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## PROBLEM SOLVING IN CHEMISTRY

George M. Bodner and J. Dudley Herron

## INTRODUCTION

When the first author began work in chemical education, he became interested in research on problem solving for several reasons. First, problem solving is what chemists do, regardless of whether they work in the area of synthesis, spectroscopy, theory, analysis, or the characterization of compounds. Second, it was clear that individuals who were successful in chemistry courses either developed good problem solving skills — more or less on their own —or brought these skills to their chemistry courses. Finally, it was obvious that we weren't doing as good a job as we could in helping less successful students learn how to build problem solving skills.

This chapter provides a review of the research literature devoted to the study of problem solving in chemistry, including research on instructional strategies that might lead to improvements in students' problem solving ability. This literature runs the gamut from studies of high-school students working on stoichiometry or gas law problems through studies of problem solving by advanced graduate students in chemistry. Our primary goal in writing this chapter is to point the reader toward appropriate literature, that can (and should) be read for further details. We will also provide our biased perspective on some of this work.

### *Definitions Of Terms*

The literature on problem solving in chemistry is complicated by the absence of agreement on the meaning of such basic terms as "problem" and "problem solving" (Smith, 1988). Let's therefore start with operational definitions of these terms. Hayes (1980) defined a problem as follows:

> Whenever there is a gap between where you are now and where you want to be, and you don't know how to find a way to cross that gap, you have a problem.

Wheatley (1984) coined the following consummate definition of problem solving:

> What you do, when you don't know what to do.

These definitions imply a fundamental difference between two related concepts: *routine exercises* and *novel problems* (Bodner, 1991). We routinely encounter tasks for which there is a gap between where we are and where we want to be, but we feel confident that we know a way to cross the gap. When this happens, we are faced with an exercise, not a problem.

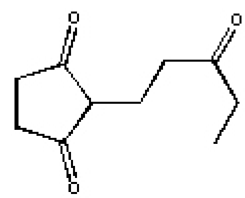
There is no innate characteristic of a task that inevitably makes it a problem. Status as a problem is a subtle interaction between the task and the individual struggling to find an appropriate answer or solution (Bodner & McMillen, 1986; Bodner, 1987). The following question, for example, is a problem for most students when they begin their study of chemistry, but a routine exercise for their instructors.

How many grams of oxygen would be needed to burn 10.0 grams of magnesium?

$$2\ Mg(s) + O_2(g) \rightarrow 2\ MgO(s)$$

Similarly, while the following exam question would be a problem for some who read this chapter, it is a routine exercise for chemists who specialize in organic chemistry.

> Robinson annulation reactions involve two steps: Michael addition and aldol condensation. Assume that Michael addition leads to the following intermediate. What would be produced when this intermediate undergoes aldol condensation?



*Models Of Problem Solving*

One approach to understanding "what we do, when we don't know what to do" has been to develop models that try to describe the generic steps or stages problem solvers go through (or should go through) as they struggle with a problem. In theory, if a good model of problem solving were available, we should be able to create an instructional strategy based on this model that would improve students' problem-solving abilities. However, when we compare various models with what people do when they solve problems, it becomes clear that teaching problem solving isn't this straight-forward.

Any description of problem solving is likely to oversimplify this complex and somewhat eclectic process. That is especially true of Polya's model, which grew out of his work on relatively well-structured problems in mathematics. Polya's (1946) popular model, consists of four steps: (1) understand the problem, (2) devise a plan, (3) carry out the plan, and (4) look back. For many years, one of us has used the following problem in seminars on problem solving to probe the validity of Polya's model:

> A sample of a compound of xenon and fluorine was confined in a bulb with a pressure of 24 torr. Hydrogen was added to the bulb until the pressure was 96 torr. Passage of an electric spark through the mixture produced Xe and HF. After the HF was removed by reaction with solid KOH, the final pressure of xenon and unreacted

hydrogen in the bulb was 48 torr. What is the empirical formula of the xenon fluoride in the original sample? (Holtzclaw, Robinson, and Nebergall, 1984)

It is rare, indeed, to find a practicing chemist who truly "understands" this problem until he or she arrives at the answer, $XeF_2$. Their behavior is more like the general, tentative steps outlined by Dewey (1910).

Lee and Fensham (1996) note that Dewey's model of problem solving consists of five stages that might be described as follows: (1) A state of doubt or awareness of difficulty, (2) an attempt to identify the problem, (3) transforming problem-setting propositions into problem-solving propositions or hypotheses, (4) successive testing of hypotheses and reformulation of the problem as necessary, and (5) understanding the successful solution and applying it both to the problem at hand and other exemplars of the problem. The difference between Dewey's model of problem solving and Polya's can be related to the difference between a routine exercise, which is worked in much the way Polya suggested, and a novel problem, which is best addressed via general models similar to the one outlined by Dewey.

We have used the following model of problem solving developed by Wheatley (1984) to teach chemistry (Bodner & Pardue, 1995):

- Read the problem.
- Now read the problem again
- Write down what you hope is the relevant information.
- Draw a picture, make a list, or write an equation or formula to help you begin to understand the problem.
- Try something.
- Try something else.
- See where this gets you.
- Read the problem again.
- Try something else.
- See where this gets you.
- Test intermediate results to see whether you are making any progress toward an answer.
- Read the problem again.
- When appropriate, strike your forehead and say, "son of a ...".
- Write down *an* answer (not necessarily *the* answer).
- Test the answer to see if it makes sense.
- Start over if you have to, celebrate if you don't.

Whereas exercises are worked in a linear, forward-chaining, rational manner, this model of problem solving is cyclic, reflective, and might appear irrational because it differs from the approach a subject matter expert would take to the task. One limitation of Polya's model is the assumption that we begin by "understanding the problem." The models proposed by Dewey and Wheatley presume that "understanding the problem" arises toward the end of the problem-solving process.

