CHAPTER 2: Literature Review

This chapter will explore the literature that is relevant to understanding the development of, and interpreting the results of this convergent study. The first two parts of this review of the literature will describe two types of research: research on teaching and research on teachers' conceptions. Each section will summarize the assumptions and major findings of these types of research. The third part of this literature review is a summary of research on effective problem solving. This is not meant to be an exhaustive review of the literature. It is intended to familiarize the reader with the basic assumptions about problem solving that went into the design of this research program and the interpretation of the results.

Research on Teaching

Typically, research on teaching is conducted in order to improve teaching. The results of the research are often used to make recommendations for improving pre-service and in-service teacher programs. With the goal of providing effective instruction, this type of research is usually consistent with the dominant instructional techniques of the time. The earlier research on teaching was clearly influenced by the behaviorist approach to teaching. The behaviorist approach operates under the premise that complex tasks could be broken into a set of discrete skills that could then be taught, and this earlier research treated teaching as such.

More recently, however, instructional techniques have shifted the focus towards information processing and constructivism. This development began to center more on student thinking, and the ways that students' prior experiences, ideas, and ways of thinking influence how they react to instruction. Therefore, research on teachers has followed, and efforts began to focus on teachers' thought processes associated with teaching and the knowledge and beliefs that were necessary to support these thought processes.

Research on teaching is most frequently done on pre-service and in-service K-12 teachers. There are relatively few research studies done on college teachers.

Nevertheless, these studies tend to use research methods that are similar to those used with K-12 teachers and, for the most part, the findings have been similar.

Teachers' Cognitions

In the late 1960's and early 1970's, the psychological theory of information processing began to influence research on teachers. Early research into teachers' thinking was based on the premise that their thought processes could be considered as a series of decisions that they explicitly make (Calderhead, 1987). Consequently, the underlying goal undertaken was to determine the information utilized by the teachers for making decisions, and develop guidelines to regulate the decision-making process. Research findings in this area indicated that teachers often did not carry out the same high degrees of deliberation that one would generally associate with decision-making (Calderhead, 1996; Mitchell and Marland, 1989). Further research findings led to the realization that teachers' thinking was very implicit, and they often could not easily articulate the information that influenced those thoughts. This influenced the research focus to be shifted towards teachers' conceptions.

Teachers' Decision-Making

A major factor in shifting the focus of research to teachers' thought processes was credited, by Clark and Peterson (1986), to the June 1974 National Conference on Studies in Teaching. Panel 6 of this conference, "Teaching as Clinical Information Processing", put forth a report in support of this focus, primarily due to the argument that teachers' actions are directed by their thought processes. In addition to calling on the research community to shift and focus their attentions and efforts, the Panel 6 report further influenced the development of an Institute for Research on Teaching at Michigan State University in 1976, which subsequently established the first large research program on teachers' thought processes.

Research in this area often focuses on one of three times when teachers might engage in making decisions: prior to instruction (preactive decision-making), during classroom instruction (interactive decision-making), and after instruction (postactive decision-making). Some researchers (e.g., Clark and Peterson, 1986) argue that, due to the cyclical nature and the continuity of teaching, postactive decision-making after a particular period of instruction may be more appropriately thought of as preactive decision-making for the next period of instruction. Consequently, relatively little research has been done on postactive decision-making. Therefore, discussions here will not separate the two. More recently, researchers have begun to focus on postactive reflection as a way of developing teaching skills. This role of reflection in the development of teaching skills will be discussed in the section on Teachers' Conceptions.

Preactive Thinking

Most of the research on teachers' decision-making has been on preactive thinking, or planning. Much of this research has been conducted with teachers at the elementary level. Nevertheless, these studies have influenced those researchers conducting studies on teachers at higher levels. In his review of the literature on teachers' planning, Calderhead (1996) described six features of actual teacher planning process: 1) Planning occurs differently for different time spans (Clark & Yinger, 1987; Shavelson & Stern, 1981) and units of content (Clark and Peterson, 1986); 2) Planning is mostly informal (Clark and Peterson, 1986; Clark & Yinger, 1987); 3) Planning is creative and does not follow a linear process as often presented in teacher preparation courses (Clark & Yinger, 1987; Shavelson & Stern, 1981); 4) Planning is based on knowledge of subject matter, classroom activities, children, teaching, school conventions, etc. (Clark & Yinger, 1987; Shavelson & Stern, 1981); 5) Planning allows for flexibility; and 6) Planning occurs within a practical and ideological context.

Research with high school teachers yielded similar findings (Duschl & Wright, 1989; John, 1991; Taylor 1970). Taylor (1970) concluded that teachers, when planning, did not appear to follow a linear strategy from objectives to activities. Major findings from the Duschl and Wright study were that high school teachers' planning decisions were dominated by considerations for the level of the students, the objectives as stated in the curriculum guide, and the pressures of accountability. Their study also concluded that teachers "hold a view of science that does not recognize theories or theory development as centrally important in the scientific enterprise," (Dushl & Wright, p. 493) and thus their understanding of the nature of scientific theories is not an important part of their planning.

John (1991) also came to the same conclusion as Duschl and Wright (1989). John found that one of the main concerns of student teachers in his sample were the abilities and needs of their pupils. In contrast to the Duschl and Wright (1989) study, however, John (1991) found that the teachers' understandings of the nature of the subject had a significant impact on their planning. These teachers planned in a manner that was consistent with their view of the subject.

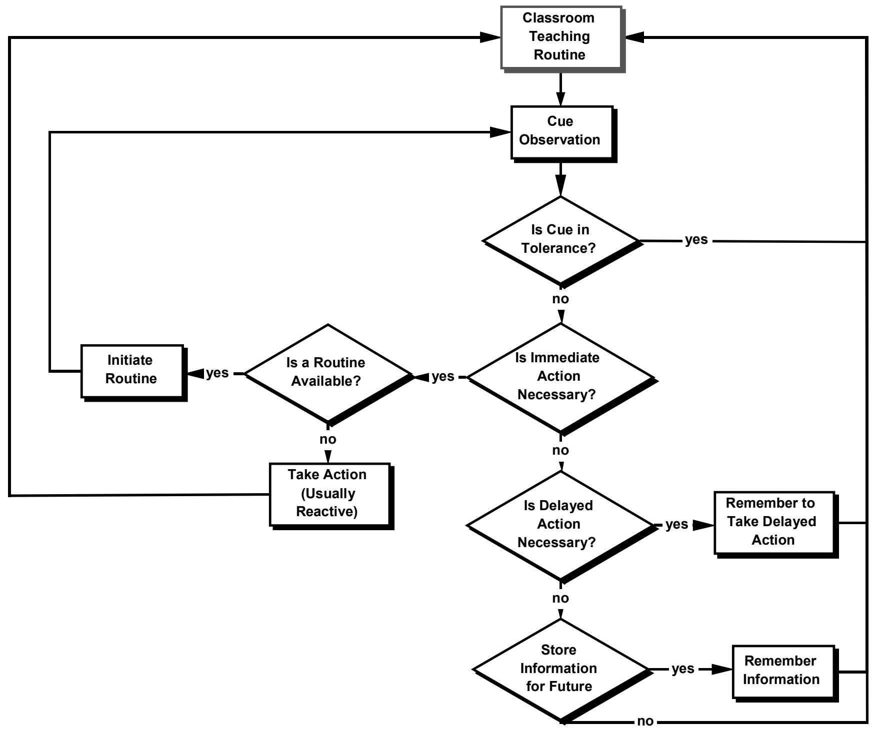
In one of the few studies conducted with college teachers, Andresen et. al. (1985) conducted weekly interviews with 7 college teachers from a variety of disciplines. They found that these teachers appeared to have a regular routine of ongoing planning, and described these teachers' attempts to get into a weekly pattern of preparing lecture notes for the following week.

Interactive Thinking

The research shows that while planning has an influence on what happens during teaching, many of the details of actual classroom teaching are unpredictable, and interactive decisions must be made (Clark & Yinger, 1987). Clark and Yinger (1987) described planning as a way of shaping the broad outline of what is likely to occur, and as a useful tool for managing transitions from one activity to another. Once teaching begins, however, the plan takes a backseat to interactive thinking.

