

CHAPTER 2 LITERATURE REVIEW

Knowledge is not constructed or learned in a vacuum. The study summarized by this thesis was certainly no exception. A large body of previous research exists in the research literature of many disciplines which examines human problem-solving, however the review for this study will focus primarily on research done on physics problem-solving. Before the methods or results of this study can be fully understood, it is necessary to be familiar with this literature. The purpose of this chapter is to give a review of this literature in sufficient depth to motivate, contextualize and inform the reader. This chapter will justify the importance of problem-solving in physics and how this is best exemplified by experts. The chapter will then review several published attempts to improve student problem-solving in physics both in the laboratory and in the classroom. From this review it will be evident of the need for this study.

Problem-solving in Physics

Problem-solving is an integral part of most (if not all) introductory physics courses. Physics textbook chapters end with many problems for the students to solve, while the chapters themselves are full of worked solutions. The traditional lectures are full of solved problems, a fact not missed by one of Tobias's expert auditors, "the class consisted basically of problem solving and not of any interesting or inspiring exchange of ideas" (Tobias, 1990, p.20). The student's knowledge of physics is traditionally checked via problem-solving exams. Physics instruction is about having students solve problems. According to Schultz and Lochhead (1991), "... the fact is that the solving of physics

problems is the preferred, almost universal, means of demonstrating mastery of physics." Clearly an emphasis on problem solving is throughout a traditional introductory physics course.

This emphasis on problem-solving in introductory college-level physics courses is justified. Students who intend to major in physics will need to know how to apply their knowledge quantitatively and qualitatively. A survey of recent graduates of physics programs conducted by the American Institute of Physics (1997) showed that problem-solving is the most frequently used skill in either academic or industrial jobs. Students who do not intend to major in physics still need physics problem-solving. In a survey of university engineering and science professors, having their students improve their problem-solving skills by taking physics was two of the top five goals for an introductory physics course (Foster, Heller, & Heller, in press).

Out of this compulsion around problem-solving comes the standard definition for a physics problem; specifically, a physics problem is what is typically found at the end of textbook chapters (Maloney, 1993). These are well-defined and very specific with all of the relevant information given numerically. There is some concern as to if these textbook problems are actually problems for the students or merely exercises (Arons, 1990; Schultz & Lochhead, 1991; Huffman, 1994). In either case, how students solve these problems is what is generally meant by physics problem-solving.

Expert-Novice Research on Problem-Solving.

Fortunately how students solve physics problems has been well-studied and reported in the literature. Physics makes an ideal vehicle for examining problem-solving

since, like chess and puzzles, it has a well-defined set of concepts and rules. It also has expert practitioners and novices just learning these concepts and rules. This distinction between experts and novices provides a useful framework for studying physics problem-solving.

Experts know more and how to use it

The obvious difference between experts and novices in physics is that experts know more physics, however there is more to this distinction than meets the eye. de Jong and Ferguson-Hessler (1986) argue that having the knowledge is insufficient; it must be organized in a useful manner. Research into this useful organization of knowledge and how it is used compose this section of the literature review.

One of the early, and still pivotal, works examining how experts structure their knowledge as compared to novices was conducted by Chi, Feltovich and Glaser (1981). The guiding principle of Chi et al. (1981) is that an expert's knowledge base "is arranged around 'problem schemata,' each of which contains information necessary to solve a specific category of problems" (p. 122). To uncover the specific categories, several studies were conducted. The first study had eight experts (Ph.D. candidates in physics) and eight novices (undergraduates who just completed a mechanics course) sort 24 problems based on similarity in solutions. What Chi et al. (1981) observed was that novices categorized problems by the surface features of the problem. Surface features mean the objects referred to in the problem, or the physical terms mentioned in the problem, or the physical configuration described in the problem. The experts did not use these surface features for their categorization. Experts tended to categorize by the major physics principles used in the solution to the problem. Chi et al. (1981) conducted a

second study using problems which had similar surface features, but different physical principles necessary for a solution. In this study they confirmed that novices use surface features.