Analysis of transcripts of problem solving protocols elicited from 10 teachers and 33 Grade 12 students led Lee and Fensham (1996) to identify seven distinguishable processes in problem solving: (1) Reading and comprehending the problem statement as a whole, rephrasing or simplifying the problem statements, using symbols or diagrams to visualize the problem so that they could understand it, (2) translating the parts of the problem statement into statements that had meaning to themselves, (3) setting goals or subgoals, (4) selecting what they recognized as important information from the translation statements obtained in the first three processes, (5) retrieving rules or facts from memory, (6) achieving goals and or subgoals by explicit or implicit linking of processes 4 and 5, and (7) checking the paths of the solution or the answers. For us, Lee and Fensham's results are more consistent with either Dewey's or Wheatley's model of problem solving than they are with the model proposed by Polya or one of the other stage models based on Polya's work.

All of these models of problem solving have merit, but problem solving is a complex process that is affected by many variables. No single model — not even the collection of models outlined here — captures all nuances of problem solving. Additional insights are provided by research that contrasts the problem solving behavior of "experts" and "novices."

## ANALYSES OF PROBLEM SOLVERS AND PROBLEM SOLVING

*Expert/Novice Problem Solvers*

Larkin, et al., (1980) differentiated between the means-end analysis used by many novice physics problem solvers and the knowledge-development or forward-chaining approach used by experts. Means-ends analysis begins by identifying the goal of the problem, finding differences between the goal and the current information, finding an equation that will reduce this difference, using this equation, and then repeating this cycle, as needed. Forward-chaining begins with the information in the problem statement and works forward, performing operations as needed until the goal is reached.

The expert/novice dichotomy was used by Chi, Feltovich, and Glaser (1981), who noted that experts and novices used different processes for sorting physics problems. Experts classified problems according to the principles governing the solution to the problem; novices categorized problems by their surface structure.

Comparing the performance of experts, who are usually faculty or Ph.D. students trained in the content area, with that of novices, who are students enrolled in the course for the first time, requires the design of problems difficult enough to require more than recall for the faculty and yet simple enough to allow the students a chance to obtain the solution (Smith and Good, 1984). Although this can be done (Camacho and Good, 1989), it is also possible to find oneself comparing the performance of experts working on routine exercises with that of students working on novel problems.

An alternative approach to expert/novice research has been reported in which "expert" students are compared with "novice" students. In a study of a HyperCard method for assessing the performance of high-school chemistry students on problems that involved balancing chemical equations (Kumar, 1983), the "expert" students were selected from a class of honors students, whereas the "novice" students came from a regular chemistry class. Another approach by Heyworth (1999) divided the students into expert and novice categories on the basis of a paper and pencil test. Students who made no procedural errors and had a good conceptual understanding were classified as experts, while those with largely erroneous procedures who had a poor conceptual understanding were classified as novices. The expert students solved the problems rapidly, using a working forward strategy. Heyworth questioned whether it might be misleading to use the term "problem solving" to describe their work; the problem had not been "solved"; the solution procedure already existed and didn't have to be created. The expert students were merely following a well-worn path toward the answer to what we would call a routine exercise. For the novice students, the problem didn't seem to be familiar or have a recognizable solution path. Their performance was slower, used a variety of formulas (some of which were erroneous), and their think-aloud protocol was characterized by frequent pauses and fewer comments. The novices mainly used a means-end analysis strategy; when this was unsuccessful, they switched to a groping forward search strategy.

Smith and Good (1984) questioned the adequacy of the expert/novice dichotomy. They found that roughly one-quarter of the novices in their study of problem solving in genetics used strategies characteristic of experts, which contributed markedly to their success. They argued that expertise in problem solving in genetics is a continuum, rather than a dichotomy, and suggested comparing the behavior of successful and unsuccessful problem solvers.

*Successful/Unsuccessful Problem Solvers*

Camacho and Good (1989) compared the performance of high-school students, undergraduates, Ph.D. students and faculty on chemical equilibrium problems. They also concluded that problem solving performance is a continuum, not a clear dichotomy between experts and novices. They noted that successful subjects exhibited certain behaviors that were fundamentally different from those of unsuccessful subjects. The successful subjects:

- Read completely before asking questions, asked better questions (reflecting more knowledge), and reread the objectives before starting the solving process.
- Began the problem solving process with an equation for the reaction and wrote down the equilibrium constant early in the process.
- Perceived the problem as a task of reasoning and development of a solution.
- Didn't mention formulas or equations until they had said how to solve it in chemical terms.
- Used new symbols to represent chemical species when needed or appropriate.
- Did the necessary steps of the process in order, did only the necessary work, and used information not given in the problem.
- Made frequent checks of their work to discover inconsistencies.
- Made proper assumptions, showed adequate chemical conceptualizations of the

concepts and principles involved, and showed proper understanding of the equilibrium constant.
- Recognized similarities among equilibrium problems.
- Didn't use trial and error, and made few careless mistakes.
- Were able to think aloud fluently, the way a well-prepared teacher would.
- Used or expressed the knowledge of more than one method or principle to solve the problem.

The differences in behavior described here call attention to the growing repertoire of declarative and procedural knowledge one can utilize in solving problems as expertise develops. They shouldn't be used, however, as guidelines for teaching students how to succeed at problem solving. For example, the fact that successful subjects in this study didn't use trial and error, did the necessary steps of the process in order, did only the necessary work, and made proper assumptions, doesn't mean that students should be discouraged from using trial and error when they don't recognize the necessary steps. Nor should they be criticized for doing unnecessary work, as they invariably will do when they make improper assumptions, and the like. As we have already pointed out, it is rare, indeed, to find a practicing chemist who *doesn't* resort to trial and error, who *doesn't* do unnecessary work, and the like when they attempt to solve the empirical formula problem shown on p. 3. But as one gains expertise in a field, one is able to formulate better representations of the problems encountered and is less dependent on general, inexact strategies to solve them. Problems metamorphose into exercises, and students are more successful because they have more declarative and procedural knowledge to work with.

