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Educating Teacher Educators

Anyone who knows me is generally aware that one of my key areas of interest is recruiting the next generation of high school physics teachers. As the number of students in teacher preparation programs begins to climb due to independent institutional and systemic initiatives such as PTEC, it is becoming more and more evident that we also need more physics teacher educators. Not only do we need more teacher educators, we also need better prepared teacher educators. We need teacher educators who can prepare teacher candidates in ways that will lead to effective teaching and long-term retention in high school teaching positions. Recruiting and preparing the next generation of high school physics teachers will do little good if novice teachers leave the profession within the first few years. The current national "drop out" rate for new teachers is 46% within the first five years. Failing to prepare physics teachers in the best possible way for the positions in which they will teach is a wasteful use of energy, time, and resources. More and more, future generations of high school physics students will pay the price by having to learn physics under the tutelage of under prepared teachers if something isn't done about the situation. Currently, out-of-field teachers teach 56% of all high school physical science courses in the United States.

The fact that we need more and better-prepared high school physics teachers implies that we need more and better prepared teacher educators. This has become extremely clear to me over the years. I have spoken to a multitude of physics teacher educators, department heads, and college deans about this topic – both nationally and internationally – and many have expressed grave concerns about finding well-qualified physics teacher educators. Recent discussions with leadership of *The Renaissance Group* are suggestive of the fact that they, too, are interested in developing new physics teacher education programs at their 34 institutions across the United States. Where will these much needed physics teacher educators come from?

My experience with physics teacher preparation – including attendance at PTEC and national and state-level AAPT meetings, committee memberships, and conversations with my peers – has suggested to me that many of us who educate future high school physics teachers have no formal preparation in this area. We often have degrees in either physics, physics education research, or some related field, but no one I have met has a degree in physics teacher preparation per se -- including myself. While content knowledge is essential to teacher preparation, it is not sufficient.

I suspect that most teacher educators, if not all, have learned how to teach teachers on the basis of our own experience. I know of no institution that prepares candidates for the role of physics teacher educator.

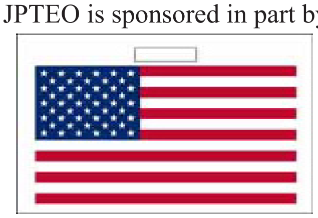
There are two possible solutions to this problem as I see it. National organizations might want to develop methods for both new and experienced teacher educators to conduct a serious self-assessment and then educate one another through national meetings, or teacher educators might want to promote a set of standards for self-education.

In my estimation, it would be very helpful to hold a series of summer institutes under the auspices of one of the national physics groups. Such institutes would be well funded with stipends for participation, housing, meals, and travel allowances. The institutes would be of sufficient duration and intensity that participants would come away with plenty of first-hand experiences that could help them to develop their own physics teacher education courses. The faculty of these summer institutes would not be theoreticians; rather, they would be experienced and highly successful physics teacher educators with their own physics teacher preparation programs. The content of the summer institutes would be worked out in advance, and could require participants to complete nearly the same set of activities that students currently do in successful physics teacher education programs. Such summer institutes ideally would be grant-funded.

If, indeed, we are to remain self-educated, then it seems reasonable that we should make reference to a set of professional development standards. One such set of standards that I have come to rely upon for my own professional growth is that promulgated by AETS (now ASTE) at the following URL: http://www.lpi.usra.edu/education/score/ASTEstandards.pdf. In addition, teacher educators seeking additional experiences might consider completing sabbaticals at institutions where there are successful physics teacher education programs. Successful programs tend to be large and growing, and a helping hand might well be just what's needed.

I think that the time is right for institutions, groups of institutions, and regional and national organizations to consider the development of a framework for masters and doctoral-level teacher educator programs. I also think that the time is ripe for a national discussion on this matter.

Carl J. Wenning
JPTEO EDITOR-IN-CHIEF



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The convergence of knowledge organization, problem-solving behavior, and metacognition research with the Modeling Method of physics instruction – Part II

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In order to understand why a teaching methodology such as Modeling Instruction in High School Physics might be demonstrating gains in conceptual understanding and problem solving on the part of the students one must review cognition-based research. This article will review the pertinent literature investigating the differences in problem-solving and knowledge structure organization between experts and novices. In addition, lab and classroom based problem-solving studies will be reviewed. The pertinent literature will then be compared with the basic tenets of Modeling instruction.

The Modeling Method of Physics Instruction is an example of a curriculum whose efficacy may be better understood by studying the pertinent cognitive science research. In order to refine a curriculum it is useful to have an understanding of why students might be exhibiting the exit skills shown. By reviewing studies in these areas this paper will expand on Malone (2006) and attempt to demonstrate how an understanding of previous research in knowledge organization and metacognition can inform the practice of modeling educators.

Knowledge Structure Training Studies

A number of the research studies discussed in Malone (2006) demonstrated a link between better problem solving and more expert-like knowledge structures such that one might want to consider teaching students to categorize problems based on principles, to chunk representations of the same principle together and ignore surface features in favor of a global view. This of course assumes that there is a link between course instruction and knowledge structures since it might be possible that a more expert-like knowledge structure might be something inherent in the nature of good problem solvers and devoid of instruction. Champagne, Klopfer, Desena, and Squires (1981) demonstrated via a card sort task in a middle school class that was studying rocks and minerals that the pre to post student knowledge structures showed a marked movement towards a structure more consistent with what is considered standard in geology. This finding was replicated by several different investigators utilizing card sorts and word association tasks in math and physics (Shavelson, 1972, 1974; Shavelson and Stanton, 1975; and Thro, 1978).

Knowledge Structure Studies Conducted in a Laboratory Setting

Given the findings of Shavelson (1972, 1974), Shavelson and Stanton (1975) and Thro, (1978) one might conclude that maybe it is the additional conventional problems students solve that helps produce a more expert-like knowledge structure. Sweller (1988) and Sweller and Cooper (1985) proved that this was incorrect and basically that no change occurred in a student's schema after having completed additional conventional problems. Sweller (1988) suggested that the use of means-ends analysis on the part of the novice student might produce too heavy a cognitive load that limits their ability to concentrate on the overall structure in the problem therefore showing no change in knowledge structure.

A series of studies looked at the differences in abilities produced when students studied hierarchical vs. linear materials that taught a knowledge structure directly. Eylon and Reif (1984) contrasted differences in these two types of instructional methods of acquiring knowledge in the domain of modern physics specifically its' theory and history. The hierarchical organization materials stressed a top down understanding of the knowledge which related how the concepts were linked with the general knowledge or principles in the top level and concept specifics located in the lower levels. Their argument was that this type of structure would allow students to systemically search for information. The non-hierarchical treatment consisted of a single level of organization of the knowledge elements contained in the lower level of the hierarchical treatment. Eylon and Reif (1984) evaluated the students after they received the treatment on a number of different tasks. The students were tested to make sure they had developed the given organization and then were given free recall, cued recall and problem-solving reasoning tasks. The hierarchical group performed significantly better than the linear groups. It was also shown that these students performed better on complex tasks requiring information from several areas since the organization allowed for higher level connections between pieces of information. In addition, Eylon and Reif (1984) discovered that the hierarchical organization did not allow students to perform better on local tasks which required knowledge of isolated pieces of information. Therefore, the linkage between chunks seemed to produce greater flexibility. This finding was replicated in the area of electricity by Smith and Goodman (1984).

Taking a slightly different tack at the problem, the physics education research group at the University of Massachusetts in a series of experiments attempted to determine if knowledge structures could be taught to novice students (Hardiman, Dufresne, and Mestre, 1989; Mestre, Dufresne, Gerace, Hardiman, and Touger, 1993; and Dufresne, Gerace, Hardiman, Thibodeau and Mestre, 1992). They trained novices who had already completed a college physics course in mechanics to categorize problems in terms of principles using a computer program called HAT (hierarchical analysis tool). Once the students selected the principle the computer provided a set of equations that could be used to determine the solution similar to the chunking of equations observed by researchers (Malone, 2006). They hoped that this type of tree-like hierarchical approach would allow the students to restructure their knowledge into a more "expert-like" format. They gave the students the Chi, Feltovich, and Glaser (1981) card sort task pre and post experimental treatment and discovered a significant increase in performance. Looking more closely at the data they discovered that the HAT program only produced a change in those students who had not already relied on principles prior to the treatment. Having shown that the treatment with HAT could produce more "expert-like" knowledge structures they then tested to determine if the subjects showed an increase in problem-solving ability. This result was obtained when the HAT subjects demonstrated a 15% increase in problem-solving score over the control students but only when the problems used in the experimental treatment were not too difficult. When the difficulty of the experimental treatment problems increased there was no difference demonstrated between the HAT and control group. This finding lends support for Sweller's (1988) cognitive load hypothesis. In addition, this provides a clue as to why the high school students in the Huffman (1994) study did not show an increase in problem-solving ability since the experimental group method employed the use of difficult context-rich problems. Maybe, as Sweller hypothesized, the students were unable to attend to the principles on which the problem because of the high cognitive load (Sweller, 1988). The context richness of the problem requires the students to use a large amount of their cognitive processing capacity in order to complete the solution process thereby being unavailable for schema acquisition based upon physics principles.