To examine the difference in the contents of the problem schemata held by experts and novices, Chi et al. (1981) developed a third study. In this study, two experts and two novices were given 20 category labels composed of principles and surface features. The subjects then had three minutes to tell everything they could about problems involving each category label. In other words, the subjects were asked to do a "core dump" on each category label. From this activity, Chi et al. were able to infer that the expert's problem schemata begins with general principles and contain an ordered hierarchy of conditions. "The expert appears to associate her principles with procedural knowledge about their applicability" (Chi et al., 1981, p. 137). In contrast, the novice still had a lot to say about the categories, but they seem to focus on surface details to find explicit unknowns and their problem schemata lacks structures concerning applying principles. To test this hypothesis, Chi et al. (1981) conducted a fourth study which invited two experts and two novices to think aloud while solving 20 problems. They again saw that experts first determined the underlying principles while the novices jumped into solving the problem.

The conclusions reached by Chi et al. (1981) are in nice agreement with the work done by Jill Larkin. In 1980, Larkin, McDermott, Simon and Simon summarized much of their (and others) research on expert and novice problem solvers. They report that cognitive science has introduced the concept of chunking of familiar stimuli to account for an expert's ability. Chunking can be modeled from computer programming as sub-routines, because chunks are more than just memorized facts, but also procedures. The

concept of chunking works well with Chi et al. (1981) exploration of problem schemata. Generally speaking, problem schemata are composed of chunked information. These chunks have been built-up over years of use. Their use is automatic for experts.

The concepts of chunking not only explains why a physics expert can solve familiar problems quicker than a novice, but why the generation of the solution by a novice shows a near random access rate for equations. In a study conducted by Larkin (1979), she asked two experts and a novice to solve five problems. The novice was an "A" student who had just completed an introductory mechanics course. Larkin first noted that the experts and the novice had adequate knowledge to answer the problems. Next, Larkin measured the time between recalling principles for both the novice and the experts while solving the problems. The time delay for a novice was consistent with the pattern for accessing the information randomly, which suggests that the novice had information stored singly. The experts however showed "bursts" of quick access, suggesting that information is stored together in chunks. Apart from the rapid access associated with chunking, chunks also only takes up one slot in short-term memory (Larkin et al, 1980). Contemporary cognitive science posits that there are five to nine such slots in every person's working memory. Novices will use most (if not all) of these slots while solving a problem as the principles are accessed independently.

Chunks are also very context dependent; they only are accessed when the stimuli is familiar. Observing a chess expert highlights this property of chunks. A chess master can recall from memory with 90% accuracy the chess piece's location during a chess game, but if the pieces are randomly placed, the experts recall accuracy falls to that of a novice. Clearly the familiarity with the game context is important for the chess master.

Familiarity is certainly a hallmark of any expert, including physicists. But is familiarity with problems enough to account for chunking and problem schemata?

de Jong and Ferguson-Hessler (1986) explored this issue by examining good and poor novice problem solvers. They tested "the hypothesis that good novice problem solvers have their knowledge organized according to problem schemata, as opposed to poor novice problem solvers, who were expected to lack this kind of organization" (de Jong & Ferguson-Hessler, 1986, p. 280). Their first step was to expand what Chi et al. (1981) meant by problem schemata. de Jong and Ferguson-Hessler (1986) posited that a problem schemata should have declarative knowledge (principles, formulae, and concepts); characteristics of problem situations to make connections between the actual problem and problem schemata; procedural knowledge for solving problems; and strategic knowledge (a plan). Next they developed a card-sorting task to elicit three of the four elements of a problem schemata. They did not explore strategic knowledge. On the cards were one of 65 elements of knowledge. The 65 elements were taken from 12 problems based on fundamental principles of introductory electromagnetism. Each problem was constructed to have at least one element of declarative knowledge, one of procedural knowledge, and one of characteristics of problem situations. The 65 cards were then given to two groups of students. One group, the good problem solvers, consisted of 13 students who scored better than 70% on the final exam. The other group, the seven poor problem solvers, scored less than 30% on the exam. The students were simply asked to sort the cards on their own criteria and to double check their piles. When the cluster analysis was run, the good problem solvers sorted by problem-type. The poor problem solvers tended to sort by surface characteristics of the elements. These results

support the hypothesis that good problem solvers have their knowledge organized around problem schemata.

