Research in Problem-Solving:
Improving the Progression from Novice to Expert

Roxi Finney

Abstract: This paper presents a review of research in problem solving. The first section includes various research papers across multiple disciplines which call for the need to improve the problem solving skills of students and the need to improve the methods of teaching problem solving skills. Many arguments are presented for the importance of research in this area. The second section defines and describes the various types of problems presented to students and presents research projects dealing with problem types. The final section provides information about novice and expert problem solvers, including characteristics of each. Several research papers are listed which focus on studies aimed to improve the progression from novice to expert. Results of this review suggest problem solving skills cannot be improved through explicit instruction in problem solving, but may be improved through increased instruction in conceptual chemistry.

I. The Need for Research and Reform

"Many instructors, myself included, have believed (or hoped) that teaching students to solve problems is equivalent to teaching the concepts. If, as is now being proposed, this axiom is not true, then we all must rethink our approach to chemical education." (Sawrey, 1990)

In 2000, Cohen, Kennedy-Justice, Pai, Torres, Toomey, DePierro and Garafalo published a paper on improving quantitative problem solving in chemistry. In this paper, the authors address the problems associated with introductory-level students engaging in quantitative problem solving activities without having a strong understanding of the algorithms (problem solving strategies that may or may not involve mathematical equations) or equations they use to solve such problems. Without understanding fundamental mathematical concepts used in solving problems, such as the meaning of ratios, problem solving has the potential of becoming "an exercise in mere symbol manipulation" as described by Cohen et al. For example, introductory students may memorize the algorithm for converting moles to grams as such:

To convert from moles to grams, multiply by the formula weight.

While this algorithm is correct in the sense that it will give the correct answer, it shows no understanding of the physical situation at hand. An introductory student lacking in conceptual knowledge may not understand why this algorithm works. They will, however, be able to correctly apply this meaningless algorithm to homework and exam questions. Using this algorithm without conceptual understanding does not enhance or improve a student's problem solving abilities.

Cohen et al. (2000) respond to this common occurrence by proposing "meaningful" problem solving in the classroom. When students are solving quantitative problems, instructors should not be satisfied with numerically correct answers. Rather, they should require students to demonstrate their conceptual understanding of every aspect of the problem, including the equations and ratios used to solve the problem. Cohen et al. propose that this process of developing conceptual understanding of problem solving should occur at the secondary level, as it requires more time than may be available in a college course.

"If a student's first response is to decide which algorithms to use, then he or she is not solving a problem at all." (Frank, Baker & Herron, 1987)

Additional publications (Bodner, 1987; Fortunato, Hecht, Tittle & Alvarez, 1991; Frank et al., 1987; Halmos, Moise & Piranian, 1975; Nurrenbern & Pickering, 1987) reiterate the need to supplement the use of algorithms with conceptual understanding of the entire process of problem solving. Students should not be taught to rely entirely on algorithms or equations to solve problems. Algorithms or equations, such as the mole to gram conversion described above, are shortcuts to solving commonly encountered exercises. These shortcuts lose their value when the student encounters a problem for which their algorithm is not appropriate. For example, the mole to gram conversion could not be directly applied to a problem requiring the student to convert from gram to mole.

If the student is equipped with a strong conceptual understanding of this topic (stoichiometry), they will see the similarity of the two problems and will be able to arrive at a solution with minimal complications. On the other hand, if the student lacks a solid conceptual understanding of stoichiometry, they may not recognize the relationship between the two problems. They may seek out and memorize a separate algorithm for converting grams to moles.

When a student approaches a problem by asking themselves the question, "Which equation do I use to find the answer?" that student has not learned good strategies for solving problems. By focusing directly on an equation, the student bypasses critical steps in the problem solving process, such as determining the type of problem or forming valuable problem representations. This automatic response to seek out an equation may stem from typical homework assignments, such as those found in the back of textbooks, where problems are grouped by the algorithm used to obtain the solution. This repetitive application of identical algorithms eliminates crucial steps in the problem solving process, such as understanding the conceptual nature of the problem. This presents students with an inadequate problem solving experience.