Bagno and Eylon (1997) designed a study that connected the solving of physics problems to the reorganization of high school students' knowledge structures after a year-long course. They used concept maps to aid their students in relating concepts together in a hierarchical knowledge structure in the area of electricity and magnetism. The students would actively create the concept maps while solving problems utilizing a problem-solving strategy that consisted of the following:

- Solve – the students would solve a set of problems
- Reflect – the students would reflect on the what principles and concepts were involved in the set of problems
- Conceptualize – the students elaborate on the concepts and principles reflected upon in step two
- Apply – the students apply their new knowledge and concept map to novel physics problems
- Link – the students consistently link new concept maps developed for one problem set to the concept maps developed for previous sets of problems.

The experimental students' performance was compared to two control groups. One control received no additional training while the other did work on improving their conceptual difficulties but received no training on concept maps. Bagno and Eylon (1997) found that the experimental students performed better on all of the final tasks which included a summary of the main ideas of the domain (in order to determine the form and content of their knowledge structure), explaining the correctness of statements in electromagnetism, problem-solving ability on standard and nonstandard problems and a transfer task (asked to read a unfamiliar text and write out the main concepts and their relations). Bagno and Eylon (1997) concluded that actively constructing concept maps did indeed create a link between those concepts and problem-solving applications. Bagno, Eylon and Ganiel (2000) redesigned the materials from this study to link mechanics with electromagnetism topics and replicated the findings of the 1997 study. The study showed that one could change a student's knowledge structure after a year long course with a problem-solving strategy that was designed to help them focus on the structure and function of the connections.

Weber (2001) designed a study in the domain of mathematical proof to determine if students' inability to solve homomorphism problems was due to the lack of conceptual knowledge or the lack of strategic knowledge. He discovered that the students seemed to be missing strategic knowledge (i.e., the ability to determine when to apply their conceptual knowledge to particular problems). Weber (2001) then designed a five-step procedure that would help students to apply their conceptual knowledge to prove statements about group homomorphism. This procedure required the students to initially categorize the problems based upon four structures that were typically used to prove statements about group homomorphism problems. Weber (2001) taught the students this procedure using the cognitive apprenticeship model. It was determined that the students who were taught the procedure were able to construct significantly more proofs than they were prior to instruction.

Knowledge Structure Studies Conducted in a Classroom Setting

Van Heuvelen (1991) created a totally restructured college physics course called: Overview, case study physics (OCS). This restructuring includes a problem-solving strategy that was directly linked to principles. The structure of the class seems very similar to many of the Modeling Instruction activities (Wells, Hestenes, and Swackhamer, 1995). Van Heuvelen used a slightly different approach than the studies above by explicitly developing and using multiple representations, hierarchical organization charts of topic areas, problem-solving strategies and active reasoning during classes. There seem to be a number of similarities between this approach and the one used in the Eylon and Reif (1994), Bagno and Eylon (1997) and Bagno et al (2000) studies. The physics concepts were divided into a small number of chunks each semester and developed in a hierarchical fashion. The students created hierarchical organization charts to use during problem solving. The multiple representations developed included the use of graphs and motion maps. The problem-solving strategies included the evaluation of the final solution in terms of the units, sign and magnitude of the answer. This class design was taught both in precalculus and calculus based physics courses. In order to test for concept knowledge the Mechanics Diagnostic Test (MDT) was utilized pre and post course. The MDT is a precursor of the Force Concept Inventory (FCI). The increase from pre to post test on the MDT for both courses was significantly greater than traditionally taught classes and they also outperformed them on quantitative problem-solving measures. Compared to a conventional class the OCS students preformed better on the advanced placement physics test and on the MBT. In addition, when a group from this class and the conventional class were tested qualitatively several months after the course the OCS students still scored higher. While this study showed dramatic results it did not attempt to discover if students did develop more expert-like knowledge structures. Although it was clear that Van Heuvelen realized the importance of a problem-solving strategy that categorized the problems based upon principles in this study we can only surmise that the problem-solving strategy might be affecting the OCS students' final performance. However, the continued performance of the OCS students after a large respite from class leads one to think that a change in knowledge structure might be one of the reasons for the performance since once the expert-like knowledge structure was in place it would be easier for them to link to it because of the interconnections rather than using a novice listing of equations.

There have been a handful of studies completed that look directly at knowledge structure development in classrooms. Keith (1993) conducted a card sort analysis of students who completed a course using the Minnesota Problem-Solving Strategy (discussed in Malone, 2006) which included the use of a problem-solving strategy sheet. This sheet required the students to record the physics terms associated with each problem, draw out force diagrams, and write down the equations used. Keith (1993) thought that since students using this strategy would be considering the physics terms needed to solve the problems to a greater extent they would develop a more expert-like knowledge structure. However, it is unclear how much the students would be actually referring to physics principles when describing the physics terms since the student solutions shown in Heller, Keith, and Anderson (1992) consist mostly of forces diagrams and the relation between those forces instead of first identifying a principle such as Newton's second law. Keith (1993) tested the students' knowledge structure via a Chi et al (1981) post course card sort and then a second sort to determine hierarchical relationships. He compared sorts between users and nonusers. The two groups were distinguished based upon test performance (i.e., those that consistently used the strategy (Users) vs. those that did not (Non-Users)). Based upon the card sort Keith (1993) found that the only significant differences in knowledge structure were at the subordinate level, what Sabella and Redish (in press) might consider local coherence. Therefore, the students using the strategy demonstrated a knowledge structure similar to physics experts at the lower levels of their hierarchical structure (i.e. contained solution procedures) but the upper levels were not organized based upon fundamental principles. Unfortunately, this study detracts a bit from the others since it seems to cast a shadow on the ability to teach students by a method that allows them to obtain a more expert-like knowledge organization. However, given that the problem-solving strategy sheet does not specifically have students start from physics principles in a way similar to the laboratory based studies one could say that this lack might have caused the knowledge structures developed to be less expert-like than if they had started the method with a principle selection.

Leonard, Dufresne, and Mestre (1996) implemented a strategy in a calculus based physics class that they hoped would help students develop a more expert-like knowledge structure. The strategy included a qualitative description of the problem starting with selecting the principle involved in the solution, justification for selecting the principle, and a procedure to use the principle to determine a solution. The students were encouraged but not required to use the strategy when solving homework problems; however, they were required to complete a strategy writing task on exams. The researchers determined that the principle trained students performed better than students from a traditional class on a forced choice categorization task designed by Hardiman et al (1989). Therefore, it would seem that forcing students to initially categorize problems based upon principles produces students with a more expert-like knowledge structure than conventionally trained students. Leonard et al (1996) analyzed the strategy writing tasks given on exams and found that the deficient strategy writing task samples taken from the experimental class displayed a focus on surface features; however, two-thirds of the experimental class completed good sample tasks based on principles. Therefore, they concluded that the strategy writing task backed up the more expert-like knowledge structures obtained by the experimental class. However, strategy writing task samples were not taken from the traditional class so no additional comparisons between the two groups could be made. They also tested the students' knowledge by a free recall task where the students from both classes were asked to identify the important ideas used to solve problems. The two groups (experimental vs. traditional) identified Newton's three laws of motion with the same frequency but the strategy class identified the four remaining principles (conservation of energy, conservation of momentum, angular momentum, and work-energy theorem) at a higher frequency. This study seems to contradict the Keith (1993) study since this method used an even less intensive strategy as there were no problem-solving sessions incorporated in the course. However, this also seems to support the idea that one of the reasons for the Keith (1993) failure might have been because the strategy did not highlight the principles used to solve the problem. It is somewhat disappointing that the Leonard et al (1996) study did not attempt to appraise the differences between the two classes in the area of conceptual understanding nor problem-solving practices, thereby correlating them to the knowledge structure obtained on the part of the student. However, the lab-based studies performed by this group have already shown that there is a correlation between the two so therefore they may not have felt it was necessary.

Alan Schoenfeld (1985) developed a mathematics based problem-solving course that incorporated the use of deep structure and metacognitive skills while solving problems. The students of the course demonstrated a significant increase in problem-solving ability compared to a control group (which showed no change pre to post). Schoenfeld demonstrated via a card sort task and a statistical cluster analysis that the knowledge structures of his students' pre to post course were highly correlated to that of expert mathematicians. The correlation between the two knowledge structures pre course was 0.54 whereas the post course value was 0.72 even though the course did not specifically address problem perception although the techniques used did increase the students' attention to the problem structure since they were looking for examples and examining goals (Schoenfeld, 1985; Schoenfeld and Herrmann, 1982). This course was a semester long intervention that was extremely intensive and did show that the students had a large increase in problem-solving ability but they did not correlate the obtained knowledge structure to that ability.