Another more recent study examining differences between stronger and weaker novice was conducted by Zajchowski and Martin (1993). In particular, Zajchowski and Martin (1993) wanted to know (1) if the stronger students simply had more knowledge, and (2) how is this knowledge organized. Ten students who had just completed an intensive summer course were asked to solve two problems using a think aloud protocol. Six of the students were considered stronger students based on their grade in the course. The two problems were mechanics problems requiring Newton's second law. The first problem was considerably easier than the second. Zajchowski and Martin (1993) found that both groups of students could solve the easy problem demonstrating that both groups had the requisite knowledge. However, this trend did not continue into the hard problem. The stronger students solved the harder problem by applying basic principles while the weaker students attempted to use memorized formulae. The weaker students were also much less successful at reaching the correct solution. This study by Zajchowski and Martin (1993) reached a different conclusion than de Jong and Ferguson-Hessler (1986). Zajchowski and Martin (1993) suggested that strong problem solvers organize their knowledge hierarchically while de Jong and Ferguson-Hessler (1986) suggest problem schemata.

There is other research which suggests that knowledge structures organized around problem schemata may not be the most efficient. Fred Reif and Joan Heller (1982) have explored this issue by examining what effective and efficient problem solving would be like without turning to experts for this model. Reif & Heller (1982) did

a theoretical exploration searching for the best knowledge structure for mechanics. This is a mental exploration into what knowledge structures a hypothetical expert might have. Reif & Heller (1982) argue that the most efficient organization for knowledge would be if it were hierarchically structured. The top-most level contains information about individual descriptors, interaction descriptors, interaction laws, and motion principles. Nowhere at this level are there any equations or mathematical principles. Only in subsequent levels of detail are equations evident.

While there may appear to be a contradiction between the studies of de Jong and Ferguson-Hessler (1986) and Reif & Heller (1982) regarding how knowledge is organized, Maloney (1993) warns us that it this may just be semantic. Some of the items studied could be the same thing. What Reif and Heller call functional knowledge components may be the same as problem schemata. It is also possible that hierarchical maybe the best, but real people don't work that way. However, from these studies we know that physics experts have more than just lots of declarative knowledge in physics, they have this knowledge organized into usable pieces, that these pieces are most likely composed of many chunked subparts, and that there is probably some form of hierarchical structure of this knowledge. Experts have their expansive knowledge structured in such a way that they can use it quickly, accurately, and efficiently.

Experts are deliberate and planful

Another hallmark of an expert, especially those in physics, is their carefully pre-analysis of a problem. Rather than jumping directly into a quantitative description of the problem, experts tend to insert a step. Jill Larkin (1979) reports that this extra analysis by experts is a qualitative description based on principles and not a mathematical reduction.

This extra step probably serves two functions. First, it reduces the chance of error since the qualitative description can be checked against both the problem statement and subsequent equations. Second, the qualitative analysis serves as a concise reduction of the salient features of the problem (Larkin, 1979). The qualitative analysis is the problem-solver's interpretation of the problem statement.

Qualitative analysis is very much a part of the expert's discipline. Larkin and Reif expanded this concept and called it domain specific representations (Larkin & Reif, 1979). They asked an expert and a novice to solve five problems while thinking aloud. They determined that the expert constructed a "low-detailed qualitative physical description" (Larkin & Reif, 1979, p. 196) after the initial sketch. This was used to make certain there were no inherent problems in the expert's approach. The novice lacked either the knowledge or the access structure to construct this representation.

But what do experts do when faced with challenging problems instead of typical introductory physics problems used in these studies? This question was explored by Larkin (1983). Larkin asked six advanced physics graduate students to solve a very hard physics problem. Two of the students immediately recognized how to do the problem and selected the correct representation, implying that perhaps it was not difficult for them. Three other experts initially constructed an incorrect representation and only after working with it qualitatively was this representation abandoned and another tried. The last expert was unable to solve the problem. Of the five experts in this study, all of them created and used their domain specific representations to guide their solution before any serious mathematics was begun.

