Principles for Teaching Problem Solving

Technical Paper #4

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Part

1

The Need to Teach Problem Solving

Problem solving is a basic skill needed by today's learners. Guided by recent research in problem solving, changing professional standards, new workplace demands, and recent changes in learning theory, educators and trainers are revising curricula to include integrated learning environments which encourage learners to use higher order thinking skills, and in particular, problem solving skills.

As education has come under criticism from many sectors, educators have looked for ways to reform teaching, learning, and the curriculum. Many have argued that the divorce of content from application has adversely affected our educational system (Hiebert, 1996). Learners often learn facts and rote procedures with few ties to the context and application of knowledge. Problem solving has become the means to rejoin content and application in a learning environment for basic skills as well as their application in various contexts.

Today there is a strong movement in education to incorporate problem solving as a key component of the curriculum. The need for learners to become successful problem solvers has become a dominant theme in many national standards (AAAS, 1993; NCSS, 1997; NCTE, 1996; NCTM, 1989, 1991). For example, the 1989 Curriculum Standards of the National Council of Teachers of Mathematics (NCTM) states: "Problem solving should be the central focus of the mathematics curriculum. As such, it is a primary goal of all mathematics instruction and an integral part of all mathematical activity. Problem solving is not a distinct topic but a process that should permeate the entire program and provide the context in which concepts and skills can be learned" (National Council of Teachers of Mathematics, 1989).

While many learners of all ages lack necessary basic literacy skills as well as higher order thinking skills, today's workplaces often demand high levels of both skill sets. Economic, organizational, and technological forces have changed the nature of most workplaces. Among these forces are globalization of the marketplace, democratization of workplace decision-making, synchronous production, new technologies, and multiple roles on most jobs (Mikulecky & Kirkley, in press). In 1991, the U.S. Department of Labor's Secretary's Commission on Achieving Necessary Skills (SCANS) made recommendations on how to educate students to meet future workforce needs. A key element to emerge from the SCANS Report (1991) was that "teaching should be offered in context, and students should learn content while solving realistic problems." Professional training standards are addressing problem solving skills as well. Medical, engineering, and business schools are revamping their curricula to focus on problem solving as a key component of the professional curriculum (Barrows, 1980; Woods et. al., 1997).

With scientific knowledge doubling every 5.5 years (Nash, 1994), it becomes increasingly important for students to develop higher order thinking skills. This involves basic skills, but also requires learners to use their knowledge in a variety of domains, perform critical analysis, and solve problems. As educators call for more integrated instruction, problem solving often serves as a core curriculum strand that joins together various disciplines, rules, concepts, strategies, and skills.

It is important to note that the emphasis on problem solving should not detract from the urgency of attention to basic literacy skills in schools. Problem solving skill depends on mastery of basic literacy skills. Bintz (1997) reported that the results of the 1994 National Assessment of Educational Progress (NAEP) indicated:

- At least one third of students in 4th, 8th, and 12th grade failed to read at a basic level
- Twenty four percent of fourth graders, slightly more eighth graders, and more than 33 percent of 12th graders scored at a proficient level
- Fewer than five percent of fourth, eighth, and 12th graders reached an advanced level.

Thus, the emphasis on problem solving is in addition to, and does not replace, the emphasis on basic literacy skills in the schools. In national standards and tests, problem solving "raises the bar" from minimum competency to world-class skills.

Even basic problem solving skills are scarce in the work force, as well. The 1993 National Adult Literacy Survey (NALS) found that more than half of employed adults had difficulty with completing various problem solving tasks—even simple ones. One such task tested to see if adults could solve problems such as determining the correct change using information from a menu. Another test involved answering a caller's question using information from a nursing home sign-out sheet (Kirsch, Jungeblat, Jenkins, & Kolstad, 1993). It is evident that for adults, as for learners in school, we must continue to emphasize basic literacy skills while we give additional attention to problem solving and other higher order thinking skills.

Part

2

Defining Problem Solving Skills

What is Problem Solving?

For much of the 20th century, educators have devoted their attention to trying to define and teach problem solving skills. In the early 1900s, problem solving was viewed as a mechanical, systematic, and often abstract (decontextualized) set of skills, such as those used to solve riddles or mathematical equations. These problems often have correct answers that are based on logical solutions with a single correct answer (convergent reasoning).

Under the influence of cognitive learning theories, problem solving shifted to represent a complex mental activity consisting of a variety of cognitive skills and actions. Problem solving included higher order thinking skills such as "visualization, association, abstraction, comprehension, manipulation, reasoning, analysis, synthesis, generalization--each needing to be 'managed' and 'coordinated'" (Garofalo & Lester, 1985, p. 169).