As Herron and Greenbowe (1986) put it, successful problem solvers have a good command of basic facts and principles; construct appropriate representations; have general reasoning strategies that permit logical connections among elements of the problem; and apply a number of verification strategies to insure that the representation of the problem is consistent with the facts given, the solution is logically sound, the computations are error-free, and the problem solved is the problem presented.

In addition to describing differences in the behavior of successful and unsuccessful problem solvers, Camacho and Good also questioned the following features of textbook problems: They are too easy for experts or too complex for novices; can be solved by one method only; can be solved by direct application of a formula or equation; ask for mathematical results without reasons or justifications; emphasize quantitative aspects of learning at the expense of qualitative reasoning; and are solvable in one or two steps.

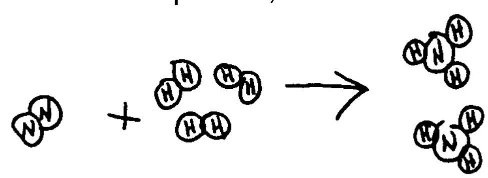
It isn't just textbook problems that have questionable features; the solutions presented in textbooks are also problematic. As Herron (1996, p. 72) puts it, "The solutions given by authors in textbooks bear little resemblance to what experts do when they work *unfamiliar* problems. (Textbook solutions are generally algorithmic. They describe the most efficient pathway to a solution and probably represent how an expert who solves such problems routinely would approach the task.)"

*Conceptual Understanding*

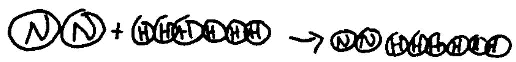
A significant fraction of the literature on problem solving in chemistry and physics has focused on quantitative problems that could be solved algebraically. These problems were studied because they represent a large fraction of the tasks given to students in introductory chemistry courses. The kinds of problems practicing chemists encounter, however, are more likely to be non-mathematical, such as predicting the product of a chemical reaction, envisioning a reaction mechanism, interpreting NMR or IR spectra, designing an experiment, and so on.

About 15 years ago, papers started to appear that studied problem solving in non-mathematical domains within chemistry. One of the first was a study of high-school students' performance on tasks that asked them to balance equations. Yarroch (1985) noted that the students in his study were all able to successfully balance the four equations presented to them, but 7 of the 12 students weren't able to construct diagrams consistent with the notation of the balanced equation.

The students in this study were in the upper-third of their chemistry class and well into the fourth quarter of the course. They were asked to represent chemical equations using circles with letters in the center to represent atoms. Some students presented diagrams that were valid interpretations of the equation, such as the following:



Others presented diagrams that were consistent with a simple mathematical interpretation of the numbers and symbols of the equations.



Yarroch concluded that students who gave these answers could balance simple equations, but had little understanding of the implications of these equations.

*Conceptual Versus Algorithmic Problem Solving*

Nurrenbern and Pickering (1987) proposed an alternative to the quantitative approach to teaching chemistry that had become the accepted one. In their study, students were asked to do both a traditional problem on gases and a multiple-choice question that had no mathematical content but asked for a purely conceptual understanding of gases. They found that the students had far greater success answering the traditional questions than the conceptual questions.

Nurrenbern and Pickering argued that the traditional questions could be answered using algorithmic strategies, and subsequent work has frequently revolved around "conceptual" versus "algorithmic" problem solving. The term *algorithm*, however, has been defined as "Rules for calculating something that can be followed more or less automatically by a reasonably intelligent system, such as a computer" (Ehrlich et al., 1980). It might therefore be best to think about the literature in this area in terms of "conceptual" versus "algebraic" or "numeric" problem solving.

Sawrey (1990) repeated the work by Nurrenbern and Pickering with a larger, more uniform group of students. She compared success on conceptual versus numerical problems for students in the top and bottom of the class, to see if the effect disappears for higher achievers. Even the best numerical problem solvers, however, performed poorly on the conceptual questions. She argued that the qualitative, conceptual side of chemistry has suffered as a consequence of the emphasis in recent years on quantitative problems and argued for simultaneously giving attention to both the qualitative and quantitative nature of chemistry.

It might be worth noting that neither Nurrenbern and Pickering nor Sawrey addressed the question of whether student performance on the traditional questions is better because the students are more familiar with these questions. To some extent, this is still an open question.

An interesting question was addressed by Pickering (1990), who asked: What happens to students' ability to solve conceptual versus algebraic problems when they go on to take organic chemistry? He found that 95% of his organic chemistry students could do the traditional numerical gas problem from the earlier study by Nurrenbern and Pickering, but only 40% could do the conceptual gas problem. Students who could do both problems were called "successful"; those who could only do the traditional problem were labeled "unsuccessful." The "successful" students had scored statistically higher than those who were "unsuccessful" in the second semester of the general chemistry course. There was no difference, however, in their performance in the organic course.

*Conceptual Versus Traditional Mathematical Problem Solving*

Nakhleh (1993) probed whether there were students in our classes who might do well on conceptual questions but not on the traditional mathematical problem-solving questions. She placed a set of five matched pairs of questions on the final exams in courses for remedial students, science and engineering majors, chemistry majors, and honors students. One question was phrased as an algebraic problem-solving question, the other was phrased as a conceptual question. She found that many students can answer an algebraic question but cannot answer a conceptual question dealing with the same topic. There was a gradual increase in the means for both the algorithmic and conceptual questions as one proceeds from the remedial to the science/engineering population to the majors to the honors course, but the lines for the two types of questions are parallel. Roughly half of the students were high on both algorithmic and conceptual questions, 31% were high on algorithmic but low on conceptual questions, 10% fell in the low algorithmic, high conceptual quadrant, where they were looking for students, and 10% were low on both algorithmic and conceptual questions.