Chabay and Sherwood (2002) developed a Modern Mechanics course called *Matter and Interactions I: Modern Mechanics*. One of the goals of the course is to involve the students in attempts to predict and explain physical phenomena using the fundamental principles of physics thereby stressing the coherence of the conceptual structure of the physics (Chabay and Sherwood, 2006). This text is designed around the application of fundamental physics principles (i.e., momentum principle ($\Delta p = F_{net} \Delta t$), angular momentum, etc). The students construct simple models of physical systems. Large numbers of simple problems have been replaced by more realistic, complicated problems that encourage the initial categorization of a fundamental principle for ease of solution. The course instructors model the procedure of solving problems based upon fundamental principles in lecture and this is followed up in recitation sessions. In addition, the students use a 3-D computer language called VPython. The VPython programming language allows students to simulate physicals systems by the construction of programs based upon symbolic vector algebra and to visualize external vector representations of the system in 3D. In order to program a working model the students learn they must start with a fundamental physics principle and program forward from there. This course seems to implicitly teach the students a coherent knowledge structure. The efficacy of this approach has been reported by Kohlmyer (2005). Kohlmyer found some interesting qualitative differences between students taught using Matter and Interactions (M&I) and traditional curricula. It was determined that during talk aloud problem solutions M&I students started their problem-solving paths by invoking a fundamental principle thereby demonstrating a more expert-like problem-solving behavior. On the other hand, the traditional students emphasized equations such as F=ma and special case formulas during their talk aloud problem solutions. This finding implies that the students may be developing a more expert-like knowledge structure and completing an initial breadth search of that structure.

A companion text developed by Chabay and Sherwood (2002) called *Matters and Interactions II: Electricity and Magnetism* uses the emphasis on fundamental principles to teach students during a second semester physics course. Chabay and Sherwood identified the principles that were fundamentally important in order to develop the material in a coherent fashion. They completed a complex problem-solving study by including three standard problems on the E&M final exams in one traditional class and one class using the M&I sequence. There was no significant difference between the numbers of students who completed two of the problems correctly. However, on the third and most complex problem the M&I students' performance was four times higher than that of the traditional students. The efficacy of the M&I electricity and magnetism sequence was also tested by Thacker, Ganiel and Boys (1999). Thacker et al (1999) used both a questionnaire to probe traditional and M&I students understanding of the transients in dc circuits and an interview to test for effectiveness. The M&I group performed better on the understanding of the transient phenomena and were able to give valid explanations even of situations unfamiliar to them while the traditional groups had a tendency to rely on algebraic manipulation as a means of explaining the situations. Engelhardt and Beichner (2004) discovered that the M&I students outperformed traditional students on a test for understanding of dc circuits they designed called DIRECT. Ding, Chabay, Sherwood and Beichner (2006) used the BEMA (Brief Electricity and Magnetism Assessment developed by Sherwood and Chabay in 1997) to analyze the effectiveness of traditional and M&I electricity and magnetism courses in a longitudinal study. It was discovered that M&I students who had scored a B in the original course obtained the same score on BEMA as that of traditional students who had scored an A in their original course. This effect was observed over the course of five semesters. When using the BEMA as a pre and post-test assessment for several sections of traditional and M&I courses it was determined that the M&I students scored significantly higher producing twice the gain as traditional E&M students. It is possible that the development of a more expert-like knowledge structure is allowing the M&I students to demonstrate this enhanced performance.

Summary of Classroom and Lab Knowledge Structure Studies

The studies both in and out of the classroom showed that one can teach students to reorganize and/or develop a hierarchical knowledge structure producing varying rates of success depending on the methods used. A correlation between problem solving and knowledge structure was suggested in the findings of a majority of the lab based studies and in a number of the classroom studies. However, none of the studies reviewed used card sorts in order to correlate the "expert-likeness" of the knowledge structures with problem-solving ability. It is possible that the hierarchical knowledge structure helps one become a better problem solver because it consists of a basic set of principles that students can apply with the representations for these principles chunked together, so that the problem-solving process should become easier. It should be much easier for students to choose between a handful of principles vs. a large and unwieldy list of equations attached to surface features. It is no wonder that the novice student has such difficulty with problem solving since their unexpert-like structure requires them to select a "correct" process from a number of choices since they would normally be searching through a large equation list while the expert only must select from a handful.

Metacognition Research

So far this paper has described a number of methods that would allow students to become better problem solvers via changes in knowledge organization and problem-solving methods. The question becomes how does one manage the process from beginning to end in an efficient manner so that a correct solution can be reached. Schoenfeld (1992), in a review of metacognition and mathematics, said "it's not what you know; it's how, when and whether you use it" (p. 355). Studies have demonstrated that most students do not develop proficient control strategies and, thus, their ability to solve problems is lessened (Schoenfeld, 1985).

Just what is metacognition? Metacognition was defined by Flavell (1976) as follows:

> "Metacognition refers to one's knowledge concerning one's own cognitive processes or anything related to them, e.g. the learning-relevant properties of information or data. For example, I am engaging in metacognition….if I notice that I am having more trouble learning A then B; if it strikes me that I should double-check C before accepting it as a fact; if it occurs to me that I had better scrutinize each and every alternative in a multiple-choice type task before deciding which is the best one…Metacognition refers, among other things, to the active monitoring and consequent regulation and orchestration of those processes in relation to the cognitive objects or data on which they bear, usually in the service of some concrete (problem solving) goal or objective." (p. 232)

Flavell (1979) encouraged the training in metacognitive skills as he felt that training in these specific skills should allow not only for improved learning to occur but also a greater amount. In addition the habit of using metacognitive skills should be useful in a number of fields and not only in the field in which they were initially trained since they are general rather than specific.

In order to study metacognitive processes one must have a framework on which to identify and categorize metacognitive aspects of problem solving. Paris and Winograd (1990) described metacognition in math education as self-management reflected "in the plans that learners make before tackling a task, in the adjustments they make as they work, and in the revisions they make afterwards. " (p. 18). Silver (1987) described these self-management processes as planning, monitoring and evaluation. This study will use Silver's (1987) description of these processes as the framework on which to identify and categorize the metacognitive processes and behaviors observed.

Differences in Metacognition between Experts and Novice

If the hypothesis is that metacognition is necessary for being a successful problem solver then one would expect to observe differences in the metacognitive abilities between experts and novices or between good and poor problem solvers as has been seen in the case of knowledge structures and problem-solving strategies. Simon and Simon (1978) found that novices made more metastatements than experts. However, a limitation of this study was that the problems were very simple for the experts such that they probably had to do little planning, monitoring or evaluating of the problem-solving process. Other problem-solving studies in physics did discover that experts and successful problem solvers made a qualitative analysis of the problem or underwent reflective thinking about the problem which under the chosen framework could have been coded as metacognitive statements in the area of planning or monitoring (Champagne, Klopfer, and Anderson, 1980; McDermott and Larkin, 1978; and Larkin, 1979). Other studies in physics, math, Lisp programming and biology found that during verbal protocols experts and good problem solvers seemed to be constantly evaluating their progress towards a solution and that these subjects demonstrated improved task performance (Dhillon, 1998; Pirolli and Bielaczyc, 1989; Schoenfeld, 1983, 1985, 1987; Smith and Goodman, 1984; Veenman, and Verheij, 2003; Zhang, Wu, Fretz, Krajcik, Marx, Davis, and Soloway, 2002). Therefore, it seems that there might be a connection between metacognitive skill usage, problem-solving ability and knowledge organization.

It would seem that the monitoring of one's comprehension during problem solving is an important behavior if one is to be a successful problem solver. Evidence of metacognition differences between good and poor problem solvers was discovered in studies conducted about self-explanations. Chi, Bassok, Lewis, Reimann, and Glaser (1989) analyzed self-explanations made by good and poor problem solvers in physics as they studied worked out examples. The good problem solvers produced self-explanations that were guided by active and accurate monitoring of their comprehension of the material. Chi et al (1989) found that detection of comprehension failures did initiate explanations for both good and poor problem solvers. Eighty-five percent of the good problem-solvers' detections of comprehension failures were followed by explanations describing their understanding; whereas, only sixty percent of poor problem solvers' followed comprehension failures with explanations. When the poor problem solver did produce an explanation following the detection of a comprehension failure they were usually about quantitative expressions in the problem while the good problem solvers' explanations were split between quantitative expressions and ones explaining the physics principles and concepts. This same effect was discovered by Ferguson-Hessler and de Jong (1990) when they discovered that when studying a physics text poor problem solvers failed to detect and therefore correct their comprehension failures. Therefore, these findings suggest that experts and good problem solvers might use metacognitive skills differently and more often than poor problem solvers or that the difference in use of these metacognitive skills might be due to the greater degree of conceptual understanding on their part.