One of the goals of many researchers on interactive thinking was to create a flow chart model of a teacher's interactive thinking process. This again required an understanding of the types of decisions that teachers made and information they used in making these decisions. Figure 2-1 is a model of teachers' interactive decision-making created by Shavelson and Stern (1981) in their review of the literature. This model has several important features based on the research literature. There is substantial and consistent evidence that teachers, on average, make an interactive decision every two

Figure 2-1: Model of teachers' interactive decision-making during interactive teaching



minutes (Clark & Peterson, 1986). These decisions are primarily based on information of the progress of the planned lesson (Calderhead, 1996; Clark & Peterson, 1986; Shavelson & Stern, 1981). The type of information most frequently considered has to do with student behavior (Clark & Peterson, 1986; Shavelson & Stern, 1981). At a decision point, a teacher has to decide either to continue with the lesson, or make some modifications. Most often the teachers choose to continue the lesson (Clark & Peterson, 1986; Shavelson & Stern, 1981). In some cases the decision is based on a choice to deal with the problem at a later time, and in other cases that decision due to a lack of alternatives (Clark & Peterson, 1986; Shavelson & Stern, 1981).

One explanation for the resistance of teachers to make midstream adjustments to their lessons is to minimize disruption of the flow of the lesson. Studies suggest that teachers develop a mental script of what the teaching will look like during planning to reduce the information-processing demands during instruction. To deviate from the mental script, however, requires a higher level of information processing which can interrupt the flow of the lesson and increase the likelihood of classroom management problems (Shavelson & Stern, 1981). A study conducted with six Australian high school teachers (Mitchell and Marland, 1989) supports this idea.

Summary of Research on Teaching

Research on teachers' decision-making marked a distinct shift from research solely on teaching behavior to a focus that includes the mental processes behind that behavior. This research agenda provided an understanding of the different types of teacher thinking and was successful in identifying the types of necessary decisions that teachers make in various situations. The research agenda was also successful in developing a new set of research methods that could be used in the study of teachers' thinking. Qualitative research methods such as *think aloud procedures* (subjects are asked to talk aloud about their thoughts while completing a planning task), *stimulated recall* (subjects are videotaped while teaching and later asked to view the tapes and report on thoughts and decisions), and *policy capturing* (subjects are asked to make judgments or decisions about hypothetical teaching situations or materials) were all introduced to research on teaching during this period. They continue to be among the prominent methods used by research in this area.

The most important result of the research on teachers' decision-making is the realization that teachers work in rich and complex environments, and are constantly required to make a large number of decisions. Teachers, however, do not deliberately and explicitly make many of these decisions; often the decisions are made implicitly. Despite many efforts, this research agenda was unsuccessful in developing any workable model of a teacher's decision-making process. Therefore, research expanded to include not only explicit teacher thinking, but implicit teacher thinking as well, and the mental constructs that guide such implicit thinking.

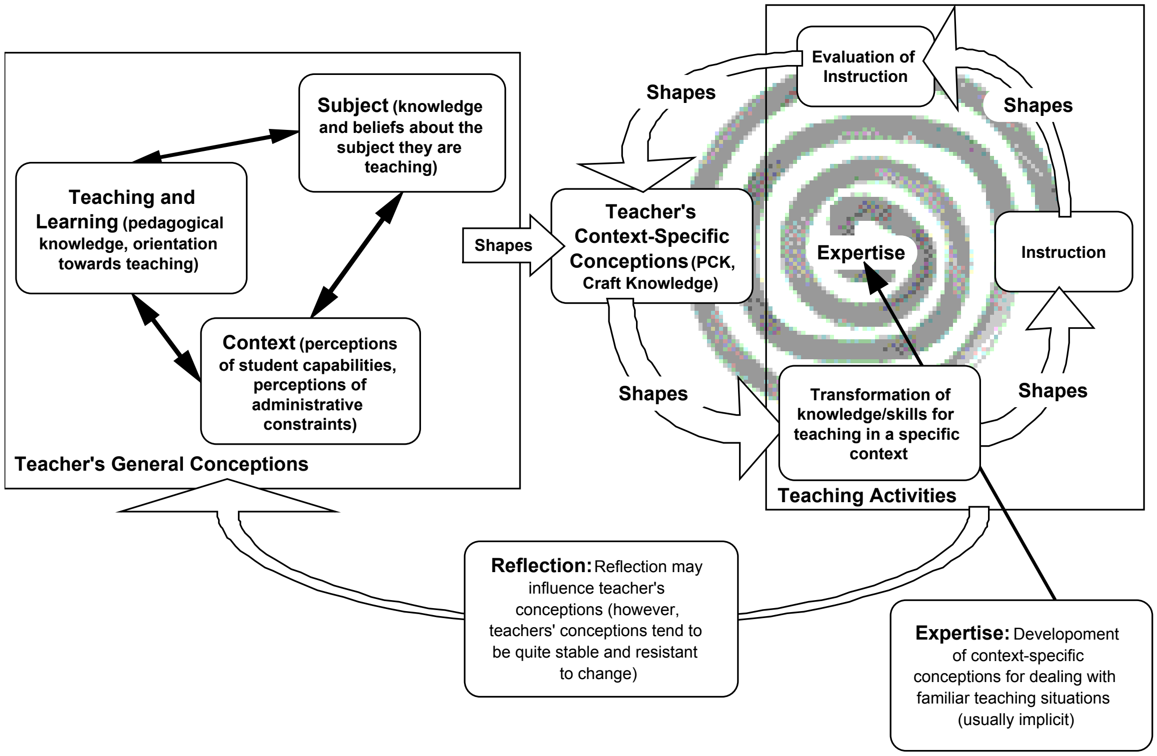
Although the current research program was conducted from a teachers' conceptions perspective, it was influenced by the research on teachers' decision-making. This research program made use of many research methods initially developed for decision-making research. Much of the interview was based on policy capturing techniques that seek to learn about teacher thinking by asking them to engage in hypothetical teaching activities. The interviewees were asked to complete three activities in which they examined and evaluate different types of instructional artifacts. For example, in a planning activity, instructors were shown three different instructor solutions and asked to describe how they are similar or different to the solutions that the instructor typically uses. The instructors were also asked to explain their reasons for using a particular type of solution. The interview questions were designed to help the instructors explicate as much of their decision-making process as possible.

Research on Teacher's Conceptions

The shift towards research on teachers' conceptions occurred gradually. There was no important event that signaled the end of research on teachers' decision-making and the beginning of research on teachers' conceptions. This research agenda began with investigations into the knowledge and knowledge structures used in teaching. That focus quickly expanded to include examination of various types of conceptions that teachers have, how these conceptions are related to teaching, and how these conceptions develop and change. The research also expanded to include college teaching, which, until this period, had been very minimal.

In reviewing the research on teachers' conceptions, there appears to be three general bodies of literature. One body describes teachers' general conceptions that are related to teaching. This type of research is called by such names as teachers' conceptions, teachers' perceptions, teachers' mental images, or teachers' orientations. The second body of research deals with conceptions of teaching in a specific context. This type of research is called by such names as pedagogical content knowledge or craft knowledge. The third body of research deals with expertise and how expertise develops. Henderson (2002) developed the framework shown in Figure 2-2 to help in the organization and discussion of this literature review. The next section will first present an overview of the framework and then look at the literature relevant to each of the parts in more detail.

Figure 2-2: Framework for understanding research on teaching



General Conceptions. The types of general conceptions that have been examined can be classified as conceptions of teaching and learning, conceptions of the subject, or conceptions of the teaching context. Most of these conceptions are implicit. Although these conceptions have been shown to affect teaching practices, they do not always do so in a logical manner. Research has also shown that teachers can possess conflicting conceptions, and it is often difficult to predict how these conflicts will be resolved. The resolution of these conflicts may be dependent on the relative strengths of the conflicting conceptions and, possibly, on other factors. Studies have shown that these general conceptions influence how teachers interpret events, and can account for differences in the way different teachers interpret curriculum materials (Lantz & Kass, 1987).