Part of the qualitative description of experts includes drawing diagrams. While most experts readily draw figures to help them understand the problem, this skill is absent in most novices (Schultz & Lochhead, 1991). Alan Van Heuvelen (1991) lists three reasons why students do not draw diagrams. First, the students do not understand the meaning of the concepts and principles displayed on diagrams. Second, students are rarely taught the skills to create their own diagrams. Third, the alternative conceptions held by the students often are in direct conflict with the concepts being taught and this internal contradiction bogs the student down. Students evidently lack both the knowledge and the initiative for a qualitative analysis. This conclusion is also evident in their theoretical work.

In their theoretical exploration, Reif & Heller (1982) also examined the process of solving a problem. They broke it into three phases: the description phase; the search for a solution phase; and the assessing the solution phase. The description phase is essentially a translation of the problem statement into a clear description of the problem and the information to be found. This is clearly a domain specific representation. The next phase, the search for a solution, is greatly facilitated by the use of generally applicable procedures, such as constrain satisfaction, decomposition, and multiple levels of description. Constrain satisfaction is a time honored approach used in physics and it has two steps: "(a) Generate enough constraints so that only one solution exists that is consistent with all of them. (b) Construct an actual solution that satisfies all these constraints. This must then be *the* solution [emphasis in original]" (Reif & Heller, 1982, p. 117). Decomposition is breaking a problem in to progressively easier to solve subparts. Multiple levels of descriptions refers to the level of detail necessary to solve a

problem. This is most useful when planning a solution. The final phase of assessing a solution is essentially ensuring that the solution meets all of several criteria. These criteria are clear interpretation, completeness, internal consistency, external consistency, and optimality. All of these phases are guided by domain-specific knowledge but the phases themselves are general. Essentially, there is a sequence to solving a problem.

Another part of the qualitative analysis conducted by experts is to plan their solution to the problem before they start detailing their solution mathematically. Larkin (1980) watched an expert solve five mechanics problems and developed a protocol (non-computer program) to mimic the expert's behavior. The expert's behavior had four different types of work: (1) Assembly; (2) planning; (3) solving; and (4) checking. The computer model (HIPLAN) first constructed a final goal based on the initial state. Next HIPLAN constructs a series of abstractions to reach the final state instead of attacking the final state directly. This concentration on the planning phase of problem-solving is the emphasis of HIPLAN. Comparing the protocols generated by HIPLAN to the expert's worked showed remarkable agreement. Larkin's work strongly suggests the importance of planning to experts.

Planfulness is also evident in students. In a study using eight good problem solvers and eight poor problem solvers taken from a high school advanced placement physics course, Finegold and Mass (1985) found that the good problem solvers are more planful. Specifically, they found that the good problem solvers tended to plan their solutions more fully and that the poor problem solvers rarely planned at all. Good problem solvers also spent more time on translation and planning than the poor problem

solvers did. Planfulness is evidently another hallmark of experts and an important element of qualitative analysis of a problem.

Experts work forwards and evaluate often

This section of the review of the expert-novice physics problem-solving literature is concerned with what an expert does after the knowledge of how to proceed in a problem is accessed and the qualitative analysis is complete. When the expert is ready to begin an easy problem, the physicist tends to work forward from the given, known quantities to the desired quantity. A novice tends to work backward from the desired quantity to the given variables (Larkin, et al., 1980). A useful analogy for understanding the difference is hiring a plumber. An expert plumber comes into your home to stop a drip, assesses the situation, decides a plan of attack to solve the cause of the leak, goes to her truck, and returns with exactly the right tools. This is working forwards. A novice plumber would need to make continual trips out to the truck, getting new tools each trip, as he works backwards from the drip to the cause of the drip. This observed difference in experts and novices is surprising since the backward approach of breaking the problem into goals and subgoals should be a cognitively more sophisticated approach. However, without the benefit of knowing ahead of time which equations to use, a novice solves a problem the hard way.