Metacognition Training Studies

The earlier studies dealing with the training of metacognitive skills occurred in the area of comprehension monitoring in reading and the use of these strategies by "retarded students". It was found that indeed metacognitive training of "retarded students" allowed them to assess and check their readiness to complete serial recall tasks. (Brown, Campione, and Barclay, 1978 and Lawson and Fueloep, 1980). In addition, Brown et al (1978) demonstrated that the individuals in their study were able to use the strategies a year later and to transfer them to other recall tasks thereby, showing the general nature of the skills taught. In the area of reading August, Flavell and Clift (1984) found that skilled readers demonstrated greater amounts of comprehension monitoring and when monitoring comprehension skills were taught to fifth graders, they improved their reading ability. These early studies showed that metacognitive behaviors can be very important skills. It would follow that these same skills could be important contributors to improving problem-solving abilities in students. In the preceding section a number of the problem-solving studies discussed had a metacognitive component built into the strategies taught to the student. Therefore, the significant findings in these studies may be due in some part to the metacognitive behaviors they engendered on the part of the subjects. However, none of the studies tested to see to what extent the subjects utilized the different behaviors taught by the strategy – both cognitive and metacognitive for the most part.

Metacognition Studies Conducted in a Laboratory Setting

There are not many metacognition studies that occurred in a laboratory setting that fit our framework for problem solving except for studies in the area of self-explanations and then only in the area of Lisp programming. Bielaczyc, Pirolli, and Brown (1995) identified a set of metacognitive strategies used by high performers in previous studies which included monitoring their comprehension, monitoring learning activities and clarifying and addressing their comprehension failures. Bielaczyc et al (1995) divided their participants into two groups. Both groups received Lisp training but the control group received none of the strategy training developed for the experimental group. The two groups were balanced based upon Lisp programming performance levels. The experimental group became familiar with asking *why* questions, summarizing the main ideas and were given self-monitoring questions (such as do I understand this and what is the purpose of such and such). Therefore, the experimental group was trained in techniques that identified and elaborated the relations between the main ideas in the text, looked at the examples in order to determine the form of the code and then explicitly connected the concepts between the text and the examples studied. This seems very similar to some of the techniques used by studies attempting to develop more "expert-like" knowledge structures. After a verbal protocol analysis of the pre and post programming lessons it was determined that the experimental group performed significantly better than the control group by producing fewer errors, making more monitoring comprehension statements and clarifying a greater number of comprehension failures. This study did not monitor metacognitive abilities in planning or evaluation directly.

Metacognition Studies Conducted in a Classroom Setting

Some of the initial studies to train students in metacognition behaviors in a classroom setting occurred in the area of reading; such as in Palincsar and Brown (1984). Palincsar and Brown (1984) taught students via a cognitive apprenticeship model four strategies designed to foster and monitor reading comprehension. The four strategies were predicting, questioning, clarify and summarizing. The student demonstrated marked improvement in their reading abilities by the end of the intervention. Was the success demonstrated due to the cognitive apprenticeship pedagogy which allowed for the emulation of the behaviors modeled by the instructors or the new metacognitive skills the students developed or a combination? Could the large success have been caused by the pedagogical usage allowing for the students to internalize the metacognitive skills to a much greater extent than other past interventions? Salomon, Globerson and Guterman (1989) utilized a computer program to teach metacognitive skills to a seventh grade experimental group whereas the control group only received non-strategic advice (such as read more carefully). They were able to show that the significant difference between the two groups could be accounted for solely by the metacognitive training.

The domain of mathematics has also been very active in the metacognitive training arena. Schoenfeld's (1985) college problem-solving course contained a very large metacognitive aspect. Schoenfeld explicitly role modeled the decision making processes during problem solving. The discussions always started off with the question: "What do you think we should do?" (p. 221) thereby initiating a planning sequence. Multiple ideas of initial problem-solving starting points were asked for and the class planned which path to take. Once the class reached a solution they always evaluated the final solution. As the students solved problems on their own Schoenfeld was always asking them "Why are you doing that? and "How does it help you?" (p. 221). These two questions ask the students to monitor their comprehensions and explicitly evaluate their progress towards the solution. Schoenfeld analyzed video taped student solutions pre and post course and discovered that the students were using a greater number of metacognitive skills, thereby demonstrating more control of the solution path and performed more expertly post-course. Schoenfeld (1985) also demonstrated that the students in the course performed significantly better than a control group on problem-solving tasks. This analysis is limited as there was no analysis of error revision and correction via verbal protocols comparing the control group and those students taking the problem-solving course.

A number of studies in middle school math were completed by Mevarech and her associates. Mevarech and Kramarski (1997) developed a strategy, called IMPROVE, and showed

EXPERT BEHAVIORS

- Typically use a working forward strategy except on more difficult problems
- Performs an initial qualitative analysis of the problem situation
- Constructs diagrams during solution process
- Spends time planning approach sometimes via models of the physical situation
- Uses fewer equations to solve the problem
- Usually solve problems in less time
- Refers to the physical principles underlying the problem
- Concepts more coherent and linked together
- Fewer errors – concepts usually deployed correctly
- Can use more than one representation to solve problems – which usually allows them to deviate to other solution paths when stuck
- Checked solution by a variety of methods (i.e., more flexible)
- Rarely refer to problem statement or text

NOVICE BEHAVIORS

- Typically use a working backward strategy
- Usually manipulates equations discovered via equation hunting
- Rarely constructs or uses diagrams
- Rarely plans approach – simply dives in
- Uses more equations to solve problem
- Usually takes more time to solve the problems
- Refers to the numeric elements of the problem
- Concepts not coherent and lack applicability conditions for special cases
- More errors – concepts usually deployed incorrectly
- Usually only utilize a numeric representation to solve problems – once they become stuck rarely can free themselves
- Superficially check solution if at all
- Frequently refer to problem statement and textbook (especially examples)

Table 1: *Comparison of Expert and Novice Problem-Solving Behaviors*

that students using this strategy outperformed a control group. IMPROVE stands for "introducing new concepts, metacognitive questionings, practicing, reviewing and reducing difficulties, obtaining mastery, verification, and enrichment" (p.369). The strategy taught students possible strategies to solve the problem, to ask metacognitive questions dealing with comprehension and to make connections between this problem and past problems (in this way they might learn to categorize the problem types). The metacognitive questions were placed on strategy cards for ease of usage by students and were designed to help students become aware of self-regulation by planning the solution, monitoring the progress and allocating resources. The IMPROVE groups significantly outperformed the control group in all areas except that the low-achieving students did not demonstrate any increases in mathematical reasoning. In an additional study using a metacognitive cooperative problem-solving experimental group that used IMPROVE, a cooperative problem-solving experimental group and a control group showed that the metacognitive group outperformed the other two on all measures while the cooperative group outperformed the control (Mevarech, 1999). This same study demonstrated that the low ability students performed best under the metacognitive strategy and that the metacognitive strategy group was able to solve significantly more complex transfer problems than the other two groups.

The only high school metacognitive study in the domain of physics was conducted by Neto and Valente (1997). In this study, the authors taught one high school class a metacognitive strategy for solving problems while the other was a conventional physics class. The metacognitive group also studied more difficult problems thus possibly allowing for the development of enhanced problem-solving processes due to the complexity of the problems and not solely due to the metacognitive strategy. The metacognitive group did outperform the traditional class on both qualitative and quantitative problem sets. Neto and Valente (1997) did not look directly at the metacognitive abilities used via think aloud protocols; but, only obtained a sense of student usage of metacognitive strategies by a questionnaire administered about the usage of such techniques.

White and Frederiksen (1998, 2005) developed an inquiry curriculum called ThinkerTools which explicitly taught self–assessment in the form of self-monitoring and evaluation and utilized the ThinkerTool microworld. The ThinkerTool students reflected at the end of each unit on their processes and final product while the control group completed the same ThinkerTool curriculum but did not reflect on their own processes. The experimental group's reflective assessment gave them the advantage over the control group in areas of scientific inquiry and science knowledge as it related to the models developed but there was no difference between the two groups in applied physics problems (these were questions similar to the FCI). At first, this may seem to be a discrepant finding. However, since metacognitive strategies were only modeled in the inquiry and model development phases with the class it is possible that they did not know how to transfer these skills to a qualitative problem-solving domain.

Summary of Classroom and Lab Metacognition Studies

The studies in metacognition have demonstrated an improvement in performance in a number of areas. However, in a number of these studies the metacognitive strategy is confounded because it is taught along with other improvements to the curriculum such as general self-explanations, general problem-solving strategies, inquiry concept development, and more complex problem analysis. However, this is typically what happens in research dealing with classroom studies and can be said about many of the studies reviewed in this thesis. Through the use of verbal protocols the Bielaczyc, et al (1995) and Schoenfeld (1985) studies demonstrate that the experimental group used more self-regulation post-treatment. In addition, Bielaczyc, et al (1995) show that the number of errors decline; however, they do not directly connect this decline with metacognitive abilities.

In addition, if one looks back at the studies in problem-solving strategies there are a number of them that also include some form of metacognitive processes. Were the metacognitive processes responsible for the increase in post-test performance in those cases? Or is it more likely that problem-solving heuristics included in the strategies, the metacognitive strategies and the development of a more expert-like cognitive structure overlap with each other?