"Chemistry teachers have assumed implicitly that being able to solve problems is equivalent to understanding of molecular concepts." (Nurrenbern & Pickering, 1987)

Chemical educators (Nurrenbern & Pickering, 1987; Pickering, 1990; Sawrey, 1990; Yarroch, 1985) emphasize the need for instructors to recognize the common disconnection between conceptual understanding and problem solving ability. In the studies cited above, researchers found that students are significantly more successful at solving traditional quantitative problems (applying an algorithm or equation) than they are at solving conceptual qualitative problems (representing a system at the molecular level) of a similar level of complexity.

In separate studies, Nurrenbern and Pickering (1987), and Sawrey (1990) found that some students could correctly solve problems pertaining to the ideal gas law without being able to represent the behavior of gases at the molecular level. Both studies also found that some students could solve stoichiometry problems without being able to represent the reaction with an illustration. Yarroch found that some students could correctly balance chemical equations, but could not sketch a diagram of the chemical equation or explain the meaning of coefficients or subscripts in molecular formulas. In the conclusions to their study, Nurrenbern and Pickering state that teaching students how to solve chemistry problems is entirely different from teaching students about chemistry, and that achievement in one area does not guarantee achievement in the other.

II. What is a Problem?

"Whenever there is a gap between where you are now and where you want to be, and you don't know how to cross that gap, you have a problem." (Hayes, 1981)

Overuse of the word "problem" is prevalent in the chemistry classroom and science education literature. "Problem" has been used to refer to everything from simple worked-out exercises within the chapter of a textbook to complicated research questions. As a result, many researchers have taken measures to classify and define various forms of problems. At a minimum, these researchers recognize the difference between an exercise and a problem. Distinguishing exercises from problems cannot be done without consideration of the problem solver (Bodner, 1987; Lyle & Robinson, 2001). When a student is faced with a problem that he or she knows how to solve, it is correctly defined as an exercise. It is only when the student lacks sufficient knowledge to produce an immediate algorithm (strategy) for the solution that a problem is truly a problem. After a student solves a particular problem, that problem becomes an exercise.

Problems are further described as being well-structured or ill-structured (Brabeck & Wood, 1990; Jonassen, 1997; Shin, Jonassen & McGee). Well-structured problems have a known solution and provide all information necessary for solving the problem. They require the use of a limited number of concepts and are arranged in a predictable manner. They often have a preferred method of solution; however, when used appropriately, multiple methods of solution will produce the same correct result. All solutions to a well-structured problem can be deemed either “correct” or “incorrect.”

In contrast, ill-structured problems may have multiple solutions or, in some instances, no solution at all. Ill-structured problems may not present all the information necessary for solving the problem. They may integrate multiple concepts and sometimes provide very little information about the concepts relevant to the problem. Ill-structured problems have multiple solution paths. Solutions are very difficult to evaluate, as the goal of an ill-structured problem is often vague. Ill-structured problems require the student to make multiple decisions or judgments about the problem: What is the goal? What concepts are used to solve the problem? How can I obtain a solution? Does this solution meet the goal of the problem?

Well-structured problems have also been classified as being either “generic problems” or “harder problems” (Middlecamp & Kean, 1987). While this terminology is less common, it is nonetheless valuable to recognize a continuum of complexity within well-structured problems. Generic problems are defined as being straight-forward and without extra information. They can be solved by the simple application of an algorithm or equation. Harder problems are more complicated, sometimes contain extraneous information, often require the integration of more than one concept, are unfamiliar or are presented in unfamiliar terms. In addition, solving harder problems requires more than the simple application of an algorithm.

The following table summarizes the four types of problems described above.