In a second study, paired exam questions on gas laws were used to identify students in a general chemistry course for chemistry majors as being either conceptual or algorithmic problem solvers (Nakhleh & Mitchell, 1993). Slightly more than 40% of the students were labeled as high conceptual/high algorithmic and slightly more than 40% were low conceptual/high algorithmic. Only 5% were low algorithmic/high conceptual and 10% were low conceptual/low algorithmic. Six students were interviewed, two from three of the four possible categories. (No students were available from the low algorithmic/high conceptual category.) During the interview the students worked through the same questions from the exam and an additional pair of stoichiometry problems. The students all answered both gas law problems correctly. Half used an algorithm (one of the gas laws) to solve this problem. Two others used an elimination approach, eliminating the obviously wrong answers and then deciding between the remaining choices. Nakhleh and Mitchell argue that this “test taking strategy” is another algorithmic approach because the students clearly didn’t understand the kinetic-molecular theory concept behind the problem.

Pendley, Bretz and Novak (1994) also found that students’ performance on exam questions doesn’t accurately reflect their understanding of the concepts. Most student’s answers, even of questions that required general/qualitative answers, were indicative of essentially rote memorization of concepts and propositions, which rapidly became non-retrievable from memory, rather than answers that indicated meaningful learning and restructuring of concept/propositional knowledge in memory, which may be retrievable for months or years. They noted that concept maps are useful tools to illustrate change (or lack thereof) in a student’s conceptual understanding and therefore represent a viable alternative to interviews.

*Problem Solving Without Conceptual Understanding*

Smith and Metz (1996) probed the assumption that performance on general chemistry exams that feature mathematically based questions is a legitimate measure of an understanding of chemical concepts. They tested the conceptual knowledge of acid strength and solution chemistry of undergraduates. They also tested graduate students and faculty to see if conceptual weaknesses persist past the undergraduate level. The sample population was given a series of four microscopic representations and asked to choose the representations that best illustrate a strong acid (HCl) and a weak acid (HF). Slightly less than half of the undergraduates and slightly less than 10% of the graduate students chose a representation for HCl in which the acid was undissociated. Slightly less than half of the undergraduates and roughly 90% of the graduate students and faculty chose a representation in which the HCl dissociated completely. (The rest of the faculty chose a representation in which there was only a single HCl ion pair.) Smith and Metz concluded that students often learn how to solve mathematical problems without understanding the chemistry. They memorize chemical definitions and use chemical terms without true comprehension, and without being able to visualize the concepts.

Mason, Shell, and Crawley (1997) studied the problem solving schemas of both general chemistry students and faculty on paired conceptual and algebraic problems. Students were divided into four categories: high algebraic/high conceptual (HA/HC); high algebraic/low conceptual (HA/LC), low algebraic/high conceptual (LA/HC), and low algebraic/low conceptual (LA/LC). They noted that the number of LA/HC students was relatively small (5%) and concluded that it appears to be the rare (or unusual) student who understands the concepts but lacks the ability to formulate a mathematical solution to an algebraic problem.

Mason, et al., analyzed the time required to complete a problem and the number of transitions between "episodes" in the problem solving strategy. They defined episodes as distinct modes of operation within a problem solving strategy, such as *read*, *define*, *setup*, *solve*, and so on. They found that algebraic problems always required more time and a greater number of transitions for completion than the paired conceptual problems, regardless of the students' problem-solving ability. They also found that all students correctly solved the algebraic problems more frequently than the corresponding conceptual problem, regardless of topic.

They noted that experts solve both algorithmic and conceptual problems quickly and effortlessly (i.e., with few transitions between episodes). Both the time needed to complete the problem and the number of transitions increased as the level of problem-solving performance decreased. The rate at which transitions occurred, however, appeared to be similar for algebraic and conceptual problems. They noted that LA/LC students had difficulty following a direct pathway; they appeared to shift back and forth between episodes, especially when solving an algebraic problem.

Research on conceptual understanding was extended to students enrolled in physical chemistry by Thomas and Schwenz (1998). They noted that students defined thermodynamic concepts according to their usage in everyday language instead of the precise scientific meaning; confused various thermodynamic concepts; used informal prior knowledge from everyday experience to explain the thermodynamics of chemical phenomena; generalized thermodynamic principles beyond the specific conditions under which they apply; and used concepts from kinetics to explain the thermodynamics of chemical phenomena. They calculated a "quality of student conception" rating for each subject by comparing conceptions expressed in the individual interviews with those expressed in textbooks. The "quality of student conception" rating was best predicted by an aggregate *t* score for the results on instructor-designed in-class exams. This result indicates that instructor's exams and grades may, in fact, demonstrate the level of a student's understanding of the course material.

Voska and Heikkinen (2000) identified and quantified chemistry conceptions students use when solving equilibrium problems requiring application of LeChâtelier's principle and explored the feasibility of designing a two-tier paper and pencil test to accomplish these purposes. Their results support the view that some students answer questions correctly using erroneous reasoning. This study also supports Treagust's (1988) argument that conventional multiple choice tests don't adequately assess student understanding; a significant proportion of students can select correct answers but provide incorrect or incomplete reasons.

*Why Students Get the Wrong Answer*

Herron and Greenbowe (1986) provided insight into how students get wrong answers in their case study of "Sue." "Sue" was a college freshman who had been "successful" in high school and continued to "succeed" in college. But she had serious weaknesses that interfered with her success on unfamiliar problems. In spite of two years of high school chemistry, she wrote $AgSO_4$ for silver sulfate, MgFl for magnesium fluoride, and $SbI_2$ for antimony(III) iodide. Although her procedure for solving a limiting reagent problem was correct, she arrived at the wrong answer because her facts were wrong. Although Sue had developed the general intellectual skills required for problem solving, she didn't always use them effectively. She occasionally arrived at an answer that was correct, but not the answer called for in the question. Sue's representations of problems were inconsistent with the physical reality described, but she evidently didn't realize that.