Studies Linking Metacognition, Problem-Solving Behaviors and Knowledge Structure – the Case of the Self-Explanation Effect

A number of studies have shown that the number of self-explanations students produce correlates with problem-solving ability (Bielaczyc, Pirolli, and Brown, 1995; Chi, Bassok, Lewis, Riemann, and Glaser, 1989; King, 1992; Nathan, Mertz, and Ryan, 1994; Neuman, Leibowitz, and Schwarz, 2000; Pirolli, and Recker, 1994; Renkl, 1997; Siegler, 1995, 2000; Webb, 1989)**.** By self-explaining text examples the students should be connecting the main ideas together therefore producing more interconnected chunks which should aid in recall as shown in expert/novice studies. As shown in the review of metacognition studies the self-regulation skills of planning, monitoring and evaluating comprehension and strategy use should help students determine if they are achieving a good understanding of the materials and enabling them to catch any errors produced. This is similar to the idea Chi (2000) postulated - that one needs to be actively involved in order to acquire new knowledge and to reorganize one's knowledge structure. She postulates that students develop self-explanations when they find a discrepancy between the text and their own mental model. Therefore, it would make sense that a greater number of self-monitoring questions would lead to finding more of these discrepancies thus leading to a greater reorganization of one's knowledge structure. Therefore, self-explaining could be one method by which one becomes an expert and develops an expert knowledge structure. Studies in this area that prompt students to self-explain show the same correlation between the number of self-explanations and problem-solving abilities; therefore, it seems that having students self-explain might allow for the development of a more expert-like knowledge structure.

Therefore, in order to answer a portion of the questions posed at the end of the last section, a review of the studies linking metacognition to the production of more expert-like knowledge structures via self-explanations is required. Chi, de Leeuw, Chiu, and LaVancer, (1994) prompted an experimental group of eighth graders to self–explain a textbook chapter on the circulatory system while a control group was allowed to read the material twice. The experimental group was asked to self-explain after each sentence of text (i.e., explain the meaning of each sentence). The pre to post test comprehension questions showed that the experimental group had a 32% pre to post test gain while the control only had a 22% gain. However, much more impressive was the fact that if one looks only at the more difficult questions the gain is 22.6% vs. 12.5% demonstrating that the prompted group understood the material more deeply as these questions required the production of knowledge inferences. In addition, when Chi et al (1994) split the prompted group up into hi-explainers vs. lo-explainers it was found that the hi-explainers generated a greater gain. In addition, the students were allowed to use the textbook on the test. The hi-explainers referred to the textbook examples 2 times vs. 11 times by the lo-explainers. This is very similar to research on the problem-solving behaviors between expert and novice subjects where the experts referred back to materials to a lesser amount. This suggests that the hi-explainers are more expert-like thereby having constructed a more coherent expert-like knowledge structure. Chi et al (1994) compared the mental models of the circulatory system produced by the prompted and control groups. The prompted group produced a correct model 57% of the time vs. 22% of the time for the control group. In addition, within the prompted group the hi explainers all attained the most accurate model possible while only 1 out of four of the lo-explainers did so. Finally, it was determined that at least 30% of the self-explanations produced by the students actually integrated new information with their older existing knowledge. However, one-fourth of all self-explanations were incorrect but they still allowed for the production of more expert-like mental models. It is possible that the integration of incorrect information could allow the students to experience conflict when comparing it to more correct information thus leading to a more correct mental model. These findings support the idea that self-explanations allow students to reorganize their knowledge structures towards a more "expert-like" structure.

Since self-explanations have been shown to have a core component of metacognition involved in their usage Aleven and Koedinger (2002) designed an experiment using the computer-based cognitive tutor for geometry. The only self-explanation that was asked of the students was to name the principle that would be used to solve the problem. Aleven and Koedinger (2002) believe that this would allow them to be more metacognitive and in the framework initially discussed this procedure would allow the students to start planning the solution method. However, it is also very similar to the studies done by Hardiman et al (1989) that showed problem-solving improvement when asking students to initially categorize physics problems based upon principles. Using this procedure Aleven and Koedinger (2002) were able to demonstrate that the explanation group significantly outperformed the non-explanation group on the post–task. However, the experimental group also spent a significantly larger amount of time completing the training. Therefore, they performed a second experiment controlling for time spent. The students were advanced out of each instructional level when they either reached mastery or met the pre-established time limit. In this study the gain on the problem-solving task was only marginally significant for the experimental group. However, their performance on the questions requiring a deeper understanding of the concepts was significantly better than the control group while the control group performed better on those questions needing only shallow knowledge. This is very similar to Chi et al's (1994) finding about self-explanation and the circulatory system. Finally, when looking at errors the experimental group produced fewer errors by commission. The findings that the number of errors decline are similar to the earlier studies on expert/novice differences seen in several sections of this thesis.

Van Lehn and Jones (1992) analyzed the Chi et al (1989) data to determine if the self-explanation effects could have been caused by students uncovering gaps in their knowledge and then filling those gaps. Van Lehn and Jones analyzed all of the errors produced by both the high self-explainers and the low self-explainers. The types of errors made by both groups were classified in order to determine which errors were reduced by self-explanation. They discovered that only gap errors were significantly different for the two groups. A gap error was caused by a lack of knowledge concerning a physics principle or concept. For example, some students were unaware that an inanimate object such as a table applies a force of any object interacting with it thereby demonstrating a gap in their knowledge. They also analyzed if schema selection and analogical problem solving could be producing the self-explanation effect. However, the differences in errors due to incorrect schema selection could not account for the difference in scores between the two groups. The idea that the high self-explainers might be producing greater number of inferences also was disproved. Therefore, it seems that self-explanations might be allowing one to reorganize the knowledge structure as postulated earlier and over time producing an expert-like knowledge structure.

Central Features of Modeling Instruction in Physics

The evidence above affirms that a science curriculum based on constructing models produces students that have greater abilities in the areas of problem solving, conceptual understanding, and scientific reasoning. However, in order to continue to improve on the Modeling Instruction pedagogy I believe that one needs to understand the cognitive and metacognitive skills that are developed by modeling students and how research in cognitive science informs one about these processes of change. In this section I will review the central tenets of Modeling Instruction and connect them to the pertinent literature reviewed in this chapter.

Model Development

During model development the students obtain data to develop a model of a physical system via an experiment which they have designed. They use the data to produce several representations of the model (see figure 1): verbal, diagrammatic, graphical and algebraic.

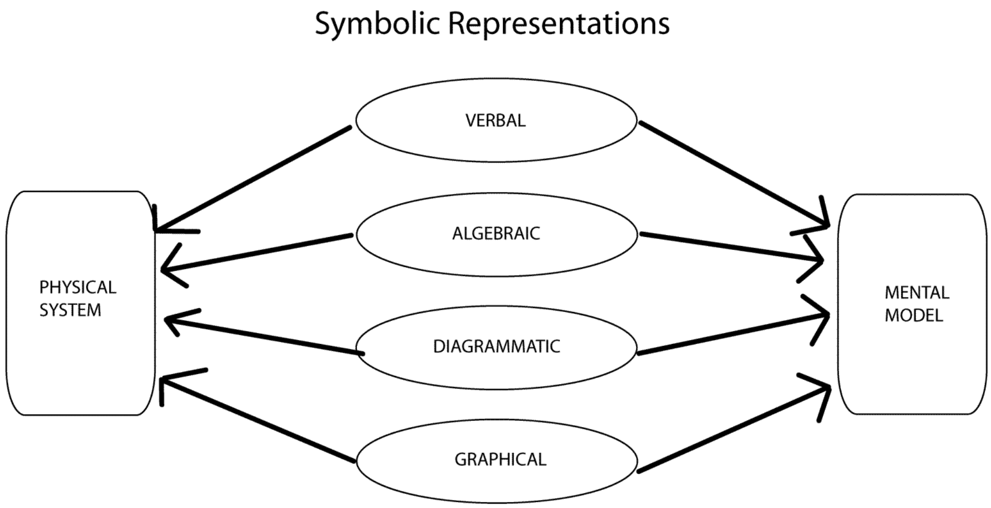

Figure 1: *Explicit Representations produced between the physical system and the mental model (adapted from presentation by Swackhamer and Dukerich, 1996)*

The students present their model representations to the rest of the class and justify the conclusions. The class as a whole arrives at a consensus concerning the representations generated. Although there are a number of beneficial processes occurring in this period of the class, I will focus on those dealing with the main sections of this literature review. The students are organizing their understanding of the concept in question by chunking together all of the needed representations. This is an activity that infrequently occurs in a conventional class. The students are constructing a model that has local coherence since all the representations are required to arrive at the same conclusion. As they move through the course they develop a series of models (See Figure 2) which have local coherence.

Kinematical Models	Causal Models
Constant Velocity	Free Particle
Constant Acceleration	Constant Force
Uniform Circular Motion	Central Force
Collision	Impulsive Force

Figure 2: *Basic Models developed in the Mechanics Modeling Course (adapted from Hestenes, 1996)*

For example, the model of constant acceleration is on the same level as Newton's second law and each branches off toward its own representations. However, global coherence might be developed if the dependence on acceleration in Newton's second law allows the students to develop a linkage to the constant acceleration model developed earlier. This process is very similar to studies reviewed that dealt with the teaching of a knowledge structure that is hierarchical vs. linear such as in Eylon and Reif (1984), Bagno and Eylon (1997) and Bagno et al (2000). Therefore, one would expect to reap similar rewards as shown in these studies such as increased problem solving and conceptual understanding. While the Modeling research has demonstrated a correlation between these two they have not linked either to the development of a knowledge structure by modeling students.