Type of Problem	**Characteristics**	**Solution Path**
Exercise	The student can immediately recall an algorithm for solution	Apply the recalled algorithm (solution strategy)
Generic Well-Structured Problem	The problem and goal are clearly stated and familiar to the student	Understand the problem, recall an algorithm, apply it to the problem, and reflect on the solution
Harder Well-Structured Problem	The problem and goal are clearly stated but unfamiliar to the student	Understand the problem, formulate or recall an algorithm, apply it to the problem, and reflect on the solution
Ill-Structured Problem	The problem and goal are unclear; information is missing	Determine the goal, formulate an algorithm, apply it to the problem, and reflect on the solution

Solving an exercise, therefore, involves reading the exercise and recalling the appropriate algorithm. In contrast, solving a problem involves reading and understanding the problem, formulating a strategy, applying the strategy to produce a solution, and then reflecting on the solution to ensure that it produced an appropriate result (Bodner, 1987).

Examining well-structured and ill-structured problems and problem solving abilities is an active area of research in science education. In one study (Shin et al., 2003), researchers aimed to determine the factors that predict success in well- and ill-structured problem solving ability. Results showed that both well- and ill-structured problem solving ability was dependent upon an integrated and organized knowledge base and justification skills. In addition, ill-structured problem solving was also found to be dependent upon personal experiences related to the context of the problem. Metacognition was found to be important in solving unfamiliar ill-structured problems, while science attitude was found important in solving familiar ill-structured problems.

Another study (Brabeck & Wood, 1990) aimed to determine if ill-structured problem solving ability was dependent upon well-structured problem solving ability. Results showed that students can continue to develop their ability to solve ill-structured problems without demonstrating any change in their ability to solve well-structured problems. This indicates that abilities to solve the two types of problems are unrelated.

Understanding the differences between problems (primarily generic and harder well-structured problems) and exercises is of significant importance when considering the teaching of chemistry. Most (if not all) questions posed to students are exercises to the instructor. Therefore, instructors often demonstrate solving these questions as exercises: they simply apply the appropriate algorithm. Many instructors fail to recognize that these questions/exercises are true problems for students. As a result, students are incorrectly taught to solve problems by seeking and applying algorithms. They are not taught to seek conceptual understanding of the problem, nor are they taught to formulate strategies based on their current knowledge.

III. The Novice and the Expert

"We 'explain' superior problem-solving skill by calling it 'talent,' 'intuition,' 'judgment,' and 'imagination.' Behind such words, however, there usually lies a reality…" (Larkin, McDermott, Simon & Simon, 1980)

Success in problem solving is based on two factors: Knowledge base and skills base (Gick, 1986; Taconis, Ferguson-Hessler & Broekkamp, 2001). Knowledge base consists of knowledge within a particular subject, such as the ideal gas law, as well as general or "common" knowledge. Skills base consists of specific cognitive activities or abilities, such as the ability to rearrange equations to isolate a variable. The difference between knowledge base and skills base can be illustrated with the following example:

> *Given that a 1.0 L glass bulb contains 2.5 mol* H_2 *at 20°C, what is the pressure inside the bulb?*

Using their knowledge base, the student *understands* this problem can be solved using the ideal gas law, and that to solve the problem they must isolate the pressure (P) variable. Using their skills base, the student *does* correctly isolate and solve for pressure.

When an individual has both a strong knowledge base and skills base in a particular area, that person is able to solve problems in that area quickly, without hesitation, and with a high degree of accuracy. This combination of knowledge and skills is characteristic of an expert problem solver (Gick, 1986; Taconis et al., 2001; Larkin et al., 1980; Sweller, 1988). Expert problem solvers have been found to possess the following additional characteristics:

- Experts categorize problems before attempting to solve them, which aids in recall of knowledge relevant to the problem (Bunce, Gabel & Samuel, 1991; Chi, Feltovich & Glaser, 1981)
- Experts categorize and store problems in memory based on the concepts featured in the problem (Bunce & Heikkinen, 1986; Gick, 1986; Sweller, 1988)
- Experts construct representations of the problem, such as sketches or verbal descriptions, based on the actual physical situation of the problem (Bunce & Heikkinen, 1896; Gick, 1986)
- Experts solve problems by working forward from the given quantities to the solution (Gick, 1986; Larkin et al., 1980; Sweller, 1988; Ward & Sweller, 1990)