The Teaching Cycle. The proposed idea was that a teachers' pedagogical reasoning occurred in a cyclical fashion. Teachers must first use their context-specific conceptions to select the appropriate content to teach, and the teaching strategy that would be appropriate for the given context. Teachers then teach the material in the decided way. After teaching, teachers would evaluate the experience, which may lead to the decision to implement a different strategy for the content, or choose a different content, in the future (Wilson, Shulman, & Reichert, 1987).

Context-Specific Conceptions. Initially, a beginning teacher has few context-specific conceptions; he or she must make decisions based on general conceptions. This process consequently leads the teacher to develop conceptions that are more context-specific. Therefore, these conceptions are experience-based. Context-specific conceptions help teachers relate past experiences to current situations, define problems, and potentially test possible solutions (Calderhead, 1996). These conceptions guide much of a teacher's activities and reduce the mental load of teaching.

Expertise in Teaching. As a teacher goes through the teaching cycle and develops more context-specific conceptions, the decisions become more and more automated. Eventually the teacher implicitly knows what to do without engaging in conscious thought. This is what Berliner (1987) defines as expertise. It does not mean that the teacher always does things in the best possible way, only that the teacher's thought processes are highly automated.

Reflection. There have been suggestions that the best way to get teachers to change their teaching practices is to change their general conceptions. It has been proposed that this change occurs through a process of conceptual change (Posner, Strike, Hewson, & Gertzog, 1982), and that can only be accomplished through reflection. Similar to students, however, teachers do not frequently engage in this type of reflection, thus their general conceptions tend to be highly resistant to change.

General Conceptions

Conceptions play a critical role in defining behavior and organizing knowledge and information (Knowles & Holt-Reynolds, 1991; Nespor, 1987; Pajares, 1992). They are instrumental in defining tasks and selecting cognitive tools with which to interpret, plan, and make decisions regarding such tasks. It has been suggested that these conceptions function as paradigms: general conceptions "(1) define what is recognized as notable in the stream of experience; (2) specify how issues and problems can be thought about; and (3) persist even in the face of discrepant information" (Carter and Doyle, 1995, p. 188).

Conceptions of Teaching and Learning

Research into college teachers' conceptions of teaching had produced a hierarchical list of different ways that teachers understand teaching (Martin & Balla, 1991; Prosser & Trigwell, 1999; Prosser, Trigwell, & Taylor, 1994; Samuelowicz & Bain, 1992). The conceptions are hierarchically ranged from the less complete conceptions (teaching as presenting information) to more complete conceptions (teaching as facilitating student learning). Thompson (1992) reported similar results in a review of the literature on conceptions of mathematics teaching with preservice mathematics teachers. In an interview study with 24 college physics and chemistry teachers, Prosser and Trigwell (1999) and Prosser et. al. (1994) identified six conceptions of teaching first year university physical science: 1) teaching as transmitting concepts of the syllabus; 2) teaching as transmitting the teachers' knowledge; 3) teaching as helping students acquire concepts of the syllabus; 4) teaching as helping students acquire teachers' knowledge; 5) teaching as helping students develop conceptions; and 6) teaching as helping students change conceptions.

Research has shown that although these conceptions were found to be rather stable across disciplines, there are indications that they appear to be dependent on course level. Samuelowicz and Bain (1992) reported that several teachers in their study expressed different conceptions of teaching at the undergraduate level than at the graduate level. Conceptions of teaching at the undergraduate level seemed to be lower in the hierarchy, while conceptions at the graduate level seemed to be higher in the hierarchy. Similarly, Prosser et. al. (1994) report that teachers of science service courses were more likely to report lower conceptions of teaching than teachers of introductory courses for science majors.

Prosser and Trigwell (1999) and Prosser et. al. (1994), in the same interview study, also identified five conceptions of learning first year university physical science held by college teachers: 1) learning as accumulating more information to satisfy external demands; 2) learning as acquiring concepts to satisfy external demands; 3) learning as acquiring concepts to satisfy internal demands; 4) learning as conceptual development to satisfy internal demands; and 5) Learning as conceptual change to satisfy internal demands. The high degree of similarity between teachers' conceptions of teaching and their conceptions of learning is attributable to the teachers' lack of ability to differentiate between teaching and learning (Prosser et. al., 1994). Only teachers with the higher conceptions were able to differentiate between teaching and learning. Prosser et. al. (1994) also found that these conceptions of teaching and learning are largely held implicitly by teachers. They reported that, "it was clear from the interviews that these teachers did not spend a lot of time thinking about the way their students learn" (p. 227). They suggested that this might explain the difficulty that many teachers had in expressing their views about the process of learning.

The interaction between the conceptions of teaching and the conceptions of learning was also reported within the same set of studies discussed above (Prosser and Trigwell, 1999; Trigwell, Prosser, & Taylor, 1994). The researchers identified 5 approaches to teaching adopted by the college science teachers in their study: 1) a teacher-focused strategy with the intention of transmitting information to students; 2) a teacher-focused strategy with the intention that students acquire the concepts of the discipline; 3) a teacher/student interaction strategy with the intention that students acquire the concepts of the discipline; 4) a student-focused strategy aimed at students developing their conceptions; and 5) a student-focused strategy aimed at students changing their conceptions. It was concluded that the approaches towards teaching were relatively consistent with these teachers' conceptions of teaching and learning. Consequently, a teacher's intentions in teaching are strongly related to the strategy used (Prosser and Trigwell, 1999; Trigwell & Prosser, 1996; Trigwell et. al., 1994). The study found that an information transmission intention is always associated with a teacher-focused strategy and a conceptual change intention is always associated with a student-focused strategy. The researchers argued that this finding has important implications for professional development efforts. They propose that, "just helping academic staff become aware of, or even practicing, particular strategies will not necessarily lead to substantial changes in teaching practice. The associated intentions or motives also need to be addressed" (p. 85).

Gallagher & Tobin (1987), in a study with high school science teachers, also found this association between teachers' conceptions of teaching and learning and their teaching practices. These teachers were found to hold conceptions of teaching and learning that would be relatively low on previously mentioned hierarchy, and tended to equate task completion with learning. The teachers believed that their job was to cover the material in the text, and learning was the responsibility of the students. Therefore these teachers tended to teach in a way that would ensure the coverage of the content. Gallagher & Tobin (1987) noted that, for the teachers in their study, a majority of their class time was spent in a fashion where the teacher had control over the pacing of the lesson. They also found that the teachers would generally interact with only the top 25% of the students, and if these "target students" appeared to understand the material, the teachers would typically move on to new material.

It becomes increasingly difficult to determine the relationship between teachers' conceptions of teaching and learning and their teaching practices when the teachers have conflicting conceptions. Lumpe, Czerniak, & Haney (1998), in a study with K-12 science teachers, found that although these teachers "believed that including cooperative learning in the classroom could help increase student learning, make science more interesting, increase problem solving ability and help student learn cooperative skills" (p. 128), they also believed that the use of cooperative learning would increase student off-task behavior and take up too much class time. It was found that the concern for off-task behavior was a bigger predictor of a teacher's intention to use cooperative learning. Although Lumpe et. al. (1998) did not draw this conclusion, it seems that the conception of teachers needing to gain control over student behavior is a conservative force that makes many curricular innovations difficult. However, this may not be as much of a force in the post-secondary level.

Reviews of the research literature suggested that teachers' conceptions of teaching and learning are well established by the time they enter college, and that these conceptions are developed and formed during a teacher's experience as a student (Knowles and Holt-Reynolds, 1991; Pajares, 1992). Researchers on college teaching come to the same conclusion (Counts, 1999; Grossman, 1988). In a case study of one college physics teacher, Counts (1999) noted that the teacher based his ideas of good and bad teaching on his experiences as a physics student. The teacher in the study recounted his experiences in a particular class with a professor who "held a positive regard for the students and was very challenging but reasonable" as being the model of an excellent professor (Counts, 1999, p. 129).

Previous research studies suggest that the college physics teachers interviewed in this research program will have a range of conceptions of teaching and learning from teaching as transmission of information to teaching as facilitating conceptual change. They also suggest that most of the interviewees will likely have conceptions of teaching and learning that are similar to transmission of information. Furthermore, it may be impossible, for many of the interviewees, to distinguish between conceptions of teaching, their conceptions of learning, and their teaching intentions. Thus, the interview was designed to allow the researchers to probe for distinctions between these three different types of conceptions when they are able, but not forcing distinctions where none existed.