The model development stage also scaffolds the students in the use of metacognitive skills since the students when justifying their work are continually asked the following questions: "How do you know that?", "Why do you think that?" and "Does that make sense?". These questions are similar to the ones used by Schoenfeld (1985) in his problem-solving course which has been proven to increase the metacognitive skills of his students. In addition, this is very similar to the self-explanation prompts used by Chi et al (1989) during their self-explanation studies. As demonstrated by Bielaczyc, et al (1995) one would expect modeling students to self-monitor their understanding and be able to discover comprehension failures which should lead to error corrections and revisions. Finally, during this development the students are making connections between the current model and the past ones which is similar to what occurs when using the IMPROVE strategy (Mevarech, 1999; and Mevarech and Kramarski, 1997).

Model Deployment

During the modeling deployment stage the students deploy the model developed in the paradigm lab, the initial lab conducted in each modeling cycle, to new contexts so that the students can abstract the model thereby allowing them to use it in other situations. This is done by deployment labs when they test their models to determine if they are predictive and by problem sets similar to regular physics textbook problems except that the initial deployment problems ask the students to solve them using the various representations of the model. During the problem-solving deployments the teacher models and scaffolds the student in the use of a problem-solving strategy based upon the physics models. Before every problem the students are asked to first select a physics model that one can deploy to solve the problem thereby reinforcing the idea of an initial breadth search across all physics models which is similar to the method used by Aleven and Koedinger (2002). From this physics model they have several representations with which to solve the problem. The requirement that the students first select a principle is very similar to the strategies used in the research attempting to produce more "expert-like" or coherent knowledge structure in students such as those completed by Chabay and Sherwood (2006), Hardiman et al (1989), Leonard et al (1996), Larkin and Reif (1979) and Van Heuvelen (1991). In addition, the use of multiple representations allows the students to be more flexible when one strategy does not work, as shown by Lewis (1989). As students are working through a problem solution they are always reminded that after planning they must monitor their comprehension and evaluate the final solution. During whiteboard presentations the students get to see the various ways that one can solve a particular problem, reinforcing the fact that there is not only one way to skin a cat but also justifying their answers as the students are always asked: "Does that make sense to you?" and "How do you know that?". Therefore, this should increase the metacognitive skills of planning, monitoring, and evaluating as shown by Schoenfeld (1985). In conclusion, the students are asked to constantly reflect and explain to themselves what they know and how they know it in all areas of the class: notebook reflections/homework, whiteboard presentations, and tests and quizzes. This type of self-explanation prompting has been demonstrated to help students construct more "expert-like" knowledge structures (Chi et al, 1994). In addition, Van Lehn and Jones (1999) found that it is likely that the knowledge structure is changed because self-explanations discover gaps in the structure which need to be filled. This is modeled in the modeling classroom by demanding that the models have local coherence such that the minute that a discrepancy in predictions is observed one goes back and refines the model.

In addition, several researchers (Aleven and Koedinger, 2002; Bielaczyc et al, 1995; Hegarty et al, 1995; and Lewis, 1989) dem-

EXPERT KNOWLEDGE CHARACTERISTICS	NOVICE KNOWLEDGE CHARACTERISTICS
• Hierarchically structured knowledge	• Knowledge structure in pieces
• Knowledge structure based on physics principles	• Knowledge structure based upon surface features
• Knowledge structures richly interconnected – global coherence	• Knowledge structure mostly disconnected – local coherence
• Knowledge structure links multiple representations to the principles	• Knowledge structures a few usable representations
• Greater amount of domain specific knowledge	• Small amount of domain specific knowledge

Table 2: *Comparison of expert and novice knowledge structures*

onstrated that the use of "expert-like" skills and behaviors seems to allow one to produce fewer errors and also possibly catch those errors more frequently. There has been little research into this error production and its revision. However, one might expect that modeling students would produce fewer physics errors.

Skill Expectations

This literature review hints at a number of possible skills that the modeling students could be developing and using through the course of a school year that non-modeling students would not be able to develop easily, as the modeling course activities implicitly and explicitly contain a number of the strategies used in the studies reviewed as shown above. After reviewing the Self-Explanation Effect research one would expect modeling students to have a more "expert-like" knowledge structure and exhibit more "expert-like" problem-solving behaviors such that when solving problems students would:

- Use multiple representations to solve problems (such as graphical methods vs. algebraic methods)
- Identify the method of solution via models instead of equations
- Complete a breadth search of knowledge structure instead of a depth search
- Use metacognitive skills continuously (setting goals, monitoring, and evaluating)
- Produce fewer physics errors

This paper and Malone (2006) brings together the research in all these areas reviewed to further the understanding of what problem-solving behaviors, knowledge structures, and metacognitive skills are developed by modeling students vs. non-modeling students. One can see that there are a number of holes in the cognitive and metacognitive underpinnings of Modeling instruction that need to be filled. There have been no classroom studies correlating a student's knowledge structure to their problem-solving ability (only lab based studies) and no studies correlating conceptual understanding as shown on the FCI to one's knowledge structure. For that matter there have been no studies that show that the modeling students even internalize a more "expert-like" knowledge structure. There have been no studies conducted to observe and compare the specific problem-solving characteristics and metacognitive skills utilized between modeling and non-modeling students. Future research should expand on the present findings of the Modeling Instruction method to include experiments designed to answer these questions.

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Collaborative action research to improve classroom assessment in an introductory physics course for teachers

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"Assessment" usually brings to mind tests and quizzes. Because the goal of such traditional assessment has been on determining "whether students know" rather than "what students know," it has been criticized for ignoring the critical role students' prior knowledge plays in the learning process. In this paper, we describe a collaborative action research effort involving science faculty and graduate teaching assistants in the implementation and use of classroom assessment techniques in an introductory-level physics course designed specifically for preservice elementary teachers. We believe this model is an effective means for reforming instruction, in that it promotes an open dialogue on teaching and learning and an evidence-based means for assessing the impact of instructional interventions.

INTRODUCTION

"Assessment" usually brings to mind tests and quizzes. Because the goal of such traditional assessment has been on determining "whether students know" rather than "what students know," it has been criticized for ignoring the critical role students' prior knowledge plays in the learning process (McDermott, 1991; McClymer & Knoles, 1992; Tobias, 1990). While reforms (AAAS, 1998; NSF, 1997) have called for changes to curriculum and instruction of undergraduate science courses, research indicates that changes to traditional assessment practices must also occur. In their study of an introductory physics course, Dickinson and Flick (1998) depicted how a traditional assessment system could undermine the goals of a well-meaning instructor. The students they studied focused on developing elaborate (and sometimes unethical) strategies for obtaining passing grades, rather than on developing their understanding of the content.

Increasingly, however, college level instructors are utilizing multiple and alternative forms of assessment to develop a clearer picture of what students know and are able to do before, during, and after instruction. Examples include minute papers, one-sentence summaries, and directed paraphrasing (Angelo & Cross, 1993). These classroom assessment techniques (CATs) differ from traditional assessments such as tests or quizzes in that their purpose is course improvement, rather than assigning grades. The primary goal is to better understand student learning and, as a result, to improve teaching. Research demonstrates that classroom assessment can have positive impacts on student achievement when it is used to inform teaching and learning (NRC, 2001). In this way, "assessment is an ongoing process aimed at understanding and improving student learning" (Angelo, 1995, p.7). Heady emphasizes, however, that there is still a "gap between the ideal and the actual use of assessment that should be closed by more research" (2001, p.421).

REFORM THROUGH SCHOLARSHIP OF TEACHING

Action research, one form of scholarship of teaching, has been identified as an effective means of reforming the teaching of introductory science courses (Chism, Sanders, and Zitlow, 1987; Cross, 1990; Fedock, Zambo, and Cobern, 1996; Schratz, 1990). As the National Research Council indicates, "reflection and inquiry into teaching, and the local and practical knowledge that results, is a start towards improved assessment in the classroom" (2001, p. 80). Through classroom-based research such as action research, instructors systematically and consciously examine classroom actions and student outcomes for the purpose of improving their practice.

Collaborative action-based research teams involving scientists, science educators, graduate students, and practitioners have been successfully utilized in science courses for education majors at other universities (Krockover, Adams, Eichinger, Nakhleh, & Shepardson, 2001). We utilized a similar team approach to explore the implementation and use of classroom assessment techniques in an introductory-level physics course designed specifically for preservice elementary teachers. This project was a collaborative effort among two faculty members (first and third authors), their graduate teaching assistants (fourth and fifth authors), and an undergraduate researcher (second author). In this paper, we describe the lessons learned during our collaboration, and how these have continued to shape our use of classroom assessment techniques. Though our context is a specialized content course for teachers, the strategies we employed are easily transferable to other physics courses.