"If students cannot correctly categorize a problem, they will not be able to retrieve pertinent information from long-term memory for use in solving it." (Bunce et al., 1991)

A great deal of research has been conducted in the area of problem categorization. Chi et al. (1981) conducted a research study on the difference between expert and novice categorization of physics problems. In the first part of their study, subjects were presented with 24 physics problems and asked to group the problems by similarity. From this, they found that experts form groups based on the concepts or principles represented in the problem, such as Conservation of Energy. In contrast, novices form groups based on the surface features of the problem, such as pulleys or inclined planes. This has implications on the ability of a novice problem solver to recall or formulate appropriate algorithms.

Following this study, Bunce et al. (1991) conducted a research study on categorization of chemistry problems. Based on the findings of Chi et al. (1981), the researchers in this study investigated the effect of providing students with instruction and practice in problem categorization. Students showed an improvement in ability to solve multiple-concept (combinational) problems when provided with specific instruction and extra practice in problem categorization. However, the same students showed no significant improvement in ability to solve single-concept problems. Furthermore, through student interviews on problem categorization, the researchers found additional evidence for the lack of connection between successful problem solving and conceptual understanding of chemistry.

"During construction of a problem representation, certain features of the problem may activate knowledge in memory. A schema for that particular type of problem may then be activated." (Gick, 1986)

In 1986, Bunce and Heikkinen reported on a study in which they attempted to improve the problem solving skills of chemistry students by teaching them an "explicit approach to problem solving." In this approach, students were taught to state the problem using words, sketch the problem, recall concepts relevant to the problem, create a solution diagram, solve the problem, and review the solution process. This step-wise process of problem solving required students to mimic expert problem solvers by carrying out problem representation in multiple ways: Verbally representing the problems, sketching out the problem, and diagramming the solution process. Results showed no significant improvement in problem solving ability. In addition, the researchers found that 54% of the students claimed the problem solving approach was too time consuming and, on any given hourly exam, no more than 44% of the students actually applied the problem solving approach.

"…working backward is usually thought to be a more sophisticated strategy than working forward. But experts work forward…" (Larkin et al., 1980)

Larkin et al. published a paper in 1980 to report the results of a study in which they examined problem solving in physics. By asking subjects to "think aloud" while solving problems, they determined that novices solved problems by working backward, while experts solved problems by working forward. When solving problems, novices start by selecting an equation that contains the goal of the problem. If that equation contains additional unknown variables that are not provided in the statement of the problem, the novice selects a second equation to solve for those unknown variables. This process is repeated until all variables are known or can be solved. The novice then works forward through the series of equations generated in the working backward strategy. In contrast, experts start by applying an equation to the information provided in the statement of the problem. If this equation does not produce the goal of the problem, experts will apply additional equations to the newly calculated information until the goal is met (Gick, 1986).

Sweller (1988) found that when novices are forced to employ a working forward strategy, they generate significantly fewer mathematical errors than novices who are not forced to work forward. In his study, Sweller compared students solving traditional trigonometry problems to students solving problems with nonspecific goals. Students solving traditional problems were not forced to work forward. Students solving problems with nonspecific goals were presented with information and asked to calculate everything they could. Because these students were not presented with a goal, these students were forced to use a working forward strategy. Sweller attributes the difference in mathematical errors to the difference in cognitive load between the two groups of students. Working backwards demands a large cognitive load and leaves little for carrying out calculations. Students who were forced to work forward, therefore, had more working memory to devote to calculations and made fewer mathematical errors.