Conceptions of Subject Matter

Much of the research on science teachers' conceptions of subject matter has been focused specifically on the nature of science (Abd-El-Khalick, Bell, & Lederman, 1998; Bell, Lederman, & Abd-El-Khalick, 2000; Brickhouse, 1990; Hodson, 1993; Lederman

& Zeidler, 1987). The results of much of this research have indicated no apparent link between a teachers' conception of the nature of science and their teaching behavior. (Abd-El-Khalick et. al., 1998; Bell et. al., 2000; Hodson, 1993; Lederman & Zeidler, 1987). In a study of preservice high school teachers' conceptions of the nature of science, Bell et. al. (2000) found that although these teachers had views of the nature of science that were consistent with contemporary conceptions, and indicated that the nature of science was an important instructional goal, none of them thought that they had adequately addressed the nature of science during their teaching. They mentioned a number of constraints to explain this apparent discrepancy. Most frequently these teachers perceived a conflict between teaching the nature of science and teaching the science content and process skills. Another source of constraint was the substantial amount of time that was required to teach the nature of science, and thus teaching the nature of science would cause them to fall behind other teachers in the content coverage. Hodson (1993) reported similar findings a study conducted with secondary science teachers. He found that even those teachers who hold clear and consistent views about the nature of science do not plan activities consistently in relation to those views. Instead, the teachers were again more concerned with issues of classroom management and course content coverage.

There is some evidence, however, that some teachers have beliefs about the nature of science that influence their classroom practice. Brickhouse (1990), in her study with science teachers, found that the teachers' views of the nature of scientific theories, scientific processes, and scientific progress were all correlated with their views of teaching and with their teaching actions. Some of the teachers considered scientific progress as a process that occurs through "the accumulation of facts rather than by changes in theory. Similarly, they expected their students to learn by accumulating bits of information" (p. 57). Others, however, believed that science progress occurs through new interpretations of old observations, and so students learn science through the interplay between thinking about old information and assimilating new information. Brickhouse (1990) concluded that these teachers' teaching strategies were well aligned with their views about the nature of science.

The subject matter of primary concern in this research program is problem solving in physics. The studies of teachers' conceptions of the nature of science may provide some insight into the possible relationships between teachers' conceptions of problem solving in physics and their teaching practice. Since this is as yet a new area and a major focus of this research program, in order to determine this relationship between conceptions of problem solving in physics and teaching practice, the interview was designed to elicit teachers' conceptions of problem solving separately from their conceptions of the teaching and learning of problem solving.

Conceptions of the Teaching Context

Many studies have focused on teachers' conceptions of various aspects of their teaching context (Abd-El-Khalick et. al., 1998; Bell et. al., 2000; Boice, 1994; Carter & Doyle, 1995; Hodson, 1993; Lantz & Kass, 1987; Prosser & Trigwell, 1997, 1999; van Driel, Verloop, Werven, & Dekkers, 1997). The discussions below will address some of the findings in these studies.

Prosser and Trigwell (1999), in their study on approaches to teaching, identified several context variables that were related to approaches to teaching. In that same study they also found that "a conceptual change/student-focused approach to teaching is associated with perceptions that the workload is not too high, the class sizes are not too large, that the teacher has some control over what and how he/she teaches and that the variation in student characteristics is not too large" (p.156). Conversely, they indicated that, "an information transmission/teacher-focused approach to teaching is associated with perceptions that the teacher has little control over how and what he/she teaches and that there is little commitment to student learning in the department" (p. 156). Trigwell and Prosser (1997) suggested that teachers' choice of a particular teaching approach is dependent on both their prior experience with such an approach and their perceptions of whether such an approach is compatible with the teaching situation.

A large study on college teachers across multiple disciplines (Boice, 1994) concluded that both new and experienced teachers describe their teaching practices as dominated by lecturing of facts-and-principles. Boice (1994) identified these teachers' conceptions of the teaching context as a factor in the stability and ease of their teaching practices. While experienced teachers do so because of familiarity, new teachers do so because of their concerns about how criticism of their teaching might affect their tenure review. This led them to teach defensively and made sure that they had the facts straight. Instead of reflecting on their teaching styles upon receiving low teaching ratings, they tended to blame teaching failures on contextual factors such as poor students, heavy teaching loads, and invalid rating systems.

Although a teacher's perception of students can be an important contextual variable, Carter & Doyle (1995) suggested that teachers are often not good at perceiving student abilities or interests. They noted that teachers often judge instructional practices based on how they themselves reacted, or would have reacted, to similar practices as students. Since most teachers were successful as students, Carter & Doyle (1995) suggested that teachers base their teaching practices on incomplete assumptions about "the range and diversity of students' capabilities and interests and on unrealistic beliefs in the attractiveness of their own preferences" (p. 189). They also see this tendency of teachers to think about teaching from their perspective as students as a conservative force against innovations in curricula.

The research reviewed here suggests that teachers have many different contextual variables that they refer to when talking about their teaching. Further, these perceptions of contextual variables often serve as conservative forces that lead to the continuation of current teaching methods. Thus, knowing about teachers' conceptions of these variables is very important to the goals of this research program. The interview was designed to give teachers many opportunities to discuss these variables when talking about their instructional decisions.

The Teaching Cycle

Wilson et. al. (1987) described a model of pedagogical reasoning that is useful in understanding the basis of the teaching cycle. Their model has six components: comprehension, transformation, instruction, evaluation, reflection, and new comprehension. Pedagogical reasoning begins with the teacher's comprehension of the subject matter to be taught. The teacher must then transform this subject matter into a plan or set of strategies for teaching the subject matter to a particular group of students. The instruction is then the execution of the plan. During and after instruction, the teacher must also engage in evaluation and reflection. This process of learning from experience may lead the teacher to a new comprehension, which in turn informs the teacher during the next transformation phase. Herein lies the cyclical nature of teaching. The teaching cycle highlights the importance of experience in the development of context-specific conceptions and expertise in teaching.

Teachers' Context-Specific Conceptions

Each teaching cycle begins with teachers' context-specific conceptions. These conceptions had been described as pedagogical content knowledge (Fernandez-Balboa & Stiehl, 1995; Grossman, 1988; Shulman, (1986); van Driel, Verloop, & de Vos, 1998; Wilson et. al., 1987), craft knowledge (van Driel et. al., 1997), and practical knowledge (Beijaard & Verloop, 1996; Berliner, 1986; Elbaz, 1981; van Driel, Beijaard, & Verloop, 2001). The essence of all of thee different ways of thinking about context-specific conceptions is that, as part of their classroom practice, teachers acquire conceptions that they use in their day-to-day teaching (Calderhead, 1996). These conceptions are considered as the interface between teachers' conceptions of the subject matter and the transformation of this subject matter for the purposes of teaching (Geddis, 1993). Similar to general conceptions, these context-specific conceptions are usually implicitly held, and having a large network of context-specific conceptions is one of the signs of expertise.

The most common way that these context-specific conceptions are currently discussed is as Pedagogical Content Knowledge (Shulman, 1986). In their review of the literature, van Driel et. al. (1998) concluded that there are two elements that all researchers include as part of Pedagogical Content Knowledge: knowledge of comprehensible representations of the subject matter, and understanding of content-related learning difficulties. In a study of relatively new humanities and social science college teachers, Lenze (1995) noted three characteristics of pedagogical content knowledge: it is often implicit, it is individualized with respect to the purpose of each teacher, and it is discipline-specific.

There is also evidence that suggests that pedagogical content knowledge is developed primarily during classroom practice (Cochran, 1997; Counts, 1999; Grossman, 1988; Lenze, 1995; van Driel et. al., 1997; van Driel et. al., 1998). Thus, beginning teachers should not be expected to have extensive pedagogical content knowledge. The relationship between context-specific conceptions and classroom practice is as yet not clear. The only agreement among researchers is that pedagogical content knowledge is seen as the link between the mental processes involved in teaching and the teaching itself (Cochran, 1997).