THE COURSE: EXPLORING PRINCIPLES OF PHYSICS

Exploring Principles of Physics (Physics 2330) is an integrated lecture-laboratory course designed specifically for elementary education majors. Each semester, we teach two sections with up to 35 students each. Major units in the curriculum include electrical circuits, magnetism, light, and force & motion. Though many laboratory activities are consistent with reform recommendations for inquiry-based instruction, the assessments in the course have historically consisted of more traditional quizzes and end-of-unit tests. Often, results of these assessments indicated (too late) that students held misconceptions about the concepts. We decided to utilize Classroom Assessment Techniques (Angelo & Cross, 1993) to identify and address these misconceptions through subsequent changes in our instruction.

METHODS

Action research involves ongoing cycles of generating questions, planning actions, collecting data, reflecting and analyzing data (Hopkins, 1993). The sections that follow describe our activities during each stage of this process, as illustrated in Figure 1.

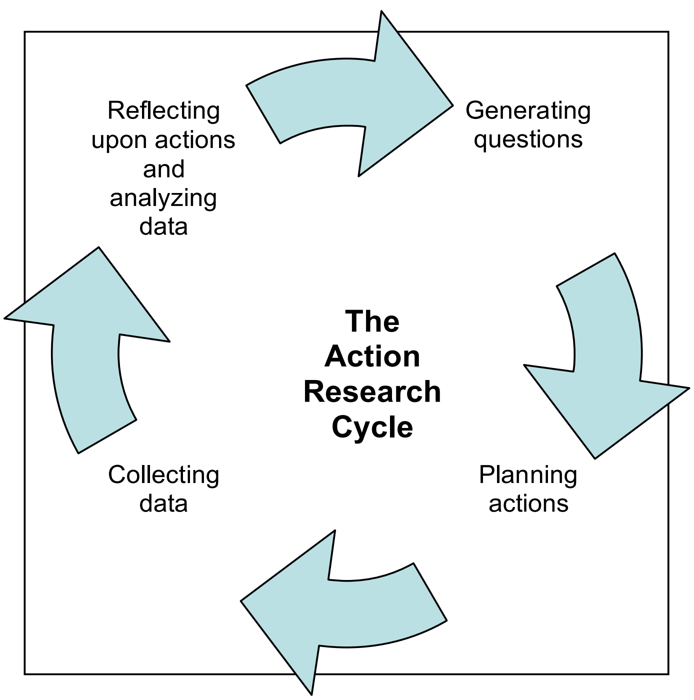


Figure 1. The Action Research Cycle

Generating Questions and Planning Actions

Our initial efforts were guided by the following questions:

- Which CATs align with our teaching goals?
- What role do CATs play in student learning?
- How can CATs be used to guide instruction?

Using the Teaching Goals Inventory (Angelo & Cross, 1993), our team reached consensus on two primary teaching goals for the course:

1. Teaching students concepts and principles of physics
2. Helping students develop higher order thinking skills

We selected several CATs based on their fit with these goals. An additional concern was ease of use—we wanted strategies that could be implemented within our existing curriculum. Many of the CATs we used took little time to accomplish and could quickly be analyzed to develop a picture of students' understanding. Figure 2 provides three examples that are typical of our use of CATs during the semester. By using only a few CATs initially, we were able to provide both students and ourselves with the time necessary to feel comfortable with these new techniques.

Collecting and Analyzing the Data

Each week, the focus of our meetings was directed toward understanding and addressing students' ideas, as assessed through the CATs. This group processing was an important step in monitoring our effectiveness and adjusting our instructional strategies accordingly. Data we collected to monitor our implementation of CATs included:

- Research team notes and anecdotal records from class sessions
- Course materials and student responses to CATs
- Transcripts of weekly meetings in which the team planned instruction and assessment
- Interviews with a randomly-selected sample of students (15%) following each of the three modules of the curriculum

Interviews with students were conducted by the undergraduate researcher (first author) on the team, so as to encourage students to more openly share their opinions about the course activities and instructors' use of the assessments.

As Angelo and Cross (1993) emphasize, following up in response to CATs is critical to their success in improving student learning. For example, after administering a minute paper at the end of class, we realized that students had multiple and conflicting interpretations of the data they had collected during the investigation. In response to this we created multiple-choice problems and a scenario that included a fictitious dialogue between two students about the data (see figures 3 and 4). We asked our own students,

Figure 2. Three Examples of Classroom Assessment Techniques Implemented in the Course

Minute Paper
Students are asked to answer two questions: 1) What did you learn today?
2) What questions do you have about what you learned?
Example: Following an investigation of reflection, students responded to these questions at the end of class.

Directed Paraphrasing
Students are directed to explain a concept to a particular audience in their own words.
Example: Students were asked to explain the concept of "force" to an elementary student prior to and after the unit.

The Muddiest Point
Students are asked, What has been the "muddiest" point so far in this unit? That is, what topic remains the least clear to you?
Example: Following investigations and discussions of voltage, current, and resistance, students were asked to respond to these questions prior to the upcoming exam.

at the beginning of the next class, to discuss whether they agreed with either of the students and why. The discussion that ensued allowed the students to reason through the evidence for themselves in order to understand the concepts of the investigation.

In this manner, our ongoing analysis and evaluation of our action plan were guided by our original questions. To identify emerging themes, two of the researchers (the first and second author) engaged in several rounds of coding, then organized codes into categories to note patterns and trends across data sources (Creswell, 1998). Themes were then peer-debriefed by the remaining members of research team as a validity-check. Two main themes emerged through this analysis, each of which has implications for our continued efforts to implement formative assessment in the course. These themes highlight areas of consistency and discrepancy between the perspectives of students and instructors of the course.

STUDENT PERCEPTIONS OF ASSESSMENT PRACTICES

We primarily used CATs to inform our teaching; however, we were also interested in understanding students' perspectives of the role CATs played in their learning. Interviews conducted with our students helped us better understand the way in which the use of CATs supported their learning, as well as identify potential barriers to effectively implementing CATs in our course.

Students were focused on figuring out "what the teacher wants"

On a consistent basis during the semester students questioned what the instructors wanted from them when they were asked to complete open-ended tasks and share their thinking. As interviews revealed, students were initially unfamiliar with and confused about the purpose of the CATs:

> *I personally don't really like when we write down what we are still unclear on ...I am not sure if I am picking out the right things to understand from the readings.*

This was particularly evident in student responses to tests and quizzes:

> *...I'm not really sure of how much detail [the instructor] wants you to go over or what she wants to include.*

When some students felt they had figured out what the instructor wanted, they became satisfied with their level of understanding, and thus "finished" learning.

> *I got a 100 on the test so I'm good.*

This highlights a discrepancy between the goals of the instructors and the students. While the instructional team viewed both higher-order thinking and understanding of the content as primary goals for our teaching, the majority of students (70%) indicated their primary goal for learning was to "get an A."

As the semester progressed, students believed CATs help them, and instructors, monitor their learning.

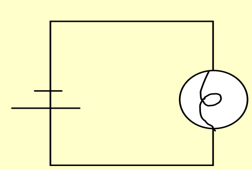
As students became more comfortable with the regular use of CATs in the course, they felt these formative assessments were effective in providing both them and the instructors with information about their understanding.

> *I don't feel like she has to use tests to make sure we understand it.*

They indicated there was "ample time" to alert instructors to their confusion, and that assessments helped them monitor their own learning:

Figure 3. Example of Student Scenarios Adapted for Discussion in Response to CATs

With which, if either, student do you agree? Why?



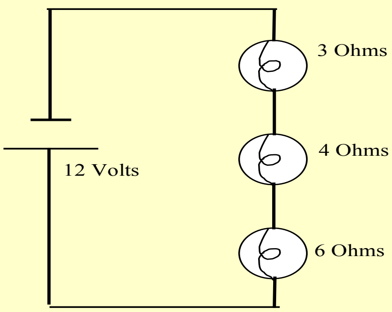
Student 1: *When the bulb is lit, the current flows from the battery to the bulb. There, current is transformed into heat and light.*

Student 2: *When the bulb is lit, the current flows to the bulb and back to the battery. The electrons flowing in the circuit do not get used up..*

Figure 4. Example of Warm-Up Problem Created in Response to CATs

With which response below do you agree? Why?

In the circuit below, what is the current provided by the battery?



1) 9amps, because each bulb has a different resistance:
$I_1 = V/R_1 = 12V/3\Omega = 4A$
$I_2 = V/R_2 = 12V/4\Omega = 3A$
$I_3 = V/R_3 = 12V/6\Omega = 2A$
$I_{total} = I_1 + I_2 + I_3 = 9A$

2) 2amps, because all resistors get the same current, equal to that of the resistor closest to the battery ($I = 12V / 6\ \Omega = 2A$)

3) 0.923amps, because the total resistance is $6\ \Omega + 4\Omega + 3\Omega = 13\Omega$ and $I = 12V / 13\Omega = 0.923A$

4) 3amps, because each resistor gets 4V because the bulbs share the voltage. So,
$I_1 = V/R_1 = 4V/3\Omega = 4/3A$
$I_2 = V/R_2 = 4V/4\Omega = 1A$
$I_3 = V/R_3 = 4V/6\Omega = 2/3A$
$I_{total} = I_1 + I_2 + I_3 = 4/3A + 1A + 2/3A = 3A$

A lot of those [CATs] really helped to compare what you know and what you didn't know.