In 1990, Ward and Sweller published the reports of a similar study aimed at examining the effects of a reduced cognitive load. In this study, students were presented with worked examples in contrast to being required to solve problems on their own. Results showed that students who studied worked examples were able to solve test problems with significantly more accuracy than students who were required to solve their own practice problems. In addition, students who studied worked examples had greater success in solving transfer problems than students required to solve their own problems.

IV. Conclusions

In the first section of this review, publications were presented which described the need for research in problem solving. All of these publications addressed the reality that many students who are lacking conceptual understanding of a topic are nonetheless capable of successful problem solving in that same topic. Authors of these publications called for instructors to supplement instruction in problem solving with separate and specific instruction of concepts. They suggested that the common homework "drills" encouraged this meaningless problem solving among students. They urged instructors to require their students to demonstrate conceptual understanding on exams. The underlying message of this section was that classroom problem solving does not lead to conceptual understanding. Conceptual understanding must be taught specifically and implicitly.

In the final section of this review, publications were presented which described the differences between expert problem solvers and novice problem solvers. However, regardless of the many unique characteristics of the expert problem solver, the underlying difference between experts and novices is their knowledge base and skills base. Experts solve problems faster and with a higher degree of accuracy because their skills base is highly developed. Experts categorize problems based on the conceptual nature of the problem because they have a heightened knowledge base. Experts form multiple representations of problems because their strong knowledge base supports this type of performance. Experts solve problems with a working forward strategy because their experience, combined with knowledge and skills, permits them to do so with confidence.

Efforts at training novice students to undertake expert problem solving strategies have, for the most part, been unsuccessful. This further validates the dependence of expert problem solving on knowledge base and skills base. Novices cannot solve problems fast or with a great deal of accuracy because they lack strong skills. Novices categorize problems based on surface features, not concepts, because they lack conceptual understanding. Novices cannot form multiple problem representations because their knowledge base is weak. Novices work backward to solve problems because they do not have enough experience to work forward with confidence.

To improve the problem solving skills of students, instructors must first focus on developing students' knowledge base and skills base. Without these tools, students will never succeed in true problem solving. Heavy emphasis should be placed on conceptual understanding of topics; secondary emphasis should be placed on carrying out and completing drills and exercises.

At the same time, instruction in problem solving should still continue in the chemistry classroom. Research by Sweller (1988) and Ward and Sweller (1990) showed that reducing cognitive load led to statistically significant learning gains for mathematics and physics students. Their methods of reducing cognitive load by presenting students with problems that had non-specific goals and by presenting students with worked examples could easily be translated to a chemistry classroom. On a small scale, this could be accomplished by instructor-generated handouts to supplement the traditional classroom. On a larger scale, this could be accomplished through the modification of textbooks and other widely distributed instructional materials. These styles of problems would still allow students to develop their skills base and would still provide exposure to the equations and algorithms central to problem solving in chemistry. However, the reduced cognitive load accompanying these problems would permit students to direct more attention to building their conceptual understanding and knowledge base. This, ultimately, would heighten their success in chemistry and would advance their problem solving progression from novice to expert.

V. Annotated Bibliography

Bodner, G., (1987). The role of algorithms in teaching problem solving. *Journal of Chemical Education, 64,* 513-514.

> This is an excellent paper on teaching problem solving. The author provides a good definition of an algorithm and explains how they are used in problem solving. In addition, he contrasts exercises and problems, and gives examples of both. The underlying message is that defining a problem as a problem is based on the person attempting to solve the problem. In closing, he proposes that problem solving be taught the way that it is conducted. When a person solves a problem, they go through a series of steps that involve a trial-and-error process. However, when students are "taught" to solve a problem, the "teaching" includes only a description of the steps and algorithms necessary to arrive at a solution. This does not expose students to the true steps of solving problems, and therefore does not prepare them to solve problems in the future.