It may be reasonable to expect differences to exist between the context-specific conceptions of college teachers and K-12 teachers, since they are primarily developed through experience. The experience of college teachers is considerably different from that of a high school teacher (Baldwin, 1995; Fernandez-Balboa et. al, 1995). College teachers typically have larger classes, which may lead college teachers to have fewer opportunities to interact with individual students. College teachers assume their students to be more mature than K-12 students, and therefore typically do not have to consider classroom management in the same degree as K-12 teachers. There is also the difference in the level of subject matter expertise. While some K-12 teachers may lack subject matter knowledge, it seems reasonable to assume that college teachers possess sufficient subject matter knowledge. Since a thorough understanding of the subject matter is a prerequisite to the development of context-specific conceptions (Grossman, 1988; van Driel et. al., 1998), this difference also leads to the expectation that college teachers and K-12 teachers will have different context-specific conceptions.

The research on context-specific conceptions points to the key role that these conceptions play in shaping teaching practice. Because these conceptions are largely implicitly held, it would not be fruitful to simply ask the interviewees to describe their conceptions. This led to the design of an interview around concrete instructional artifacts that would allow the conceptions to be inferred from what the teachers said during the interview.

Expertise In Teaching

Some researchers have focused on how teachers develop teaching skills (Berliner, 1987; Berliner, 1988; Carter & Doyle, 1987; Dunkin & Precians, 1992; Kwo, 1994). These researchers have compared the development of the skill of teaching to the development of other types of skills. These comparisons were based on the model of skill development introduced by Dreyfus and Dreyfus (1986a, 1986b). Kwo (1994) described five stages of skill development in teaching:

1. **Novice**. At this stage, a teacher is labeling and learning each element of a classroom task in the process of acquiring a set of context-free rules. Classroom teaching is rational and relatively inflexible, and requires purposeful concentration.

2. **Advanced Beginner**. Many second- and third-year teachers reach this stage, where episodic knowledge is acquired and similarities across contexts are recognized. The teacher develops strategic knowledge and an understanding of when to ignore or break rules. Prior classroom experiences and the contexts of problems begin to guide teaching behavior.

3. **Competent**. The teacher is now able to make conscious choices about actions, set priorities, and make plans. From prior experience, the teacher knows what is and is not important. In addition, the teacher knows the nature of timing and targeting errors. Performance, however, is not yet fluid or flexible.

4. **Proficient**. Fifth-year teachers may reach this stage, when intuition and know-how begin to guide performance and a holistic recognition of similarities among contexts is acquired. The teacher can now pick up information from the classroom without conscious effort, and can predict events with some precision.

5. **Expert**. Not all teachers reach this stage, which is characterized by an intuitive grasp of situations and a non-analytic, non-deliberate sense of appropriate behavior. Teaching performance is now fluid and seemingly effortless, as the teacher no longer consciously chooses the focus of attention. At this stage, standardized and automated routines are operated to handle instruction and management.

This view of skill development may lend some insight into explaining why the research aimed at modeling teachers' decision-making ultimately failed. As Dreyfus and Dreyfus (1986b) explained, "when things are proceeding normally, experts don't solve problems and don't make decisions; they do what normally works" (p. 30). This view of skill development may also help to explain how general conceptions can influence teaching behavior. Dreyfus and Dreyfus (1986a) noted that one of the key components of competence is that the performer must choose a plan, goal, or perspective that organizes the situation in order to avoid being overwhelmed with information. The competent performer can then examine the small set of features that are most important to the plan. They note that the choice of a perspective to organize information "crucially affects behavior in a way that one particular aspect rarely does" (Dreyfus & Dreyfus, 1986a, p. 322). Furthermore, this perspective is what guides the development of expert behavior, with different perspectives resulting in different types of behavior.

Several empirical studies have produced evidence supporting this view of skill development in teaching (Berliner, 1987; Berliner 1988; Carter & Doyle, 1987; Dunkin & Precians, 1992; Kwo, 1994). For example, Berliner (1987) reported that, "our experts see classrooms differently than do novices … because they no longer see classrooms literally. They appear to us to weigh information differently according to its utility for making instructional decisions. Almost without conscious thinking they make inferences about what they see" (p. 69). In addition, the report indicated that the experts recalled fewer details about individual students and the class as a whole than did the novices. The novices believed that they should have remembered all of the information presented to them about each student, while experts only used the student information briefly to convince themselves that this was a normal class. The experts saw no use in remembering information about individual students. In a study with college teachers, Dunkin and Precians (1992) compared interview results between award-winning teachers and novice teachers. They asked each of the teachers about possible ways to enhance student learning in their classes and found that the award-winning teachers were able to combine several dimensions (e.g., teaching as structuring learning and teaching as motivating learning) while novice teachers tended to answer along a single dimension.

One of the major findings from this research on expertise is that experts and novices can have different ways of looking at the same information. This required that the interview questions for this research program be designed so that both an expert and a novice could understand and answer appropriately. Understanding of the stages of expertise could also help the interpretation of the interview results. For example, describing relatively few features of an instructor solution could be a sign of a novice who is not aware of many things, or a sign of an expert who only pays attention to a few important features. Therefore, level of expertise cannot be identified solely on the basis of the amount of descriptions.

Reflection

Several studies have investigated changes in teachers' conceptions of mathematics and mathematics teaching. In a review of these studies, Thompson (1992) noted that these conceptions are quite robust. He found that in order for conceptual change, being confronted with contradictory information was a necessary, but not sufficient condition. In many cases teachers tend to assimilate the new information by modifying the new ideas to fit into existing conceptions (Briscoe, 1991; Thompson, 1992). Seldom does the new information directly and immediately cause teachers to change their existing conceptions.

There are a couple of reasons why conceptions self-perpetuate in this fashion (Pajares, 1992). First, individuals tend to view conflicting evidence as support for an existing belief, even if that completely distorts the evidence. Second, conceptions influence an individual's behaviors, and these behaviors in turn reinforce the original beliefs. For example, a teacher who thinks of teaching as an information transmission activity will likely behave accordingly, and all evidence of student learning will be credited to this approach. These reasons led Pajares (1992) to conclude that conceptions are "unlikely to be replaced unless they prove unsatisfactory, and they are unlikely to prove unsatisfactory unless they are challenged and one is unable to assimilate them into existing conceptions"(p. 321). Thus, changes in conceptions are proposed to be possible only if implicit conceptions are made explicit and reflected on (Dunn & Shriner, 1999; Ericksson, Krampe, & Tesch-Romer, 1993; Menges & Rando, 1989). In their review of the development of expertise, Ericksson et. al. (1993) pointed to continual deliberate practice, a highly reflective activity, as the most important contributing factor to developing exceptional performance.

In his interview study with college teachers from a variety of disciplines, Boice (1994) concluded that the college teachers' conceptions of teaching and their teaching practices were very stable, even in their first few years of teaching. These teachers viewed college teaching as delivering facts and principles via lecturing. Therefore, when faced with poor ratings and personal dissatisfaction, most teachers did not consider changing their approach to teaching, but rather focused on the improvement of lecture content. Furthermore, these teachers conveyed their intentions on making assignments and tests easier to reduce some of the student criticism.

The research on the role of reflection in the development of expertise suggests that conceptions tend to be self-perpetuating because teachers take on an organizing perspective that is not compatible with certain ideas. Understanding this organizing perspective is one of the goals of this research program. Thus, the interview was designed to probe the way teachers think about a variety of different situations in an attempt to uncover this organizing perspective.

Summary of Research on Teachers' Conceptions

This body of research suggests that teachers' conceptions, to a large extent, influence their instructional behaviors. Teachers hold both general and specific conceptions that are largely implicit, and these conceptions are primarily influenced by a teacher's experience both as a student and a teacher. Teachers also often have conflicting conceptions, and beginning teachers often make instructional decisions based on a poorly integrated set of conceptions. It is unclear, however, how these conflicting conceptions actually interact to affect instructional decisions. Most studies suggest that teachers with considerable teaching experience within a particular context have developed routines for many common aspects of instruction, and therefore no longer require a conscious effort in making instructional decisions. This body of research also suggests that it is very difficult to influence conceptions and practices of both experienced and beginning teachers.