Sue was a "rule learner," who viewed her primary task as memorizing rules and algorithms that she practiced until she could apply them flawlessly. She was therefore successful at tasks that required nothing more than application of a rule, even rules that other students had learned and forgotten. She had difficulty, however, when confronted with unfamiliar problems. Herron and Greenbowe argue that Sue's performance isn't unusual, it is typical of many students who are passing courses at all levels.

In a study of the role of analogies in promoting meaningful learning, Gabel and Samuel (1986) argued that a major reason why students have difficulty solving chemistry problems is because they don't understand the underlying chemical concepts. Gabel and Samuel used the dilution of orange juice concentrate as an analog for chemical dilutions and found analogies benefitted about 25% of the students on straight-forward problems that don't involve changing concentrations by adding or removing water, perhaps because they saw the connection between the analogy and the chemistry problems. On the more difficult concentration and dilution problems they concluded that the analogies don't improve problem solving performance because the students don't understand what is happening in the analog situation involving orange juice.

Hesse and Anderson (1992) studied high-school students who had completed a unit on chemical change. The students were given a paper and pencil test that asked them to explain three redox reactions. Clinical interviews were then done with a sample selected to represent a range of achievement levels. Most students failed to invoke atoms and molecules in their explanations. Many students couldn't predict or explain mass changes in the reactions. Their most common problems included a tendency to treat chemical changes as physical changes and their failure to understand the role of invisible reactants or products (such as gases) in the reactions. Many students demonstrated a preference for explanations based on superficial analogies with everyday events over explanations based on chemical theories. A majority of the students indicated that analogies with everyday events were sufficient for their personal explanations, and that chemical explanations were different mainly because they "used fancy words" or "sounded scientific."

In their study of students' understanding of the mole concept and its use in problem solving, Staver and Lumpe (1995) argued that the three primary barriers to successful chemical problem solving are: (1) insufficient understanding of the concepts involved, (2) use of memorized algorithms or rules, and (3) inability to transfer understanding between the atomic/molecular and the macroscopic levels in solving problems.

*Getting the Right Answer for the Wrong Reason*

Lythcott (1990) noted that students often produce right answers to chemistry problems without understanding the chemistry involved. "It is one thing to accept that students who *do not* solve problems correctly do not understand the chemistry; it is another to know that many students who *do* solve problems correctly also do not understand the chemistry involved." One group of her high-school chemistry students was given a set of rules for solving simple mass-mass problems, the factor-label or dimensional analysis algorithm, and practice in using those rules. The other class was taught to solve the problems using general heuristics such as means-ends analysis, working backwards, or trial and error.

Students were asked to solve two simple mass-mass problems out loud. Among students in the prescribed algorithm group, there was a slightly higher percentage of perfectly correct solutions, and of students who scored perfectly on both problems. The percentage of totally inadequate solutions, however, and the percentage of students who had no idea what to do, were also much higher for this group. Interviews suggested that most of the students, especially in the prescribed algorithm group, produced correct solutions to the problems, but with chemistry knowledge that was woefully inadequate.

*Representations*

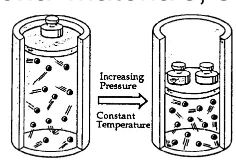
Larkin and Rainard (1984) argued that the internal or mental representation of a problem changes as the problem is worked. The first representation of many problems is the collection of words and sentences that make up its written description. The solver uses these words to build a new representation that includes the objects mentioned in the problem statement and the relationship between these objects. Solving scientific problems requires a third representation, which includes elements that are neither words nor real objects, but scientific "objects" such as pressure and area. Finally, to obtain an algebraic or numerical answer requires a fourth type of representation, which includes algebraic symbols related by operators and equalities.

In analyzing the problem solving behavior of second- and third-year graduate students taking a course in synthetic organic chemistry, Bowen and Bodner (1991) found that students used different representation systems while solving tasks in organic synthesis. They defined a representational system as a collection of interrelated concepts and processes used to solve a problem and communicate the solution to others. Seven representational systems were identified: verbal, pictorial, methodological, principles-oriented, literary, laboratory, and economic. They noted that the choice of representational system used at a given stage in the problem solving process was made with little conscious thought, and movement between representational systems was more or less automatic. They argued that the choice of a representational system is a strategic decision and that tactical decisions are made within the representational system the problem solver chooses.

Domin and Bodner (submitted for publication) studied differences in both the number and types of representations constructed by successful versus unsuccessful problem solvers within a population of first- and second-year chemistry graduate students. Two-dimensional

Fourier transform nuclear magnetic resonance spectroscopy (2D FTNMR) was chosen as the content domain for this study because a variety of representations can be used to express its concepts. Successful problem solvers constructed significantly more representations than those who were unsuccessful. They also were more likely to use *verbal-symbolic* rather than the *verbal-propositional* representations used by the unsuccessful problem solvers. The results of this study support the hypothesis that emerged from related work (Bodner & Domin, 2000) that successful problem solvers construct more representations per problem than those who aren't successful. It is important to recognize, however, that neither group constructed very many representations while solving problems. The successful problem solvers, constructed an average of about 2 representations per problem, whereas those who were unsuccessful constructed an average of just more than 1 representation per problem.

Noh and Scharmann (1997) studied the role of molecular-level pictorial representations on Korean high-school students' problem solving ability. The treatment group in this study was presented with 31 examples of pictorial materials, such as the diagram shown below.



