. Yet, these poorer students have the potential to become excellent engineers. How can you 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. Encourage students to doodle, try out ideas, and play with the problem on a separate piece of scrap paper. Encourage them to write things down since this external memory is often more effective than trying to store ideas internally and paper is much cheaper than time. Require a sketch even for students who can solve the problem without it. Students should briefly 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 and units 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 a structured 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 so long as solutions are graded with an open mind when they are different.

Give a combination of application, analysis, synthesis, and evaluation problems. Be sure that the homework problems range in difficulty from less difficult to more difficult than the test problems, 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. Encourage students to use spreadsheets to solve homework problems. 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 only **define, explore,** and **plan** steps. 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. This *deliberate practice* is slow, but very effective. Require students to completely check their solutions by solving the problem with a completely different method. Then note that the answer is wrong if incorrect values for physical parameters are used. The **check** step can also be reinforced by making up homework assignments that include solutions to some of the problems, but some of the solutions are imperfect (Armstrong, 1995). The students are required to determine when their solutions differ from the presented solution and then determine which solution is correct. Since accuracy is important for practicing engineers, students must practice this level of accuracy. For 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 that are carefully worded to be ambiguous so 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, debugging, 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 (Lochhead and Whimbey, 1987; Whimbey and Lochhead, 1999). The class is divided into pairs, and one member of each pair is designated the problem solver whose job is to solve the problem and to say out loud *everything* he or she is thinking while solving the problem. The other person is the recorder-encourager who takes notes on what the person is doing and encourages the problem solver to keep verbalizing. As the encourager he or she can say things such as, "What are you thinking now," or "Tell me what you're thinking." As 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 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 should also 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 push the students to evaluate their solution and look for a better one. When the process is completed, help 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 provides feedback. Groups help clarify difficult-to-interpret problems since each group member will look at the problem differently. 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. Finally, new engineers are expected to work in teams in industry. Providing practice in teamwork while they are students will help their transition to industry.

Do not give students what they want—the solution. You want them to find a solution on their own and to improve their problem-solving skills. 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. A brief outline or script of how you want to proceed will help you to remember to cover all important points.

5.7. CREATIVITY

Creativity can be a part of problem solving, but many successful solutions do not illustrate creativity. Creativity requires divergent thinking that usually appears at the **define** or **explore** step in problem solving if it is present. de Bono (2008) says creativity is about possibilities. Including possibilities during the explore step can lead to creative solutions. 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." More recently, the National Academy of Engineering (2004, p. 55) wrote "Creativity (invention, innovation, thinking outside the box, art) is an indispensable quality for engineering, and . . . creativity will grow in importance."

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 with a positive attitude, suitable exercises (Christensen, 1988; de Bono, 2008), and creativity training (Zappe et al., 2012). Both creativity courses (Allan, 1994) and training the faculty to include creativity in their engineering design courses (Zappe et al., 2012) increase the creativity of students.

Nurture the creative abilities everyone possesses and help stem any decline in creativity. Here's what you can do to encourage the latent creativity of every student:

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

5.7.1. 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 explicitly told to produce multiple solutions. Thus, the first step is surprisingly simple. Ask for many solutions:

"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. 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 that 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 for students at all levels, and it becomes a useful creativity exercise also if students are told that grading will depend upon the novelty of their questions. Since this exercise will be quite time-consuming, group work is suggested for undergraduates. 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 (Christensen, 1988).

5.7.2. Creativity Techniques

Cross-fertilization of knowledge is required to be creative (Prausnitz, 1985). Students should not overspecialize and take a variety of courses in many areas including advanced-level courses in different disciplines. The edges between disciplines are often the most productive areas for creative ideas.

Engineering instructors can choose from a variety of creativity techniques. Brainstorming was invented by Osborn (1991) and the term is now part of common usage. The technique is easy to use in class:

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

Encourage students to generate more ideas and ensure that there is no criticism during this stage. In a design class different design teams can be assigned to further develop these ideas.

These principles can be applied to other creative exercises. For example, individuals can brainstorm by themselves. Groups can brainstorm in a conference call, by e-mail, or through social media. In all cases the idea generation and evaluation stages must be separated; otherwise, the evaluation will inhibit idea generation. Most introductions to brainstorming skip the evaluation stage when the "grind of organization and evaluation" occurs (Allan, 1994, p. 273). In a separate creativity course several class periods can be set aside to do the complete brainstorming cycle.