Based on the supporting research literature, a teachers' general conceptions about problem solving, the role that problem solving should have in physics instruction, ways that problem solving could be taught, and students' ability to learn problem solving, would all be expected to influence a physics instructor's conceptions of teaching problem solving in a particular context. These context-specific conceptions would then have a direct impact on their instructional practices. All of these conceptions can be expected to be quite robust and strongly influence a teacher's evaluation of new instructional techniques.

Research on Problem Solving

Researchers in physics and in other fields have built up a large body of literature related to problem solving. In order to be a good problem solver, a student must possess the necessary domain knowledge, as well as an understanding of general problem solving processes (Maloney, 1994). The common instructional practice of having students solve standard physics problems, however, appears to be counter-productive for reaching these goals. This practice tends to reinforce the relatively poor problem-solving strategies and ineffective knowledge structures that some students already possess (Maloney, 1994).

Problem Solving

Martinez (1998) defined problem solving as "the process of moving toward a goal when the path to that goal is uncertain" (p. 605). There is no formula for true problem solving, only heuristics that may guide the process. A heuristic is a rule of thumb, a strategy that is both powerful and general, but not absolutely guaranteed to work. Simon (1981) likened problem solving to working through a maze. In negotiating a maze, one works towards the goal step by step, making some false moves, and gradually moves closer to the intended end point. The rule of choosing a path that seems to result in some progress toward the goal may have guided the choices that one makes in negotiating the maze. Such a rule, called "means-ends analysis", is an example of a heuristic. Means-ends analysis suggests the formation of sub-goals to reduce the discrepancy between the current state and the ultimate goal state. This heuristic helps the problem solver move incrementally towards the ultimate goal, but is not a process of trial and error because the steps taken are not random; the series of steps are applied tactically for the purpose of moving closer to the goal.

There are many other heuristics. An example of which is "working backward." This heuristic suggests the problem solver to first consider the ultimate goal. From there, the problem solver should decide what would constitute a reasonable step just prior to reaching that goal. Then, decide what would be a reasonable step just prior to that. Beginning with the end, the problem solver builds a "strategic bridge backward and eventually reaches the initial conditions of the problem " (p. 607). Another heuristic is solving problems through "successive approximation." Like writing, the initial goal of successive approximation is to produce a rough draft or an outline of ideas. Over time, the draft is organized and refined into something better, with new ideas added and old ideas removed. Eventually, a polished form emerges that finally approximates the effect that the problem solver intended.

Traditionally, the teaching of problem solving has not explicitly included the teaching of heuristics. This is not an ideal situation. A curriculum that encourages problem solving needs to provide more than just practice in solving problems; it needs to offer explicit instruction in the nature and use of heuristics (Simon, 1980). Furthermore, instruction must convey the understanding that, in its nature, problem solving involves errors and uncertainties. As such, both teachers and learners need to be more tolerant of the errors as part of the problem-solving process.

Metacognition

Although heuristics help a problem solver break down a problem into more manageable pieces, the challenge becomes one of managing the sub-goals. Carpenter, Just, and Shell (1990) regarded such goal management as a central feature of problem solving, and is an example of a more general phenomenon of self-monitoring known as metacognition. In what is now a generally accepted description, Flavell (1976) described metacognition as:

> "… one's knowledge concerning one's own cognitive processes and products or anything related to them, e.g., the learning-relevant properties of information or data …. Metacognition refers, among other things, to the active monitoring and consequent regulation and orchestration of these processes in relation to the cognitive objects on which they bear, usually in the service of some concrete goal or objective." (p. 232)

Flavell (1979) later reworded metacognition as "knowledge and cognition about cognitive phenomena" (p. 906).

It is not always easy to distinguish what is metacognitive and what is cognitive. One way of viewing the relationship between them is that "cognition is involved in doing, whereas metacognition is involved in choosing and planning what to do and monitoring what is being done" (Garofalo & Lester, 1985, p. 164). Although there are several aspects of metacognition in the research literature, this review will concentrate on the regulatory aspects that are crucial to problem solving (Schoenfeld, 1983).

Schoenfeld (1992), in a review of mathematics education literature, pointed out that research results in the early 1980's (see for example Silver, 1982; Silver, Branca, & Adams, 1980; Garofalo & Lester, 1985; Lesh, 1985) demonstrated that, for effective problem solving, "it's not just what you know; it's how, when, and whether you use it" (p. 355). Metacognitive knowledge such as these includes knowledge of general strategies that might be used, knowledge of the conditions under which these strategies might be used, and knowledge of the extent to which the strategies are effective (Flavell, 1979; Pintrich, Wolters, & Baxter, 2000; Schneider & Pressley, 1997). In addition to knowing "what" and "how", the problem solver must also develop knowledge about the "when" and "why" of using the strategies appropriately (Paris, Lipson, & Wixson, 1983).

In general, the regulatory aspect of metacognition is concerned with decisions and strategic activities that one might engage in during the course of working through a problem. Examples of such activities include selecting strategies to aid in understanding the nature of a problem, planning courses of action, selecting appropriate strategies to carry out plans, monitoring execution activities while implementing strategies, evaluating the outcomes of strategies and plans, and, when necessary, revising or abandoning nonproductive strategies and plans (Garofalo & Lester, 1985). Much of the research on the metacognition pertaining to problem solving has been done in mathematics education (e.g., Brown, Brown, Cooney, & Smith, 1982; Brown & Cooney, 1982; Schoenfeld, 1983, 1987; Silver, 1982). This research has indicated that successful problem solvers spend more time analyzing a problem and the directions that may be taken than do less successful problem solvers. In addition, successful problem solvers monitor and evaluate their actions and cognitive processes throughout the entire problem-solving process (Lester, Garofalo, & Kroll, 1989; Schoenfeld, 1983, 1985, 1987). These attributes are considered as the regulatory aspect of metacognition.

Paris and Winograd (1990) categorized research of metacognition in mathematics education as studies of self-management that help to orchestrate aspects of problem solving. The aspects orchestrated by such self-management include the plans that problem solvers make before tackling a task, the adjustments that problem solvers make as they work, and the revisions that problem solvers make afterwards. Silver (1987), when describing the structure of memory in relation to solving mathematics problems, dubbed these metacognitive processes as planning, monitoring, and evaluation. Results of the studies consistently show that students, at every stage, are deficient in such managerial skills. For example, studies with college students found that, although they are very much capable at the tactical, or "implementing things", aspect of problem solving, college students are very inept at the managerial, or decision making, aspect of problem solving (Hofer, Yu, & Pintrich, 1998; Pintrich, McKeachie, & Lin, 1987; Schoenfeld, 1983). Such research findings led to the suggestion that future studies into the role of metacognition in problem solving should start with an identifiable framework or model into which metacognition can be incorporated.

Several models of problem-solving frameworks have been developed, many of them born out of research in mathematics and physics education (these will be discussed in a later section). It is sufficient to state here that several, if not all, have been based on Polya's (1973) four-stage description of the problem-solving activity. The four stages – understanding the problem, making a plan, carrying out the plan, and looking back – serve as a framework for identifying a multitude of heuristic processes that may foster successful problem solving. Unfortunately, Polya's conceptualization considers metacognitive processes only implicitly. As such, few of the ensuing research studies had attended to metacognition. Studies that have attempted to improve problem-solving competence through task-specific and heuristics-based instructions implied an underlying assumption that "equipping students with the ability to use a variety of heuristics and skills is sufficient to make them good problem solvers" (Garofalo & Lester, 1985, p. 173). Aware of the significance of the metacognition that underlies the application of heuristics, Lester (1983) and Schoenfeld (1983) argued that the failure of most efforts to improve students' problem-solving performance is due in large part to the fact that instruction, although it emphasized the development of heuristics, virtually ignored the managerial skills necessary to regulate problem-solving activities.

Experimental psychologists have also argued for the importance of incorporating metacognitive decisions into instruction. Three types of studies on strategy training have been carried out in developmental psychology: 1) blind training – instruction on the uses of a particular strategy without help of understanding its significance; 2) informed training – instruction on the uses and information on the significance of a particular strategy; and 3) self-regulation training – supplements instruction in carrying out a strategy and information concerning its significance with training on planning, monitoring, and evaluating the strategy implementation. Research in these areas have shown that although informed training yields better results than blind training with respect to management and transfer (Kennedy & Miller, 1976; Lawson & Fueloep, 1980), the self-regulated approach is the most successful (Brown, Campione, & Day, 1981).