Another difference between an expert and a novice while generating a solution to a problem is the expert's frequent evaluation of the progress of the solution. The theoretical model of Reif and Heller (1982) gave several checks an efficient problem solver would use and evaluation processes were noticed (but not modeled) by Larkin (1980). It might be a disservice to discuss solution evaluation as only occurring after the

mathematics has begun. Recall that one of the reasons for an expert's qualitative analysis was to check the approach. Indeed, most experts continually monitor their progress throughout the solution (Schoenfeld, 1985). Checking one's work for mistakes, both silly and conceptual, is a hallmark of an expert.

Physics Problem-solving Instruction

With this empirically and theoretically derived description of the differences between experts and novices as a guide, many education researchers designed experiments to see if novices could be taught expert-like behaviors. These experiments fall into two broad categories: (1) laboratory based experiments where students were extracted from a class and taught expert-like skills; and (2) classroom-based experiments where an entire class was taught these skills. The following section of this chapter will describe several of these studies.

Laboratory

Jill Larkin and Fred Reif were not only interested in understanding the characteristics of expert problem solvers, but also if it was possible to design instruction which could teach effective problem-solving. Generally this was done in small laboratory experiments. One of their early attempts was not an extension of the expert-novice problem-solving literature, but the work of the mathematician Polya (1957) who based his four-step problem-solving strategy on "a long and serious study of methods of solution. This sort of study ... is not in fashion nowadays but has a long past and, perhaps, some future" (p. vii). The legacy of Polya's work is that it is the foundation for most of the current instructional problem-solving heuristics. His legacy was first used in physics by

Reif, Larkin and Brackett (1976) who taught Polya's four-step strategy to a handful of students. They observed that those students taught the strategy used diagrams more and had a more intelligent use of algebra. These students were also more planful and make greater progress toward a solution even when the final answer evaded them. It seemed that Polya's out-of-fashion ideas were very useful to these students.

Later, Larkin & Reif (1979) report an experiment involving ten university students who were preparing to study electric circuits. These ten students were then given instruction in seven principles of circuits until they displayed the necessary competence. Five were then randomly selected to use low-detail qualitative analysis. The other five students received more training equal in time to the treatment group. All ten students were then asked to solve three problems while thinking aloud. Three of the students in the treatment group solved all three problem. The other two students solved two problems. Of the control group, four could solve only one problem while the fifth solved all three. While these numbers are not statistically significant, they do provide evidence that teaching qualitative analysis for better problem solving seemed possible.

Heller and Reif (1984) investigated their theoretical model to see if it could be explicitly taught to students. In their earlier work, they suggest what components must be explicitly taught. They recommend that one teaches:

How to generate a good basic and theoretical description of a problem; how to analyze a problem qualitatively before its actual solution; how to search for a problem solution by decomposing the problem systematically and exploring relevant decisions; and how to assess the merits of the resulting solution. (Reif & Heller, 1982, p. 124)

Heller and Reif (1984) paid 24 undergraduates from a second-term physics course who had received a grade of B- or better in the first-term course. The students were randomly assigned to one of three groups (two experimental, one control). The first experimental group (M) was taught an explicit procedure for handling many mechanics problems. This procedure had the following elements: identifying the relevant times and systems; complete description of the relevant systems including motion and force diagrams; and finally checking the description. The second experimental group (M*) was given a less detailed procedure (essentially textbook problem solving hints). The control group was given no external guidance.

After the experimental groups were sufficiently familiar with their procedures, all three groups worked problems for thirty minutes. Heller and Reif (1984) established four measures of problem solving ability based on the students written work. The four measures were a correct motion description, a correct force description, valid equations, and a correct final answer. One week later, the students returned to solve three problems. The control group was indistinguishable from pretest measures. The first experimental group (M) was significantly better than the control group on all four measures and better than the second experimental group (M*) on three of the four measures. These results support the effectiveness of the prescriptive model developed by Heller and Reif (1984).

Another laboratory experiment conducted by Reif examined if a hierarchical knowledge structure could be taught to students and which structure would be the most effective. Eylon and Reif (1984) recruited 36 students who had recently studied the information being used in the study. The subjects were divided into three ability groups (by performance on a relevant physics test) and then assigned into three treatments. The

first treatment (H) was presented a hierarchical, two-level organization of a physics argument. The second treatment (S₁) was the same argument with only one level of detail. Students in the final group were presented the same one-level argument twice (S₂). Eylon and Reif (1984) determined that students in the H-treatment group performed significantly better on complex tasks, suggesting that a hierarchical knowledge structure might be the best to teach to students.