General Problem Solving Models of the 1960's

During the 1960s and 70s, researchers developed general problem solving models to explain problem solving processes (Newell & Simon, 1972; Polya, 1957; Bransford & Stein, 1984). The assumption was made that by learning abstract (decontextualized) problem solving skills, one could transfer these skills to any situation (context). One example of this general problem-solving model is Bransford's IDEAL model:

1) Identify the problem

2) Define the problem through thinking about it and sorting out the relevant information

3) Explore solutions through looking at alternatives, brainstorming, and checking out different points of view

4) Act on the strategies

5) Look back and evaluate the effects of your activity

This model is similar to many of the general problem solving models that were common then and that are still used with many general problem solving courses found in academic and corporate training settings. These are stand-alone courses, which teach problem solving as a "content-free" thinking skill, not integrated with the rest of the curriculum or work environment.

In schools, these models were one source of the "Inquiry" curriculum movement, which in turn led to "new" curricula such as "new math."

Current Problem Solving Models

Cognitive research done in the last 20 years has led to a different model of problem solving. Today we know problem solving includes a complex set of cognitive, behavioral, and attitudinal components. In 1983, Mayer defined problem solving as a multiple step process where the problem solver must find relationships between past experiences (schema) and the problem at hand and then act upon a solution. Mayer suggested three characteristics of problem solving:

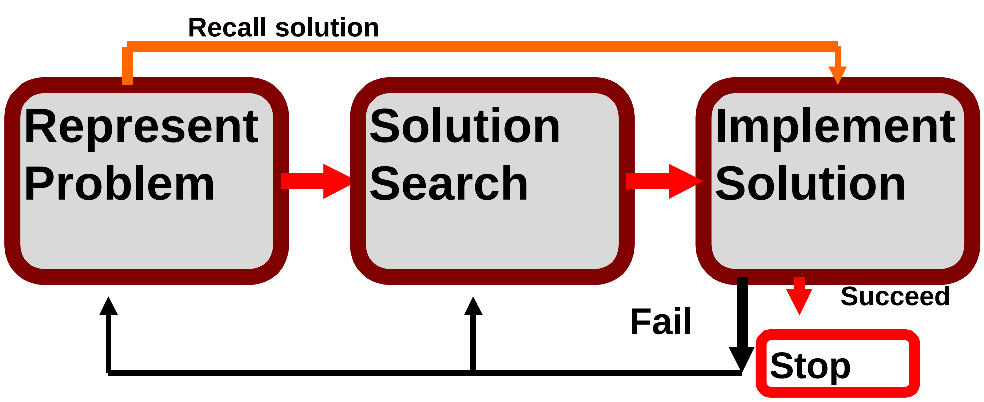
1) Problem solving is cognitive but is inferred from behavior.

2) Problem solving results in behavior that leads to a solution.

3) Problem solving is a process that involves manipulation of or operations on previous knowledge (Funkhouser and Dennis, 1992).

One frequently-used model of the problem solving process is shown in figure 1 (Gick, 1986):

• Figure 1: A model of the problem solving process



This model identifies a basic sequence of three cognitive activities in problem solving:

- *Representing the problem* includes calling up the appropriate context knowledge, and identifying the goal and the relevant starting conditions for the problem.
- *Solution search* includes refining the goal and developing a plan of action to reach the goal.
- *Implementing the Solution* includes executing the plan of action and evaluating the results.

There is an important "short cut," however: if the learner recognizes that he or she has solved a similar problem before, then all that's needed is to recall how it was solved last time, and do it again.

Of course, many problems are too complex to be solved with a single iteration of this process. In these cases, the learner breaks the problem down into *intermediate goals* and solves each one in turn, using this process. This switching between smaller, intermediate goals and a larger, final goal is an example of a higher order thinking skill called a *cognitive strategy*. Gagne's (1985) definition of problem solving reflects this principle, and positions problem solving as one kind of higher order thinking skills. He defined problem solving as the "synthesis of other rules and concepts into higher order rules which can be applied to a constrained situation."

Problem solving also includes attitudinal as well as cognitive components. To solve problems, learners have to want to do so, and they have to believe they can. Motivation and attitudinal aspects such as effort, confidence, anxiety, persistence and knowledge about self are important to the problem solving process (Jonassen and Tessmer, 1996).