Lateral thinking, (de Bono, 1973, 1985, 2008) 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. Lateral thinking is used only to generate ideas, and proposed solutions are 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. Answers to these examples are presented after section 5.8.

Example A. 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. Explain how this could be done.

Example B. 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. Try rephrasing the problem statement several different ways and then solve the different problems. The point of the example is *not* to find the exact solution deBono discusses, but to practice reframing problems.

Example C. 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 are wrong.

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 very useful for getting students to think about thinking and creativity (Allan, 1994; Raviv, 2012). Writing in a journal or diary is a useful method for encouraging creative thinking. Writing works best if done as free writing 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. You can also have students develop an idea map, which can be considered a less sophisticated version of a concept map (Figure 5-1).

Challenging students with creative games, questions, and exercises is a good way to increase their creativity (de Bono, 2008; Felder, 1988; Raviv, 2012). Although these do not have to be tied to engineering content, some students will think activities not related to the course topic are a waste of time. For example, have them brainstorm 100 possible uses for a brick. Ask them the meaning of word games such as:

Example D. What is "12safety34"?

Example E. What is "milonelion"?

Students who speak English as a second language may have difficulty with word games. There are also many mathematical exercises that require creativity to solve rapidly.

Example F. In a single elimination tennis tournament with 360 players, how many matches need to be held to determine the winner?

Gardner (1978) is a good source of both problems and references for additional problems. Open-ended creative questions do not have to have answers.

Example G. Why do bridges freeze before the road surface? How could this be prevented?

Example H. What is a good economical use for snow?

Heuristics were discussed extensively in Section 5.5, and many of them are useful for the generation of creative ideas. A few of many possible creativity heuristics are listed below.

1. *Have many ideas.* The more ideas, the more likely one will be good (Christensen, 1988).
2. *Reverse the problem.*
3. *Build on a random stimulus* (de Bono, 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* (Allan, 1994).
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 creativity methods such as borrowing brilliance, fishbone diagramming, and mind mapping* (Walesh, 2012).
8. *Show an invention or drawing of an invention and ask students what it is* (Raviv, 2012).
9. *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 (Walesh, 2012). 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.

People can learn to consciously shut off the left brain and use the subdominant right brain by giving the whole brain a job which the left brain will refuse to do (Edwards, 2012). You will do a much better job teaching students how to shut off their left brains if you become reasonably adept at this creativity approach. Practice the shift from left to right brain by looking at perceptual illusion drawings and consciously forcing 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 using the right side of the brain without using words to name parts. Edwards' (2012) 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. To be able to shift at will to right-brain thinking, you must monitor brain activity so that you know when the shift has occurred. (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 considered previously.)

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 evaluate the quality of the ideas.

To incorporate creativity successfully into a class, Flowers (1987) suggests 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. Picking good problems can be difficult because the instructor needs to know enough about the problem to know that it cries out for a creative solution, but without knowing 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, projects need deadlines. For motivational purposes it is important to have successes. Such things as a clever mechanism, a trick circuit, and a clever coupling of processes need to be celebrated as creative accomplishments. Detailed ideas most often delineate commercial successes since the development of a Xerox machine or the first introduction of a hand calculator occur rarely. Flowers (1987) suggests individual exercises before group exercises since group exercises introduce a whole new area of group dynamics.

5.7.3. Acceptance of Ideas

Foster creativity in students by accepting ideas and helping them 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 that the student 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. In either case the student will not be inhibited from generating new ideas.

A second method is to consciously use the PMI approach (de Bono, 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.

Practice building on ideas. Outline an interesting, creative idea for the class. Then assign students homework building on this idea. Or 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.

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.

5.8. CHAPTER COMMENTS

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.

Creativity Examples: Possible Solutions

Example A. If all the toll booths going onto an island are closed, the toll can be doubled for cars leaving the island.

Example B. 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.

Example C. 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 works. 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, on this diet there is little worry about going hungry later. However, the diet is not simple since it requires changing habits, but it is a different solution.

Example D. Safety in numbers.

Example E. One in a million.

Example F. Since every player except one must lose a match, there must be 359 matches (Gardner, 1978).

Example G. Less thermal mass and cooling from top and bottom. Insulate the underside.

Example H. Snow sculptures.

Many other solutions are possible for G and H.

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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