The last laboratory experiment dealing with teaching students more expert-like behavior has a more contemporary flair. Mestre, Dufresne, Gerace, Hardiman, and Touger (1993), investigated the changes in problem-solving behavior of novices as a result of a computer based treatment which facilitated the novice's practice of qualitative analysis in physics. Mestre et al. (1993) created two computer programs, hierarchical analysis tool (HAT) and equation sorting tool (EST). HAT is a menu driven program that asks the students a series of questions (basing subsequent questions on their previous answers) to produce a series of equations consistent with the given answer supplied by the students. HAT has no knowledge of the problem being solved, it does not tutor the student, nor does it combine equations. "In short, HAT can be thought of as an elaborate, hierarchical tree-like structure" (Mestre et al., 1993, p. 306). In contrast, EST contains 178 equations taken from an introductory physics textbook. The equations can be sorted by surface features, or variable names or physics terms. In effect, EST catered to the novice strategies of categorizing by surface features and pattern matching.

Mestre et al. (1993) recruited 42 students who had just completed an introductory mechanics course with a grade of B or better. The subjects were randomly assigned to one of three groups. All three groups solved 25 problems, five at a time spread over three

weeks. The students in the HAT group solved the problems using HAT, the students in EST group solved the problem using EST. The last group solve the problems using a textbook (T). All the subjects in the Mestre et al. (1993) study were also asked to complete two other tasks. The first was a problem categorization task comprising matching one of two comparison problems to a model problem. The comparison problems were constructed to exhibit either surface feature or deep structure matching to the model problem. The second task was an explanation task where the students were to describe how a physical situation would change under a particular set of conditions.

Performance on the three tasks given by Mestre et al. (1993) varied. When the performance on the 25 problems were compared across all three groups, there was no difference. However, the HAT group did significantly better on the categorization task displaying more deep structure categorizing. The EST group was not any different than the T-group. On the explanation task, the HAT group displayed an increased reliance on concepts instead of equations, while the other two groups either decreased or stayed the same in their reliance on equations. Mestre et al. (1993) believe that these results show that students can benefit from hierarchically structured problem solving.

Classrooms

All of the aforementioned studies took students out of the classroom and randomly assigned them to treatments. While these experimental studies are essential to prove that expert-like problem solving skills can be taught, they do not prove if an entire class of students can be taught more expert-like skills while also learning the physics content. This section will examine the handful of studies which tried to teach a physics

class to be better problem solvers, including examining those studies immediately relevant to this thesis.

The first two reported problem-solving studies used student evaluations to assess the effectiveness of instruction. Bolton and Ross (1997), taught their students a three-step strategy of preparation, working, and checking. The preparation phase is intended to be where the student writes down all the given information and lays out a plan. It is not as comprehensive as the qualitative analysis discussed earlier. Working is where students perform their arithmetic and checking is a chance to evaluate. Student opinion about the strategy was generally favorable with 83% finding the framework useful (p. 182).

Wright and Wise (1986) introduced the WISE strategy to their students. WISE is an acronym for what's happening, isolate the unknown, substitute, and evaluate. During the "what's happening" phase, students are asked to draw a diagram, select the appropriate physics principles, and identify the known and unknown quantities. This is the start of an expert-like qualitative analysis. In "isolate the variables" the students begin to plan their solution and then execute it algebraically. Numbers are used in the "substitute phase". Finally, the students are asked to "evaluate their solution" by looking for inconsistencies with units and examining their own intuition. When implemented, 80% students who used WISE held it in a favorable light. Generally less than 2% of the class saw it as not helpful. Lastly, Wright and Wise (1986) report that using the WISE strategy helped their students communicate effectively with instructors and fellow students while working problems together.

The remainder of the classroom based studies on problem-solving determine the effectiveness of their methodology using student performance instead of opinions.