Boyle's Law

Students in the treatment group did better than those in a traditional course on both a chemistry conceptual test and a chemistry problem-solving test. Noh and Scharmann agreed with authors of the literature on conceptual understanding who argue that the ability to solve numerical problems doesn't imply conceptual understanding. But they also questioned the assumption that the ability to solve pictorial problems necessarily implies conceptual understanding.

*Cognitive Variables*

Performance on problem-solving tasks has been correlated with a variety of cognitive variables. Bodner and McMillen (1986) found a significant correlation between performance on spatial ability tests and problem solving on topics such as the structure of solids. What was less expected was a correlation of the same magnitude with performance on multiple-choice stoichiometry questions and a comprehensive final exam. Carter, LaRussa and Bodner (1987) found that performance on spatial ability tests correlated best with exam questions that tested problem solving skills and questions that required students to disembed and restructure relevant information. The correlations were much weaker, or non-existent, for questions that required rote memory or the application of simple algorithms. Pribyl and Bodner (1987) obtained similar results in the sophomore organic chemistry course, where correlations were observed for such highly spatial tasks as mentally manipulating two-dimensional representations of molecules and for exam subscores that focused on higher order cognitive skills, such as problem solving. They concluded that high spatial ability students are better at the stage of problem solving described as "understanding the problem."

Gabel, Sherwood and Enochs (1984) studied the general problem solving skills of 266 high-school students. They noted that students with high proportional reasoning ability tended to use algorithmic reasoning strategies more frequently than low proportional reasoning students. However, the majority of all students solved the chemistry problems using only algorithmic methods, and didn't understand the chemical concepts on which the problems were based.

In contrast, student performance on balancing chemical equations by inspection has been correlated with a battery of tests, including cognitive reasoning ability, cognitive restructuring ability, disembedding ability, working memory capacity, and prior knowledge (Staver & Jacks, 1988). Factor analysis indicated that the reasoning, restructuring, and disembedding variables could be collapsed and redefined as a single "restructuring" variable, which significantly influences overall performance on the problem solving tasks.

Lee, et al., (1996) found that the cognitive variables of "idea association" and "problem translating skill" are the important predictors of success for solving familiar problems. These variables plus problem solving experience, specific knowledge, and relevant but nonspecific knowledge were significant predictors for solving a partially familiar problem, and idea association and problem translating skill are significant predictors for unfamiliar problems.

Johnstone and El-Banna (1986) noted a sigmoidal relationship between problem solving performance and the number of steps required to get to the solution. Niaz (1988) has argued that student performance on chemistry problems decreases as the number of steps or "M-demand" of the problem increases. Niaz (1988, 1989, 1995a, 1995b, 1996) has used the Figural Intersection Test (FIT) developed by Pascual-Leone to measure the M-capacity of students. Students with relatively large M-capacity perform better on questions of a given M-demand; the level of success of all students decreases as the M-demand of the problem increases (Niaz, 1989). Tsaparlis, Kousathana and Niaz (1998) found that the correlation between student performance and the number of steps in the problem solution is low when the number of schemata involved in solving the problem is low, but high when this number is high. Niaz and Robinson (1992) found that even a small increase in the logical complexity of a problem can overcome the advantages students may have gained through training on a similar problem. Niaz (1995a) and deAustdillo and Niaz (1996) have linked the variety of strategies students use in solving problems and transitions in the strategies they use to the notion of progressive transitions proposed by Lakatos.

## TEACHING PROBLEM SOLVING

### *Explicit Instruction*

It comes as no surprise that the success of efforts to improve students' problem-solving performance depends heavily on the way changes in this performance are monitored. Huffman (1997), for example, found that explicit problem solving instruction in high school physics improved the quality and completeness of students' physics representations, but had no effect on conceptual understanding. What might be more surprising is the relative effectiveness of strategies to teach problem solving versus strategies to build problem solving skills.

The relative effectiveness of four instructional strategies on the problem-solving performance of high-school students was studied by Gabel and Sherwood (1983). The four strategies used in this study were the factor-label method, proportionalities, analogies, and the use of diagrams. Although the factor-label method gave the best results, and the proportionality method the worst, the difference between the four methods wasn't large.

Bunce and Heikkinen (1986) studied the effect of using a worksheet that contained seven explicit components of the information processing model on the performance of students in a preparatory college chemistry course. No overall difference in cumulative achievement was observed because few of the students elected to implement the full problem solving approach during tests due to time and space constraints, and the percentage of students using the treatment approach on hour exams decreased as the semester progressed. When the same method was used to teach problem solving in a freshman course for health professionals, Bunce, Gabel and Samuel (1991) found no significant difference in average achievement scores, although a significant improvement was observed for complex problems that involved more than one concept. Analysis of interviews suggested that a “Rolodex approach” to problem solving was employed by students in the study, which involves organizing equations used to solve problems on mental index cards and flipping through them, matching units given when a new problem is to be solved.

*Use of Analogies and Heuristics*

Friedel, Gabel and Samuel (1990) studied whether the use of analogies increases students' conceptual understanding in a preparatory college chemistry course by relating chemistry concepts to everyday life. There was no significant difference between the performance of the treatment and control students, perhaps because the students didn't see a relationship between the chemistry problems and their analogs. Students in the treatment group who had high visualization skills were actually penalized by using analogies. These students apparently became more successful problem solvers by solving additional practice problems (in the control group) rather than by using analogies (in the treatment group). The authors concluded that analogies should be used because they give students a conceptual basis for understanding chemical concepts, such as the mole, and for solving problems that are less routine.

Asieba and Egbugara (1993) taught a system of heuristics for problem solving based on the work of Ashmore, Frazer and Casey (1979) to high-school students. This system emphasized four problem solving skills: definition of a problem, selection of appropriate information, combination of separate pieces of information, and evaluation of the solution to the problem. Students who were taught to achieve mastery of both the problem-solving heuristics and content did better than those exposed to the heuristics and taught for mastery of content or those exposed to the content and taught for mastery of the heuristics.