Brabeck, M. M., & Wood, P. K. (1990). Cross-sectional and longitudinal evidence for differences between well-structured and ill-structured problem-solving abilities. In Commons, M. L., Armon, C., Kohlberg, L., Richards, F. A., Grotzer, T. A., & Sinnott, J. D. (Eds.), Adult development 2: Models and methods in the study of adolescent and adult thought (pp 131-146) New York: Praeger.

> This chapter presents research that tested the relationship between the ability to solve well-structured problems and ill-structured problems. The ability to solve ill-structured problems was measured by the Reflective Judgment Interview, and the ability to solve well-structured problems was measured by the Watson-Glaser Critical Thinking Appraisal. A description of both types of problems is presented. The authors present some interesting ideas, but the research is questionable.

Bunce, D. M., Gabel, D. L., & Samuel, J. V., (1991). Enhancing chemistry problem-solving achievement using problem categorization. *Journal of Research in Science Teaching, 28,* 505-521.

> In this study, the researchers teach students how to categorize mathematical problems in chemistry (for example, "stoichiometry") and then examine how this categorization affects their success in problem solving. The results show that teaching categorization skills does not alter a student's ability to solve single-concept problems in chemistry. However, it does increase a student's ability to solve problems with more than one concept, and it enhances their achievement on unannounced evaluations. The paper has an extensive introduction and some good arguments for conducting research in problem solving, but is otherwise not too exciting.

Bunce, D. M., & Heikkinen, H., (1986). The effects of an explicit problem-solving approach on mathematical chemistry achievement. *Journal of Research in Science Teaching, 23,* 11-20.

> This paper describes a study in which the researchers implemented a curriculum focused on teaching general chemistry students how to solve problems. The students were trained to follow a series of problem solving steps with hopes that they would improve their ability to successfully solve mathematical problems in chemistry. Results showed no improvement in problem solving success with the trained students. Furthermore, nearly one half of the students reported that the problem solving steps were too time consuming. Only 24-44% of students actually implemented the problem solving steps on exams.

Chi, M. T. H., Feltovich, P. J., & Glaser, R., (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5,* 121-152.

> This paper compares problem solving of experts and novices. In this study, the researchers focus on categorization of problems in attempt to understand more about the differences between experts and novices. The results of the research show that experts create problem categories based on the major physics principle(s) used to solve the problem, while novices create problem categories based on "surface features." These surface features refer to superficial aspects of the problem, such as the involvement of springs or inclined planes.

Cohen, J., Kennedy-Justice, M., Pai, S., Torres, C., Toomey, R., DePierro, E. & Garafalo, F., (2000). Encouraging meaningful quantitative problem solving. *Journal of Chemical Education, 77,* 1166-1173.

> Problem solving is a challenging aspect of science education. For many students, problem solving becomes an exercise of symbol manipulation or a challenge of memorizing formulas or patterns, as they lack the ability to successfully solve problems independently. Instruction in problem solving techniques, including explanations and examples, has shown to be of little value in helping students become better problem solvers.

Fortunato, I., Hecht, D., Tittle, C. K., & Alvarez, L., (1991). Metacognition and problem solving. *Arithmetic Teacher, 39,* 38-40.

> This is a short but very interesting paper on a survey used to measure the metacognition of 7th grade students while solving math problems. The survey and results are included. The authors suggest that, when teaching problem solving, students should be encouraged to re-read the problem, determine its main ideas, collect data from the problem, and determine a method of solution. The focus should be moved away from the actual solution and moved towards the problem solving process.

Frank, D. V., Baker, C. A., & Herron, J. D., (1987). Should students always use algorithms to solve problems? *Journal of Chemical Education, 64,* 514-515.

In this paper, the authors call for a reform in the way exercise/problem solving is taught in the classroom. The authors propose that algorithms are misused and too heavily relied upon in the classroom. When faced with a true problem (as opposed to an exercise), students are often hindered by their classroom experiences of using algorithms as shortcuts. Students are generally not taught to ask about the nature of the problem or to seek out a solution. Rather, they are taught to find the appropriate algorithm and apply it. (The difference is very small, but very significant.) Furthermore, the authors propose that repeating similar problems creates a comfortable habit that is difficult to break. In addition, grouping homework problems with a title "Charles's Law Problems" eliminates the need to determine what type of problem they are facing, and therefore stunts their growth in problem solving.