Overview, Case Study (OCS) by Alan Van Heuvelen (1991) is the next classroom-based study involving problem-solving to be reviewed here. While not uniquely designed to improve problem-solving, OCS includes a mechanism to "provide students with explicit instruction in the individual skills used by experienced physicists when solving complex problems and then help them combine these skills to solve complex problems" (p. 898). This mechanism takes the form of a multiple representation problem-solving format. For mechanics, this format explicitly requires the students to produce a pictorial representation and a physical representation before proceeding onto the mathematics. These representations are an attempt to teach the students the expert trait of qualitative analysis.

OCS has been taught to several different classes. In a pre-calculus physics course at New Mexico State University, OCS students scored 75% correct on five final exam problems, compared to 40% for students in a traditionally taught course (Van Heuvelen, 1991, p. 902). In addition, OCS students were more likely to draw pictures and apply basic principles correctly, even if they got the problem wrong. These results are reminiscent of the study of Reif, Larkin, and Brackett (1976). In two calculus-based physics courses at New Mexico State University, seven particularly illuminating old AP physics exam problems were given. The OCS students scored 55% correct while traditionally taught students manages only 36% correct. Finally, when OCS was taught to high school students, 8% of the nation's highest scores on the AP physics exam came from that high school. Even though OCS represents a radical restructuring of a course, the results are impressive.

Another example of restructuring of a course around problem-solving was completed by van Weeren, de Mul, Peters, Kramers-Pals, and Roossink (1982). Their goal was to restructure the electromagnetism course for first-year Dutch college students. van Weeren et al. realized that any restructuring was doomed to fail without a solid theoretical framework, so they choose the theory of Gal'perin. This framework has two key elements. First, student actions are directed by a basis of orientation which contains the subject matter of the course including heuristics for specifically applying this subject matter. The second element is a stage-by-stage formation of the students mental actions. The students, while working unfamiliar problems, will progress through several stages. The first stage is the materialized form where every action is explicitly recorded on paper. The next stage is the verbal stage where students can express their ideas in words by explaining them to another. The final stage is the mental stage where actions are carried out entirely in the student's mind. For practical purposes, only the first stage was taught since it was entirely observable and feedback could be given.

The first element of the theory of Gal'perin was implemented by van Weeren et al. (1982) in two ways: (1) the creation of key relation (KR) cards to help the students organize the subject matter and (2) a systematic approach to problem-solving (SAP) explicitly taught to students. van Weeren et al. developed SAP after interviewing experts using a think aloud protocol. From the transcripts, a complicated model was developed, but this model could be reduced to three main steps: Analyzing, mapping, and concluding. In the analyzing step, students are given explicit suggestions to help interpret problem situations. Next the students are told to map, or plan, their actions. This mapping is identical to completing a qualitative analysis (Larkin and Reif, 1979). In

concluding, the students need to explicitly consider their answer. All of the steps and substeps of SAP are given to the students in writing and as structured worksheets, or templates, to solving problems on. The second element of theory of Gal'perin was implemented by van Weeren et al. by changing their instructional strategies. Rather than solving the problems for students in the lecture, the students now must use the KR cards and the SAP templates to solve the problems for themselves with the teacher acting as a guide.

The results of van Weeren et al. (1982) efforts were measured by comparing the student average scores from the restructured course to student performance in previous courses on the national examinations. Their analysis lead to several conclusions. First, the students in the restructured course did significantly better than their peers in the conventional course. This effect was sustainable over several years of implementing the restructured course, even when the relative difficulty of exams was controlled. Second, the student's secondary-school physics backgrounds (as measured by the national entrance examinations) affected both the restructured course and traditional course equally. Finally, students were asked to keep a log of the time the spent studying and the reconstructed course did not require more time than the conventional course. van Weeren et al. concluded that their restructuring was a success.