A major finding of the research into the role of metacognition in problem solving is that regulatory mental activities are inherent in all problem-solving actions. Since this convergent study focuses on physics instructors' conceptions of the problem-solving process, it follows that the descriptions of these conceptions will inherently include descriptions of metacognition. The results described above provide a framework with which to identify and categorize metacognition (as planning, monitoring, and evaluation), and interpret findings about metacognition in this convergent study.

Differences Between Expert and Novice Problem Solvers

Most instructional strategies designed to improve student problem solving are based on an understanding of the differences between expert and novice problem solvers. In the literature on physics problem solving, the differences between expert and novice problem solvers can be categorized into two types: differences in their knowledge and differences in their approaches to problem solving.

Differences in Knowledge

There are two ways in which experts are different than novices in this domain. First, in terms of quantity, experts have more physics knowledge than novices (de Jong & Ferguson-Hessler, 1986; Maloney, 1994). This is the direct consequence of the discrepancy in the amount of experience that these two groups have. Second, and more importantly, the structure of the knowledge is qualitatively different between experts and novices. The knowledge that experts possess is appropriately structured and hierarchically organized around physics principles to facilitate efficient use. Novices, on the other hand, have a less efficient knowledge structure, typically organized around surface features of problem situations (Chi, Feltovich, & Glaser, 1981; de Jong & Ferguson-Hessler, 1986; Larkin, 1979; Larkin, McDermott, Simon, & Simon, 1980; Maloney, 1994; Van Heuvelen, 1991a; Zajchowski & Martin, 1993). Another component that is related to the organization of knowledge is the integration of knowledge. For experts, because knowledge is well structured and organized, it is consequently well integrated. Novices, however, often have two separate banks of knowledge – one that guides their thinking in classroom situations and another that guides their thinking in everyday life (Maloney, 1994).

Differences in Approaches to Problem Solving

Researchers have found that experts and novices differ considerably in their approaches to problem solving. This is consistent in all aspects of the problem-solving process. Experts frequently approach the start of a problem-solving process by first carrying out a qualitative analysis of the situation and developing a good physical representation. Based on this analysis, experts develop a plan to solve the problem. Novices, on the other hand, frequently begin the problem-solving process by searching for equations to plug numbers in. Because of this, novices typically do not develop a plan to solve the problem (Finegold & Mass, 1985; Larkin, 1979, 1980; Larkin & Reif, 1979; Maloney, 1994; Schultz & Lockhead, 1991; Woods, 1987). This is similar to the research finding on metacognition, in that successful problem solvers tend to spend more time analyzing a problem and the directions that may be taken – planning – than less successful problem solvers (Lester et. al., 1989; Schoenfeld, 1983, 1985, 1987).

Another difference between expert and novice problem solvers is in the evaluation of the problem-solving process. Experts appear not only to continually evaluate their progress when solving a problem, but also evaluate the final answer. These evaluation processes, such as considering limiting cases and checking units, are quite common in experts (Larkin, 1980; Schoenfeld, 1985; Woods, 1987). Novices, on the other hand, do not tend to evaluate their progress, nor are they likely to evaluate their final answer. This is again similar to the research finding on metacognition. Successful problem solvers monitor and evaluate their actions and cognitive processes throughout the entire problem-solving process, whereas less successful problem solvers often do not (Lester et. al., 1989; Schoenfeld, 1983, 1985, 1987). These differences between how expert and novice problem solvers approach problems – planning, monitoring, and evaluating – are in essence identical to the attributes of regulatory metacognition found in successful problem solvers in a variety of disciplines.

Strategies Designed to Improve Student Problem Solving

Physics education researchers have developed a number of strategies that have been shown to be effective in improving student problem-solving performances in the context of introductory physics courses: 1) explicit instruction of a problem-solving framework that helps students to externalize the implicit problem-solving strategies used by experts (Cummings, Marx, Thornton, & Kuhl, 1999; Heller & Hollbaugh, 1992; Heller, Keith, & Anderson, 1992; Mestre, Dufrense, Gerace, Hardiman, & Touger, 1993; Reif & Scott, 1999; Van Heuvelen, 1991b); 2) instruction includes uses of "real" problems that require a higher level of analysis from the students and discourage poor problem solving practices (Cummings et. al., 1999; Heller & Hollbaugh, 1992; Heller et. al., 1992; Van Heuvelen, 1991b); 3) instruction includes uses of concept maps to help students understand the relationships between physics principles and to develop a hierarchically arranged knowledge structure that is more similar to that of experts (Bango & Eylon, 1997; Bango, Eylon, & Ganiel, 2000); and 4) students solve problems with peers in a group setting, where they must externalize and explain their thinking (Cummings et. al., 1999; Heller & Hollbaugh, 1992; Heller et. al., 1992; Reif & Scott, 1999; Van Heuvelen, 1991a). Curricular materials using these instructional strategies have been shown to improve students' problem-solving skill as well as their understanding of physics concepts (Bango & Eylon, 1997; Cummings et. al., 1999; Foster, 2000; Heller & Hollbaugh, 1992; Heller et. al., 1992; Mestre et. al., 1993; Reif & Scott, 1999; Van Heuvelen, 1991b).

Problem-Solving Framework

Several researchers have developed instructional strategies designed to help novices become more expert-like in their approaches to solving problems. The key component of these instructional strategies is the explicit use of a problem-solving framework (Cummings et. al., 1999; Heller & Hollbaugh, 1992; Mestre et. al., 1993; Reif & Scott, 1999; Reif, Larkin, & Brackett, 1976; Van Heuvelen, 1991b). Although each instructional strategy uses a slightly different problem-solving framework with different numbers of steps, most of the frameworks can be attribute some relationship to Polya's (1973) problem-solving stages: understanding the problem, making a plan, carrying out the plan, and looking back. The purpose of the framework is to break down and make explicit the things that experts do when solving problems. For example, Heller et. al. (1992) describe a 5-step framework (p. 630):

1. **Visualize the problem**
   Translate the words of the problem statement into a visual representation:
   - Draw a sketch (or series of sketches) of the situation
   - Identify the known and unknown quantities and constraints
   - Restate the question
   - Identify a general approach to the problem – what physics concepts and principles are appropriate to the situation
2. **Describe the problem in physics terms (physics description)**
   Translate the sketch(s) into a physical representation of the problem:
   - Use identified principles to construct idealized diagram(s) with a coordinate system for each object at each time of interest
   - Symbolically specify the relevant known and unknown variables
   - Symbolically specify the target variable
3. **Plan a solution**
   Translate the physics description into a mathematical representation of the problem:
   - Start with the identified physics concepts and principles in equation form
   - Apply the principles systematically to each object and type of interaction in the physics description
   - Add equations of constraint that specify the special conditions that restrict some aspect of the problem
   - Work backward from target variable until you have determined that there is enough information to solve the problem
   - Specify the mathematical steps to solve the problem
4. **Execute the plan**
   Translate the plan into a series of appropriate mathematical actions:
   - Use the rules of mathematics to obtain an expression with the desired unknown variable on one side of the equation and all the known variables on the other side
   - Substitute specific values into the expression to obtain an arithmetic solution