Unfortunately, directly teaching a problem solving process doesn't improve actual problem-solving performance, whether you use a model from the 1960's or one like that in Figure 1. Beginning in the mid-1980's, researchers found that attempts to teach abstract, generalized problem solving skills proved ineffective (DeBono, 1983; Beyer, 1984). They found that mastery of generalized problem solving skills did not differentiate well between good and poor problem solvers. In fact, researchers concluded that knowledge of context was the most critical feature of skill in problem solving. Thus, current research supports problem solving as a situational and context-bound process that depends on the deep structures of knowledge and experience (Palumbo, 1990). When teaching problem solving, authentic problems in realistic contexts are essential. Learners learn to solve these problems, and only after having done so will they be able to see the similarities of strategy across different contexts—and then, only with the right kind of support and structure for their thinking.

Two Types of Knowledge

Instruction in problem solving needs to focus on two distinct types of knowledge: declarative and procedural (Gagne, 1985). Declarative knowledge is closely related to the context knowledge mentioned above. A common error is to teach only declarative knowledge, and assume that learners who have mastered declarative knowledge can solve problems in a domain. Conversely, attempts to teach problem solving alone, without teaching the supporting declarative (context) knowledge are also ineffective.

Declarative Knowledge

Declarative knowledge is the "know what." It includes facts, concepts, and principles. It is the content-specific or factual knowledge within a discipline or skill domain. This table explains the three types of declarative knowledge:

Declarative Knowledge Type	Example
Facts ("know what"—simple associations)	This car is a 1998 Chevrolet Camaro
Concepts ("know that"—ability to identify and cluster examples)	Kinds of cars include coupe, sedan and station wagon
Principles ("know why"—ability to predict and explain the behavior of a system)	*If* you turn the steering wheel clockwise, *then* the car will turn right (*because* the steering wheel moves a rack & pinion gear which is connected to arms which turn the wheels).

Mental Models

Problem solvers form *mental models* (schemata) based on the situation they are manipulating. According to John Anderson (1995), the mental model is the synthesis of declarative knowledge into a structure which is optimized for solving a certain class of problems. Solving problems typically requires problem solvers to dynamically restructure and "run" their mental models of the system in order to predict the effect a proposed action on the system or to explain an observed system behavior. Thus, developing a mental model with the right kind of structure for solving a particular class of problems is a key to successful problem solving. Declarative knowledge should be taught in a way which encourages the learner to form and use the mental model best suited for solving a particular class of problems.

The kind of mental model you develop depends on what problems you expect to be solving with it. For example, the mental model you need to make a domestic telephone call includes only the visible parts of the phone, a little about the syntax of phone numbers and dialing prefixes, and almost nothing about the telephone network beyond the wall jack. A telephone serviceman's mental model of the same system has many more pieces and operating principles. At the other extreme, the strategic problems a CEO must solve are fairly loosely structured, so mental model the CEO needs of the company and its environment is quite elaborate and dynamic (Foshay, 1987).

Mental modeling is one of the most critical steps in problem representation. Therefore, it's important to help learners build their mental models successfully as they prepare to solve a problem. Manipulating the mental model is a key step in problem solving, because it helps the learner predict the effects of various possible actions, and select the one which will move him or her closer to the solution.

Expert vs. Novice Knowledge

Researchers have found there are big differences between what an expert problem solver and a novice problem solver knows about how to solve the same problems. The declarative knowledge of expert and novice problem solvers differs in three main ways:

- First, expert problem solvers have deeper understandings and representations of a domain (context). Expert problem solvers are able to draw on an extensive reservoir of past experiences solving analogous problems in the same domain, and can switch between various methods and strategies (Jonassen, 1997). Novices do not know as much as experts about the context. Novices make more errors than experts, and their errors are mostly related to misconceptions rather than carelessness or random guessing.

- Second, expert problem solvers synthesize their rich declarative knowledge to generate a dynamically changing, personal mental model of the system or problem space for solving a particular class of problems. Novices often rely on naive, less complete, poorly structured and even incorrect mental models. These mental modeling errors are often the source of novice problem solving mistakes.

- Third, expert problem solvers have a positive attitude and confidence that problems can be solved through persistent analysis (Jonassen, 1997). Novices often lack these properties.

Note how context-bound these differences are. A person can be an expert problem solver in one context, and a novice in another.

To help novices become better problem solvers, they need to develop a stronger base of declarative or domain knowledge, synthesize their knowledge into appropriate mental models, and recognize common solution strategies across many problems and contexts. Thus, it is not true that emphasizing problem solving in the curriculum comes at the expense of teaching declarative knowledge. Quite the opposite is the case: a learner's problem solving skills cannot rise above his or her declarative knowledge—*but* the declarative knowledge has to be taught in a way which causes the learner to organize it for problem solving.