*Building Problem Solving Skills*

Frank, Baker and Herron (1987) noted that students approach exercises and problems the same way — looking for an algorithm that fits their interpretation of the question. They proposed a way around this difficulty: Solve problems *with* the students, instead of *for* them; ask the students what steps should be taken, instead of running through a well-practiced script. Instead of trying to teach problem solving, this approach builds problem solving skills.

Similarly, Woods (1989a, 1989b) noted that the traditional approach to teaching problem solving has progressed over the years from simply showing sample problems to students (e.g., modeling problem solving behavior) to one in which we verbalize our thought processes and involve students as we solve problems in class. Pestel (1993) argues that this strategy often results in students memorizing how we do problems instead of learning how to solve problems for themselves. She has developed a Think Aloud Pair Problem Solving (TAPS) instructional strategy based on the pair problem solving technique developed by Whimby (1984). One member of each pair acts as the problem solver, the other is the listener. After the problem has been completed, the students switch roles. When student performance was compared, the TAPS class got fewer problems completely right, but they also got fewer problems completely wrong. The conventional class had a greater tendency to get the problems either right or wrong. Pestel argues that the fewer students getting completely correct answers may be a result of fewer students memorizing templates and solving problems on that basis.

*Working in Groups and In-Class Cooperative Learning*

Students can become more effective learners by working together in groups. Ross and Fulton (1994) used this approach in a two-course analytical sequence. Although the students worked in groups, they were individually assessed on the basis of a 30-minute oral exam. The course covered the same content and the students did roughly the same on standardized exams. Ross and Fulton report a significant improvement in student attitudes toward learning and motivation; improved attendance; and students who were more self-motivated and more satisfied with the course and with their own performance in the course.

Students' problem solving skills can also be improved by the use of in-class group discussions (Fasching and Erickson, 1985). At the end of the semester, about 40% of the students had some idea about how to proceed with complex questions, which suggests that some students developed reasoning and problem solving skills. They noted a dramatic improvement in students' opinions of the course and invoked Perry's "dualism" to explain the 20% of the students who found the course frustrating.

Tingle and Good (1990) studied the effect of cooperative groups based on differences in proportional reasoning ability on problem solving in high school chemistry. There was no significant difference in the performance of students who had been problem solving individually or in cooperative groups. But they noted that most students who had been solving problems individually weren't as persistent as those who had been working in groups. These students also exhibited anxiety and frustration and tended to seek help from the teacher more often.

The use of in-class cooperative learning activities has been studied in a graduate-level thermodynamics course (Towns and Grant, 1998). Towns and Grant found that these strategies moved students away from rote learning, toward more meaningful strategies that allowed them to integrate concepts over the entire semester. They also found that sharing insights and ideas among students leads to the development of interpersonal and communication skills that the students perceived as an important component of the discussion sections.

Robinson and Niaz (1991) studied the performance on stoichiometry problems of students in a preparatory chemistry course. The control group was taught by traditional lectures, while the treatment group was taught by an interactive technique. Although fewer examples were covered in the treatment group, students in this group were more successful in solving chemistry stoichiometry problems than those in the lecture group. In both groups, the students with better formal reasoning skills outperformed students with lower formal reasoning scores. The intervention seemed to be particularly powerful for students with low information-processing capacities (e.g., M-capacity).

Problem-based learning (PBL) shares many of the attributes of the cooperative learning experiments described above, with the added characteristic that the problem is "realistic," e.g., similar to the types of problems the students may encounter in their professional futures (Smith, Powell, & Wood, 1995). PBL assumes that it is more important for students to know how to *apply* their knowledge than to *remember* information. PBL originated in medical schools; thus, it isn't surprising that PBL has been used most often in biochemistry courses. Smith and co-workers note that PBL-trained students are more frequent users of libraries and other information resources that support independent learning. They also note that PBL doesn't significantly improve problem solving skills in general, and, in fact, PBL students tend to score lower on tests of basic science and have gaps in their knowledge. Dods (1996, 1997) has used PBL in a biochemistry course at a high school for talented students. Topics covered were traditional and arranged in a traditional manner. PBL didn't lead to a significant improvement in learning, but it led to significantly greater retention of content knowledge. The students liked the fact that the course focused on real biochemical problems, reported working in a collaborative manner, reported encountering less content material than they would have in a conventional course, but believed they learned the material more thoroughly. Dods argued that PBL promotes in-depth understanding, but content coverage is promoted by lecture.

*Different Ways Students Respond to Conceptual Problems*

Phelps (1996) studied an intervention based on an emphasis on conceptual problem solving. Much of the power of her study results from the fact that she implemented this technique in both a general chemistry course for science majors and a course for nursing and liberal arts students. Many of the same tasks were used in both courses. The very different responses these tasks elicited from the two groups of students were striking. Throughout the semester, the science majors were less willing to interact and ponder the problem at hand.

The difference between the two groups went beyond their willingness to respond to class questions, however. The science majors focused on the numbers throughout the course. When the in-class task involved nonnumerical problem solving, they would copy down the problem and patiently wait for the authority to provide the solution that they meticulously copied into their notebooks under the question.

The nonscience majors interacted more with the teacher and with each other. They used time in class to try conceptual problems and this eventually carried over to numerical problems as well. They wondered aloud and freely shared their interpretations of what they observed. Initially, the nonscience majors were hesitant to comment for fear of being wrong, but once they were convinced that being wrong was an accepted part of class discussions, they asked good questions.