The last set of studies reviewed here are especially relevant since the methodologies presented in these studies was similar to those used in this thesis. In particular, Heller, Keith, and Anderson (1992) examine the effects of cooperative group problem solving on students. The students in a college-level, algebra-based physics course for technical majors (but not necessarily pre-meds) were explicitly taught a five

step strategy. The five steps of the Minnesota problem-solving strategy were: (1) Focus the problem, (2) describe the physics, (3) plan the solution, (4) execute the plan, and (5) evaluate the answer. These steps are detailed in Chapter 3 of this thesis, however, in the context of this review, the qualitative analysis of Larkin and Reif (1979) is evident in the first and second steps and the expert trait of planfulness is the goal of the third step. In addition to this problem-solving strategy, the student were explicitly taught how to work in cooperative groups. These students used both the Minnesota Problem-Solving Strategy and cooperative groups to solve problems in weekly recitation sessions. The students also had to use the Minnesota Problem-Solving Strategy on their own to solve problems on exams.

To measure the problem-solving performance of the students, Heller, Keith, and Anderson (1992) developed two scoring schemes. The first was a measure of the students problem-solving ability. A six characteristic ranking-scheme was developed based on the expert-novice problem-solving research. The six characteristics were: (a) evidence of conceptual understanding, (b) usefulness of description, (c) match of equations with description, (d) reasonable plan, (e) logical progression, and (f) appropriate mathematics. The second measure developed by Heller, Keith, and Anderson was a six characteristic problem difficulty measure. The six characteristics of problem difficulty were: (a) problem context, (b) problem cues, (c) given information, (d) explicitness of question, (e) number of approaches, and (f) memory load. Armed with these two measures, Heller, Keith, and Anderson (1992) began their investigations discussed below.

Heller, Keith, and Anderson (1992) reached several conclusions. First, group-produced problem solutions were more expert-like than those produced independently by

the best student in the group. Second, groups do a better job at conceptual understanding, usefulness of physics description and matching of equations with description than the best students within each group. Third, there was evidence that individual student's problem-solving ability improved over time. Fourth, students from these problem-solving groups outperformed their traditionally taught peers on two problems. Clearly it is advantageous to have students solving problems in groups. However, Heller, Keith, and Anderson recommended that further studies determine if students conceptual understanding is hindered by cooperative group problem solving.

Huffman (1994) examined this issue in his doctoral dissertation. Huffman used a quasi-experimental design with suburban high school students in two groups; those taught the Minnesota Problem-Solving Strategy and those taught a textbook strategy. Huffman found that the students who used the Minnesota Problem-Solving Strategy had higher quality and more complete solutions than their peers who used the textbook strategy. However, Huffman found no difference between the two groups on the students' conceptual understanding or organization of their solutions. Huffman speculated that the reason only a limited effect was seen in his study was due to (a) the limited time spent preparing the instructors to teach using an explicit strategy (since neither instructor had used this pedagogy before) and (b) the short duration of the study may have been too brief for the student to embrace either problem-solving strategy. More work needs to be done with cooperative group problem-solving.

Summary of Literature Review

This literature review terminates with the classroom studies of Heller, Keith, and Anderson (1992) and Huffman (1994) since they are the relevant foundation from which this thesis proceeds. To get to these studies, it was necessary to review the expert-novice problem-solving literature to describe and appreciate expert-like problem solving. From this experimental foundation, a theory of expert-like behavior beyond the experts superior knowledge emerges with such characteristics as qualitative analysis, planfulness, and solution evaluation. Developed in connection with this description came several laboratory experiments that demonstrated that expert-like problem-solving skills could be taught to student.

Yet laboratory experiments, although necessary, are insufficient for many practitioners. Whole classroom experiments were conducted and demonstrate through the works of Van Heuvelen (1991) and van Weeren et al. (1982) that problem-solving could be successfully taught to a class. The works of Heller, Keith, and Anderson (1992) and Huffman (1994) reinforce these studies. These works provide the foundation for this thesis. It has been shown by Heller, Keith, and Anderson that cooperative group problem-solving can be beneficial, but which piece, the Minnesota Problem-Solving Strategy or the cooperative grouping was the most important? Also, Heller, Keith, and Anderson never really examine the problem-solving ability of those students in a traditional section to see if there results are extraordinary. From Huffman's study, he concludes that one instructional unit may not enough time to see effects, but would there be any effect over a year of instruction? These questions lie at the heart of the research questions for this thesis.