Furthermore, since experts know more declarative and procedural knowledge and structure it differently from novices, it should usually be preferable to treat learning of declarative and procedural knowledge as co-requisites, rather than attempting to teach most declarative knowledge before teaching most procedural knowledge. This can be done by building the declarative knowledge instruction directly into the problem-solving activity and inviting (or requiring) the learner to explore these "digressions" from the problem-solving. Alternatively, the learner can alternate between declarative knowledge instruction (e.g., in a tutorial format) and problem-solving instruction (e.g., in a simulation format). This principle is guiding development of the PLATO architecture (see Technical Paper #3).

Procedural Knowledge

A Continuum of Problem Types

The kinds of problems we encounter vary in the amount of structure they provide. Problems are often represented on a continuum from well-structured, through moderately-structured, to ill-structured (Newell and Simon, 1972). The position of a problem on this continuum determines the way it is taught and learned. The table on the next page compares three points on the continuum of problem types.

Type of Problem	Well structured problems	Moderately structured problems	Ill structured problems
Definition	Problems that always use the same step-by-step solution.	Problems that require varying strategies and adaptations to fit particular contexts.	Problems with vague and unclear goals. Solution strategies least constrained.
Characteristics	• Solution strategy is usually predictable • Convergent (one right answer) • All starting information is usually part of the problem statement.	• Often more than one acceptable solution strategy. • Convergent (one right answer). • Needed information often must be gathered.	• Solution is not well defined or predictable. Multiple perspectives, goals, and solutions. • There is no single well-defined and agreed-upon solution; there may not be a fully satisfactory solution at all. • Needed information often must be gathered.
Examples	Balancing a checkbook, following a recipe, and solving a crossword puzzle	Designing a spreadsheet, writing a letter, and planning a sales call	Painting a portrait, designing a bridge, and creating a new computer program
Implications for Teaching and Testing	• Depend on declarative knowledge, but with the least depth of knowledge. • The skills for these are limited to similar types of problems. Transfer is poor. • Learner simply memorizes the procedure; tasks often become automated with practice. • Easily incorporated into job aids and performance support systems.	• Require more declarative (context) knowledge. • Requires skills of mental modeling, problem representation, analogical/abstract reasoning, and evaluation, all within the context. Transfer is strong. • Learner must invent a strategy which suits the context.	• Requires extensive declarative knowledge and experience. • Uses heavy abstract/ analogical/ symbolic reasoning and cognitive flexibility. Transfer is strongest. • Must help the learner define the context and goals of the problem. • Provide opportunities for divergent practice (many right answers).

Most Jobs Have Many Problem Types

Most real-world jobs include a mixture of problems that vary in degree of structure as well as the solution strategy required. As an example, we can analyze how a team of employees working at a furniture factory design and implement a new quality control system for tracking production process errors.

- The team's overall goal is to improve quality. This is an ill structured problem where employees need extensive declarative and procedural knowledge (usually gained through experience) first to define what quality is, and then to design the new system. The solutions are not constrained. To define the goal more precisely, employees would need to know about statistical process control procedures used for calculating errors, ways in which they can adjust factory equipment to reduce production errors, and company management team structures which can be used for reporting and fixing production errors. As with any ill structured problem, there is no single well-defined and agreed-upon solution, and there may not be a fully satisfactory solution at all. There are no general rules or principles to guide the development of this process that uses a wide range of problem solving, communication, and quality control strategies
- These employees will also encounter many moderately-structured tasks such as selecting the spreadsheet for calculating statistics on errors, designing the reporting system for documenting and correcting errors, and performing root cause analysis. These problems have some well-structured parts, but employees will need to determine the adaptations that need to be made and strategies to be used in this particular context. For example, employees must decide how to set up the spreadsheet application to meet the needs of the production workers as well as the management teams. These moderately structured problems require heavy use of declarative knowledge, mental modeling, problem representation, analogical/abstract reasoning, and evaluation.
- Designing this system also involves many well-structured problems such as actually tracking and reporting production errors and making adjustments in the production process. Employees rely heavily on their declarative knowledge to solve problems using well-defined procedures, principles, concepts and facts. To reduce errors, employees enter information into a spreadsheet, print out results, and email them to management teams. They also make adjustments in the factory equipment as needed. These problems often have convergent solutions: all can agree when the statistics have been correctly calculated, and when quality has improved.