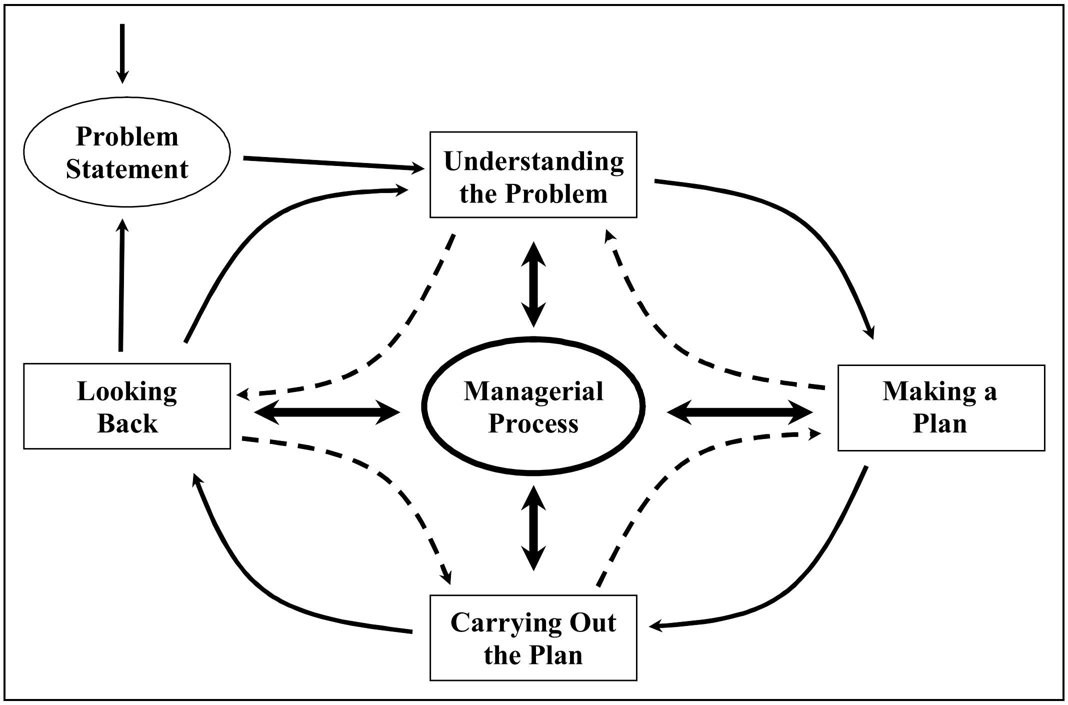
5. **Check and evaluate**
   Determine if the answer makes sense:
   - Check – is the solution complete?
   - Check – is the sign of the answer correct, and does it have the correct units?
   - Evaluate – is the magnitude of the answer reasonable?

In addition to introducing a problem-solving framework, each of these instructional strategies also specifies that this framework should be explicitly taught to students. Students are then typically provided with opportunities to practice and receive help in using the framework. Students are often also required to solve problems using the framework.

Although research has shown that explicitly including a problem-solving framework in instruction results in improvements in physics students' problem-solving performance, some researchers would suggest another implicit action that needs to be explicated during instruction. Researchers in mathematics education argued that too often problem-solving frameworks are presented as stages or steps, thus depicting "problem solving as a linear process involving a series of steps to be completed to arrive at a correct answer" (Fernandez, Hadaway, & Wilson, 1994, p. 196). Frameworks such as this do not capture the dynamic nature of problem solving, including the managerial processes, or regulatory metacognition, of planning, monitoring, and evaluation as alluded to in an earlier discussion. Fernandez et. al. (1994) suggested a framework that would present a dynamics and cyclical interpretation of Polya's (1973) problem-solving framework (see Figure 2-3).

The arrows in Figure 2-3 represent the regulatory metacognitive decisions that are implicit in the movement from one stage to another, and the overall diagram suggests that the problem-solving process is not necessarily linear. For example, a problem solver may begin by engaging in thought to understand a problem, and then move into the planning stage. After some consideration of a plan, and monitoring of self-understanding, the problem solver may recognize the need to understand the problem better. This recognition thus causes the problem solver to return to the understanding the problem

Figure 2-3: Taken from Fernandez et. al. (1973), this problem-solving framework emphasizes the dynamic and cyclical nature of the problem-solving activity. The framework starts at the upper left-hand corner, and proceeds clockwise. The dashed lines represent the "backtracking" between each step, and the oval in the middle represents the necessary regulatory metacognitive processes that are embedded throughout the whole problem-solving process



stage. This backtracking could occur between neighboring stages as well as in between any stage during the whole problem-solving process. Since students are "largely unaware of their thinking processes" (Schoenfeld, 1987, p. 199) during problem solving, it has been suggested that issues related to managerial processes should be explicitly discussed in connection with instruction on problem-solving frameworks (Schoenfeld, 1987).

"Real" Problems

Heller and Hollabaugh (1992) suggested that typical textbook "problems" reinforce novice problem-solving strategies. Textbook problems typically refer to idealized objects, and such objects often do not relate to students' realities. Furthermore, students are often able to solve these textbook problems simply by finding a relevant equation and plugging in numbers. Since students can be successful in using such novice approaches to solve textbook problems, they do not experience the fruitfulness of possessing problem-solving frameworks. In order to encourage students to adopt problem-solving frameworks and develop their own problem-solving skills, Van Heuvelen (1991b) and Heller and Hollabaugh (1992) make use of more realistic problems. These realistic problems are designed so that solving them using the typically novice approaches are no longer feasible. Although they go by different names – "context-rich problems" for Heller and Hollabaugh, and "case study problems" by Van Heuvelen – the features of these problems are similar. These realistic problems usually involve multiple steps and multiple principles, requiring students to break the problem into subparts and then recombine each part. These problems may be poorly defined, requiring students to make reasonable assumptions in order to proceed. These problems may not contain all of the necessary information, requiring students to determine what information is missing and make reasonable estimates in order to proceed. These problems may also contain more information than is actually necessary, requiring students to make decisions about what information is actually needed to proceed.

Concept Maps

Some instructional strategies focus on the development of hierarchically organized knowledge without focusing explicitly on approaches to problem solving (e.g., Bango & Eylon, 1997; Bango et. al., 2000). Students in this type of instructional strategy develop their own explicit representation of the relationships between physics concepts based on their own experiences solving problems. As they solve new problems, the students explicitly refine and expand this hierarchical organization of knowledge around physics principles. Other instructional strategies focus on developing both hierarchically organized student knowledge around physics principles and students' approaches to problem solving (e.g., Van Heuvelen, 1991b). After students have had some experience with a group of related concepts, the instructor presents a hierarchical chart that shows the relationship between these concepts, and how they are related to the concepts learned previously in the course. As mentioned earlier, this type of instructional strategy also explicitly uses a problem-solving framework.

Guided Practice

In order to learn how to effectively use and internalize the problem-solving frameworks, students must practice using them and receive feedback about their progress. In many instructional strategies, this practice occurs in an environment where students can receive immediate feedback. In addition, this type of instructional strategy also places students in the role of the coach. This explicitly provides the opportunity for students to externalize and explain their thinking during the problem-solving process. Reif and Scott (1999) do this by having students work with a computer-based tutor. In this strategy, the student and the computer, engaged in what is know as “reciprocal teaching” (see for example, Brown & Palincsar, 1982, 1989; Palincsar & Brown, 1984), takes turn giving each other guidance in solving problems. Heller, Keith, and Anderson (1992) and Van Heuvelen (1991a) do this by having the students work together on problems. For Heller, Keith, and Anderson (1992), students, working in cooperative groups, are assigned roles – manager, skeptic, and checker/recorder – that reflect the regulatory metacognitive activities of planning, monitoring, and evaluation that individuals must perform when solving problems alone. These instructional strategies provide explicit opportunities for the externalization of the metacognitive activities described above.

Summary of Strategies Developed to Improve Student Problem Solving

There is a large body of research focusing on the attributes of effective problem solvers. In physics education research, this focus has yielded evidence for differences between expert and novice problem-solving performances. Expert problem solvers are different from novices in two major ways. Experts have a more efficiently organized hierarchical knowledge structure, and approach problems differently. Combining the research from other fields, this difference in problem solving approach could be summarized as a difference in metacognitive control. Expert problem solvers qualitatively analyze the problem situation, and inherently plan, monitor, and evaluate the solution throughout the entirety of the problem-solving process; novice problem solvers often do not do any of these.

Although traditional physics instruction does little to change students' novice problem-solving approaches or help them construct knowledge that is hierarchically organized, several instructional strategies have been shown to be effective in making such changes. In order to teach problem solving well, an instructor should have an understanding of the differences between experts and novices, and how to incorporate such knowledge into effective instructional strategies. Thus, the interview and the analysis procedure were designed to investigate the level of understanding that physics instructors have in this domain.