Phelps concluded that using a more conceptual focus for these chemistry courses had many positive results for the students in both courses. The students in the nonscience major course showed more enthusiasm for the course, attended more regularly, and complained less frequently. These students were less resistant to chemistry and more involved in the course. The interest gained by focusing on the underlying concepts increased their general interest in chemistry to the point that they were even willing to tackle mathematical problems when they arose. She argued that the science majors were disequilibrated because this approach to chemistry wasn't consistent with their expectations for the nature of chemistry or the chemistry classroom. The students fought the change at first by simply refusing to interact. According to their prior experience, chemistry was about problem solving and problems had to have numbers. As the semester progressed, the women and minority males were the first to accept the protocol. These groups became the dominant responders both in and out of class. Although the science majors initially resisted the change in approach, they did ultimately benefit from it.

A new model for classroom instruction known as process workshops has been proposed by Hanson and Wolfskill (2000). They define a process workshop as "a classroom environment where students are actively engaged in learning a discipline and in developing essential skills by working in self-managed teams on activities that included guided discovery, critical thinking, and problem solving and include reflection on learning and assessment of performance. Significant improvements were reported in both student attitude toward chemistry and student performance on exams.

## FUTURE RESEARCH IN PROBLEM SOLVING

It should come as no surprise that most of the work on problem solving in chemistry, so far, has focused on the courses that serve the largest number of students — the introductory courses for high school and college or university students. As this review has noted, however, we are starting to see the results of research on problem solving in more advanced courses. Studies that were recently completed or are presently underway at Purdue University, for example, are examining some of the following questions:

- How do students in the sophomore-level organic course solve problems that ask them to predict the product of a chemical reaction, or to plan the synthesis of a molecule?
- How do beginning graduate students solve organic synthesis problems, and how does this compare to the approach taken by practicing organic chemists?
- What changes occur in the process individuals use to interpret NMR spectra as they progress from first-year graduate students to practicing organic chemists?
- What sense do beginning students make of the "arrow-pushing" symbolism used to describe organic reaction mechanisms?
- What differences occur in the way students predict the product of simple inorganic reactions as one compares students in general chemistry to undergraduate chemistry majors to graduate students in chemistry and finally to practicing inorganic chemists?

Preliminary results have also been obtained in a study of students' conceptual understanding of quantum mechanics that are relevant to the problem-solving literature. This work has found that a "problem-solving mindset" generated during students' exposure to other chemistry courses can interfere with their performance on tasks in quantum mechanics, which have a fundamentally different structure from the tasks encountered in earlier courses (Gardner and Bodner, 2001).

## CONCLUSION

Despite hundreds of studies over a quarter of a century we are a long way from understanding why problem solving is difficult or what we can do to make it simpler. Part of the difficulty is that chemistry problems differ so greatly. It is doubtful that students in a graduate level organic course fail to solve synthesis problems for the same reasons that beginners can't do stoichiometry. Consequently, we need several research programs focusing on various kinds of problem solving at different school levels. The problems used in the research need to be carefully characterized so that the results of research can be generalized with greater confidence.

Problem solving research has provided strong evidence that our students, successful as well as unsuccessful problem solvers, don't grasp the concepts very well. Indeed, one of the most important contributions of research in this area has been the revelation of just how poorly students may understand the ideas underlying problems they have answered correctly. This, in spite of the fact that teachers frequently justify their emphasis on numerical problem solving by arguing that it enhances conceptual understanding. We need research that will clarify the relationship between conceptual understanding and success in problem solving. Must a qualitative understanding of ideas precede quantitative reasoning based on those ideas? Or is it possible that mastering algebraic manipulations in an area provides a basis on which a conceptual understanding can be built? To what extent does the quantitative work enhance understanding? Under what conditions?

Regardless of whether the tasks in a given study are algebraic or conceptual, most of the research on problem solving in chemistry has focused on topics that lend themselves to mathematical problem solving, such as stoichiometry or gas law problems. Chemists, however, are routinely involved in non-mathematical problem solving such as organic synthesis or the interpretation of spectra. Are significant differences between the way chemists solve problems in the mathematical and non-mathematical domains of chemistry? What are the characteristics of a good non-mathematical problem solver?

Research has shown that the way problems are represented has considerable bearing on how quickly (or whether) they are solved, but we know very little about the factors that influence representations or how to teach students to generate effective representations. Research that focuses on teaching effective representational strategies for a well defined class of problems might pay handsome dividends.

Research has shown that we can't teach problem solving, but there is evidence that certain approaches to instruction can improve students' problem solving skills through group work. There is much to be learned, however, about effective use of either cooperative or collaborative approaches to building problem solving skills (Shibley and Zimmaro, 2002). We need to understand the interactions that occur when groups work effectively, the role of a leader, how the group leader is selected (or rejected), how group work can be enhanced, the characteristics of ineffective groups, and so on. We know that significant learning occurs in socially mediated environments among practicing chemists, from graduate school on, and yet we know so little about socially mediated learning among beginners. We also know relatively little about the changes that occur in problem-solving skills as individuals go through the progression of experiences from their first exposure to chemistry in high school through the completion of a graduate degree.

We have found examples of graduate students trying (usually without success) to use knowledge from inorganic chemistry to solve problems in organic synthesis, and we've found examples of undergraduates and graduate students failing in their attempts to use models from organic chemistry to solve problems in inorganic chemistry courses. But we know relatively little about barriers that interfere with effective transfer of problem-solving skills across domain boundaries.

At Purdue, we are looking at the relationship between research on problem solving in chemistry and work that has been done on the "problem solving" involved in the act of writing. There are many other connections that should be examined between what chemists are learning about problem solving and work in other content domains. The work on situated learning (Lave and Wenger, 1991) comes to mind, for example. Lave and Wenger argue that learning occurs as a result of participation in communities of practice. Instead of focusing on cognitive processes and conceptual structures, they suggest examining the kinds of social interactions that provide the proper context for learning to take place. Links should also be pursued between the work on model and model eliciting activities (Lesh, et al., 2000) and both problem solving in chemistry and ways to improve the problem solving skills of our students.

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