This example also highlights another common error in teaching problem solving. Often, instructors concentrate only on the well-structured problem solving procedures in a job, and fail to identify and teach the moderately- and ill-structured problem solving. This often leads to learners who are able to perform many small and routine job tasks, but who can't respond when conditions change or a new problem is encountered.

Near and Far Transfer

We rarely would be satisfied with learners who could only use their knowledge in the exact circumstances in which it was taught to them. Therefore, in education and training, the goal is always for the learners to transfer what they have learned to new situations. The less the "real world" context is like the learning conditions, the farther the transfer, and the less likely it is to happen.

Generally, moderately- and ill-structured problem solving skills are capable of far transfer, while well-structured problem solving skills are capable of only near transfer. However, even when the learners will solve mostly well-structured problems (such as operating a device or troubleshooting common faults in one), it's often important to generalize to previously unencountered problems, and to adapt quickly to changes (e.g., new equipment models or software releases) without formal retraining. If this is the case, then teaching even apparently well-structured skills as moderately problem solving may be worthwhile. This is another reason why moderately- and ill-structured problem solving is becoming an increasing component of apparently well-structured jobs, and why the need for training in moderately-structured and ill structured problem solving is growing in the workplace as well as in schools.

In general, teaching moderately or ill-structured problem solving is more complex and time-consuming than teaching well-structured problem solving, because of the increased emphasis on declarative knowledge, mental modeling, and inductive strategy. However, in some circumstances, teaching moderately or even ill-structured problem solving can be more efficient than teaching well-structured problem solving. For example, in an environment where the details of well-structured procedures change constantly, such as environments with frequently changing technology, training for moderately-structured problem solving may be more cost-effective in the long run because it will help learners adapt to the changes without retraining. Similarly, in environments where there are a large number of well-structured procedures with only minor variations between them, such as troubleshooting different models or configurations of a technology, it may be more cost-effective to train for one moderately-structured problem-solving task and let the learner generalize, rather than teaching every individual well-structured procedure as if the other similar ones did not exist.

Part
3

Principles for Teaching Problem Solving

This new understanding of problem solving leads to a number of important principles for teaching problem solving. Instructors can apply these principles whether they teach in classroom or computer-based settings. They form the basis of problem-solving instruction in the PLATO system. Here is a summary of these principles:

1) For any "real-world" job or work skill, identify both the declarative and procedural knowledge components. Give each appropriate instructional emphasis.

2) First introduce a problem solving context, then either alternate between teaching declarative and procedural knowledge, or integrate the two.

3) When teaching declarative knowledge, emphasize mental models appropriate to the problem solving to come, by explaining knowledge structures and asking learners to predict what will happen or explain why something happened.

4) Emphasize moderately- and ill-structured problem solving when far transfer is a goal of instruction.

5) Teach problem solving skills in the context in which they will be used. Use *authentic* problems in explanations, practice and assessments, with scenario-based simulations, games and projects. Do not teach problem solving as an independent, abstract, decontextualized skill.

6) Use direct (deductive) teaching strategies for declarative knowledge and well structured problem solving.

7) Use inductive teaching strategies to encourage synthesis of mental models and for moderately and ill-structured problem solving.

8) Within a problem exercise, help the learners understand (or define) the goal, then help them to break it down into intermediate goals.

9) Use the errors learners make in problem solving as evidence of misconceptions, not just carelessness or random guessing. If possible, determine the probable misconception and correct it.

10) Ask questions and make suggestions about strategy to encourage learners to reflect on the problem solving strategies they use. Do this either before or after the learner takes action. (This is sometimes called *cognitive coaching).*

11) Give practice of similar problem solving strategies across multiple contexts to encourage generalization

12) Ask questions which encourage the learner to encourage the learner to grasp the generalizable part of the skill, across many similar problems in different contexts.

13) Use contexts, problems and teaching styles which will build interest, motivation, confidence, persistence and knowledge about self, and reduce anxiety.

14) Plan a series of lessons which grow in sophistication from novice-level to expert-level understanding of the knowledge structures used.

15) When teaching well-structured problem solving, allow learners to retrieve it (e.g., from a reference card). If the procedure is frequently used, encourage memorization of the procedure and practice until it is automatic.

16) When teaching moderately-structured problem solving, encourage the learners to use their declarative (context) knowledge to invent a strategy which suits the context and the problem. Allow many "right" strategies to reach the solution, and compare them for efficiency and effectiveness.

17) When teaching ill-structured problem solving, encourage the learners to use their declarative (context) knowledge to define the goal (properties of an acceptable solution), then invent a solution. Allow many "right" strategies and solutions, and compare them for efficiency and effectiveness.

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