Gick, M. L., (1986). Problem-solving strategies. *Educational Psychologist, 21,* 99-120.

This paper presents a good background on research in problem solving in several educational areas. The author provides a description of problem solving strategies, focusing on schema-driven vs. search-based problem solving strategies. In addition, an extensive amount of comparison between expert problem solving and novice problem solving is discussed. For example, experts solve problems by working forward, from the problem to the solution, while novices solve problems by working backwards, from the desired solution to the needed problem. Problem solving by analogy and the use of worked examples is also discussed.

Halmos, P. R., Moise, E. E., & Piranian, G., (1975). The problem of learning to teach. *The American Mathematical Monthly, 82,* 466-476.

This paper is divided into three parts, the first of which is titled "The Teaching of Problem Solving." This part provides suggestions on how to teach problem solving skills within the classroom, focusing on encouraging students to ask questions and formulate their own problems. The author of this section (Halmos) states that many students are capable of applying algorithms to solve familiar problems, but are not able to apply the same algorithm to an unfamiliar, or "special" problem. The paper is very motivational in nature, but is not based on research, nor does it refer to research.

Hayes, J. R., (1981). The complete problem solver. Pennsylvania: The Franklin Institute Press.

> This is a how-to book on solving problems. It includes some interesting brainteasers, describes the process of problem solving, includes information on representation, working backwards, and ill-structured problems. Other aspects of problem solving are presented, including the effect of creativity, memory, and justification. This book has so many examples that it is very interactive and easy to read. It is fundamental in problem solving research.

Jonassen, D. H., (1997). Instructional design models for well-structured and ill-structured problem-solving learning outcomes. *Educational Technology Research and Development, 45,* 65-90.

> This is an excellent article that gives a very thorough introduction to problem solving. The author provides extensive definitions of "all" the different kinds of problems. He presents a series of steps which represent the problem solving process. In addition, he proposes a series of steps to follow when teaching well-structured problems and ill-structured problems.

Larkin, J., McDermott, J., Simon, D. P., & Simon, H. A., (1980). Expert and novice performance in solving physics problems. *Science, 208*, 1335-1342.

> This paper gives a very descriptive and unique comparison of expert and novice problem solving. The authors provide several analogies that are useful in identifying the traits of an expert problem solver. Four differences between experts and novice problem solvers are identified, including the working-forward vs. working-backward approach as well as the idea that novices distinguish finding an algorithm from substituting unknown variables into the algorithm from generating a solution, while the expert recognizes those three steps as only one. The focus of this paper is to review several computer programs that were designed to mimic the traits of expert and novice problem solvers, with hopes that new information would be revealed about how experts and novices differ. This part of the paper is not too interesting or useful.

Lyle, K. S. & Robinson, W. R., (2001). Teaching science problem solving: An overview of experimental work. *Journal of Chemical Education, 78,* 1162-1163.

> When a student is presented with a problem that they know how to solve, either through a memorized algorithm or through examples worked in class, the problem is not recognized as a "true" problem, but rather as an exercise. True problems only exist when a student is presented with a problem that they do not know how to solve, and therefore true problems require students to derive their own strategy from their knowledge base and skills base. Traditional methods for teaching students how to solve problems (giving examples, focusing on the steps, and following up with practice problems) are ineffective and need to be modified.

Middlecamp, C. & Kean, E., (1987). Generic and harder problems: Teaching problem solving. *Journal of Chemical Education, 64*, 516-517.

The authors propose classifying problems as being either “generic” or “harder” and give descriptions of the characteristics of each. Generic problems are those that are clearly and simply worded, and do not contain much (if any) extraneous information. Harder problems are those without an algorithm or those that present familiar information in an unfamiliar context.

Nurrenbern, S. C., & Pickering, M., (1987). Concept learning versus problem solving: Is there a difference? *Journal of Chemical Education, 64,* 508-510.

The authors provided statistical evidence that the ability to solve problems in stoichiometry and the gas laws does not imply conceptual understanding of the topics. Students were presented with pairs of questions that included a traditional equation-based problem as well as a conceptual non-mathematical problem. Students showed greater success with the traditional problems than the conceptual problems. The authors conclude that teaching students how to solve problems does not lead to conceptual understanding of the topic.

Pickering, M., (1990). Further studies on concept learning versus problem solving. *Journal of Chemical Education, 67,* 254-255.

This publication is a follow-up to research done by Nurrenbern and Pickering (1987). In this paper, the author follows students to their organic class and compares their ability to solve general chemistry concept problems to their success in organic chemistry. Results initially show that students who are successful at solving concept problems achieve slightly higher scores in organic chemistry. However, a carefully constructed pairing study shows that students who perform equally overall in general chemistry (regardless of their conceptual understanding) will perform equally in organic chemistry. This, along with other studies, show that there is not two “types” of students – conceptual vs. not conceptual.

Sawrey, B. A., (1990). Concept learning versus problem solving: Revisited. *Journal of Chemical Education, 67,* 253-254.

This paper reports a study that repeats the research done by Nurrenbern and Pickering (above). This study provides more detailed information about the type of students in the observed course. In addition, they use a larger and homogeneous population, on the chance that “the distinction between the ability to solve numerical problems and ability to do conceptual problems may have little practical significance, simply because the students are bright enough to do both well.” The results of this study support the results of Nurrenbern and Pickering.

Shin, N., Jonassen, D. H., & McGee, S., (2003). Predictors of well-structured and ill-structured problem solving in an astronomy simulation. *Journal of Research in Science Teaching, 40,* 6-33.

> This paper lists multiple qualities of well-defined and ill-defined problems and provides several examples of each. The research compares predictors of problem solving for both well-defined and ill-defined problems. In addition, it compares the skills needed for solving both types of problems.

Sweller, J., (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science, 12,* 257-285.

> This paper provides a very detailed introduction to problem solving which includes findings from other research projects. In this research project, the author examines the effect of cognitive load on problem solving success. High school students are presented with a diagram of a triangle; some students are asked to solve a specific problem related to the triangle while others are asked to calculate anything they can from the information provided. The researcher believed that given students a non-specific goal (calculate anything you can) reduces the students' cognitive load and therefore increases their success. The results showed that students with non-specific goals solved the problems with fewer errors.

Taconis, R., Ferguson-Hessler, M. G. M., & Broekkamp, H., (2001). Teaching science problem solving: An overview of experimental work. *Journal of Research in Science Teaching, 38,* 442-468.

> This paper provides a comparison of research in problem solving. It gives a classification scheme of problems based on five different criteria. The authors describe how students tackle the task of problem solving. The difference between a novice and expert problem solver is presented, including characteristics of each.

Ward, M., & Sweller, J., (1990). Structuring effective worked examples. *Cognition and Instruction, 7,* 1-39.

> In this paper, the researchers studied the use of worked examples as learning tools in high school physics classrooms. The results found that worked examples are generally superior learning tools than having students solve conventional problems. Some worked examples are not effective and, in fact, can hinder the learning process. Ineffective worked examples can be converted to effective examples by reducing students' cognitive load and not requiring them to split their attention between multiple sources of information.

Yarroch, W. L., (1985). Student understanding of chemical equation balancing. *Journal of Research in Science Teaching, 22,* 449-459.

> This paper describes a research project involving high school chemistry students. The researcher investigated their ability to balance chemical equations and demonstrate their understanding of the balanced equation. The results are more appropriate for studies in misconceptions. The paper has some good introductory information on problem solving and presents a unique alternative to think-aloud.