A lot of the [CATs] and activities showed where we were and what we needed to work on.

In this way, the timing of assessments allowed students to correct their misconceptions:

…[the instructor] breaks down the whole two-hour lesson into smaller parts and she always asks us to draw on our white boards our list of things that we know and if something is wrong with that she will stop and say "Are you sure about this?" and we will discuss it and correct ourselves right then.

This perspective is consistent with that of the instructors in that they believed CATs provided a snapshot of what students understood at a given moment, and also illustrates students "buy-in" to CATs as useful teaching and learning tool.

LESSONS LEARNED

In our final research retreat as an action research team, we reflected on the questions that guided our action research, and what we learned about implementing classroom assessment techniques in the course. As a team, we felt the CATs we selected aligned well with our teaching goals, and provided us with valuable evidence of students' understanding of the course material. We observed that CATs encouraged critical thinking and fostered students' awareness of their own learning by providing a clear indicator of what they understood and what they did not. This improved their ability to ask specific, rather than general questions and seek clarification of the course material. Additionally, we found CATs useful in diagnosing students' difficulty. We benefited from the awareness of alternative conceptions held by students—many of which we did not anticipate. In this way, we were better prepared to address students' prior knowledge more effectively with our instruction.

A major change in our instruction was related to the pace of the course. By using CATs, we shifted our focus from getting through the planned activities to really getting through to the students and impacting their ideas. In some cases, this meant we spent more time on difficult concepts and conducted additional laboratory explorations that would directly challenge students' misconceptions. In other cases, it meant we moved more quickly than anticipated through concepts about which students had little confusion. By using CATs throughout each unit, we were able to continually assess effectiveness of our instruction and make these adjustments. In this manner, our teaching became more responsive to students' learning needs, and indeed provided an appropriate model of teaching for both our graduate teaching assistants and our prospective teachers.

Through this work, we've realized that accomplishing substantial change takes time not only for instructors, but also for students to adjust to unfamiliar teaching approaches. Students' naïve epistemologies (e.g., the belief that learning is about figuring out what the teacher wants) initially served as a barrier, but the consistent and deliberate use of CATs encouraged them to be metacognitive and self-evaluative as learners.

RECOMMENDATIONS

Consistent with the cyclical nature of action research, what we learned from this semester has influenced our plans for subsequent semesters in regard to assessment. First, we realize the importance of bringing students on board in terms of our goals and purposes. Student expectations are a powerful influence on their orientation to learning. As such, when students' goals conflict with the purpose and intent of the instructors, progress can be slow. Second, we acknowledge that there may be a "learning curve" for both instructors and students when using CATs, and that using them on a regular basis throughout the semester can help students feel more comfortable sharing and questioning their ideas. Overall, we felt CATs were not just effective at helping the students learn-- they also help the teacher learn about the students. With this information, learning can become a community endeavor in which both sides benefit from a more open environment conducive to learning. Since our students are preservice elementary teachers, we feel this is especially critical in terms of modeling appropriate science pedagogy.

We realize that substantial changes to instruction take time, but feel that the steps we've taken so far are important to continued improvement. The collaborative action-research model was especially beneficial in guiding and focusing our work. We feel this model is an effective for other faculty hoping to enact change in their courses and instruction, in that it promotes an open dialogue on teaching and learning and an evidence-based means for assessing the impact of instructional interventions.

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Assessing inquiry skills as a component of scientific literacy

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It is frequently said that achieving scientific literacy is the main goal of science education. It would seem reasonable, therefore, that an assessment instrument would exist for measuring progress toward that goal. Unfortunately, such an instrument does not appear to exist. Indeed, a single test of reasonable length would not likely be suitable for assessing scientific literacy in a comprehensive fashion. A battery of independent tests geared toward the task of assessing scientific literacy in its many dimensions is needed. Such battery tests can provide critical information to assess gaps in student knowledge and skills, guide instructional practice, hold schools accountable for achieving specific goals, and determine program and teacher effectiveness. After establishing a framework for assessing the skills of scientific inquiry, the author makes available the second in a series of tests being developed for comprehensively assessing a previously defined form of scientific literacy. The 35-item Scientific Inquiry Literacy Test (ScInqLiT) is introduced and explained.

Scientific literacy is multidimensional, and comes in a variety of types and degrees (Shen, 1975; Shamos, 1995; National Research Council [NRC], 1996). A relatively comprehensive form of scientific literacy that teachers might attempt to achieve among their students has been defined in the *National Science Education Standards* (NRC, 1996). The *National Science Education Standards* indicate that a scientifically literate individual will possess an understanding of six major elements of scientific literacy: (1) science as inquiry, (2) science content, (3) science and technology, (4) science in personal and social perspectives, (5) history and nature of science, and (6) unifying concepts and processes. Using this description as a guide, the author of this article has begun to develop a battery of standardized tests that can be used to measure progress toward attaining the goal of achieving scientific literacy so defined. In two previous articles, Wenning (2006a, 2006b) presented a framework for teaching and assessing Nature of Science (NOS) literacy. In the current article, the author proposes an operational definition of scientific inquiry suitable for guiding high school science teaching, reiterates a framework for teaching it, and describes a standardized test for assessing student knowledge and skills associated with scientific inquiry.

Operationally Defining Scientific Inquiry

Scientific inquiry – as a component of scientific literacy – has been variously defined. For instance, the *National Science Education Standards* (NRC, 1996) defines scientific inquiry as follows, "Scientific inquiry refers to the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work. Inquiry also refers to the activities of students in which they develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world" (p. 23).

Project 2061 gives a slightly different definition in *Benchmarks for Science Literacy* (American Association for the Advancement of Science [AAAS], 1993), "Scientific inquiry is more complex than popular conceptions would have it. It is, for instance, a more subtle and demanding process than the naive idea of 'making a great many careful observations and then organizing them.' It is far more flexible than the rigid sequence of steps commonly depicted in textbooks as 'the scientific method.' It is much more than just 'doing experiments,' and it is not confined to laboratories. More imagination and inventiveness are involved in scientific inquiry than many people realize, yet sooner or later strict logic and empirical evidence must have their day. Individual investigators working alone sometimes make great discoveries, but the steady advancement of science depends on the enterprise as a whole" (p. 9).

The National Science Teachers Association (NSTA, 2004) defines scientific inquiry somewhat differently still, "Scientific inquiry is a powerful way of understanding science content. Students learn how to ask questions and use evidence to answer them. In the process of learning the strategies of scientific inquiry, students learn to conduct an investigation and collect evidence from a variety of sources, develop an explanation from the data, and communicate and defend their conclusions" (p. 1).

While such statements are true – and several specific examples of scientific inquiry are given in the associated texts – these broad characterizations and specific examples are of little help to science teachers who are looking for a detailed operational definition that can guide science teaching. For the purpose of operationally defining scientific inquiry at a level appropriate for secondary schools, the author provides a listing of fundamental scientific inquiry skills in Table 1. These processes have been roughly organized into "stages" of scientific inquiry, and are patterned on the inquiry processes described in Wenning (2005a).

While the listing in Table 1 might at first appear to be based on a rather naïve understanding of the nature of scientific inquiry encountered in the secondary school classroom, it was developed in light of works by Kneller, Bauer, Wynn, Popper, Gould, Root-Berstein, Sayer and a number of others whose writings have been included in *Science and Its Ways of Knowing* edited by Hatton and Plouffe (1997). The author is fully cognizant of the fact that there is no "scientific method" per se, and that science more often than not develops along ways that are not consistent with the traditional Baconian approach. Further, this listing was developed in light of the fact that most scientific work at the secondary school level is not driven by hypothesis or model generation and

Stages of Scientific Inquiry

- Identify a problem to be investigated.
- Using induction, formulate a hypothesis or model incorporating logic and evidence.
- Using deduction, generate a prediction from the hypothesis or model.
- Design experimental procedures to test the prediction.
- Conduct a scientific experiment, observation or simulation to test the hypothesis or model:
  - o Identify the experimental system
  - o Identify and define variables operationally
  - o Conduct a controlled experiment or observation
- Collect meaningful data, organize, and analyze data accurately and precisely:
  - o Analyze data for trends and relationships
  - o Construct and interpret a graph
  - o Develop a law based on evidence using graphical methods or other mathematic model, or develop a principle using induction
- Apply numerical and statistical methods to numerical data to reach and support conclusions:
  - o Use technology and math during investigations
  - o Apply statistical methods to make predictions and to test the accuracy of results
  - o Draw appropriate conclusions from evidence
- Explain any unexpected results:
  - o Formulate an alternative hypothesis or model if necessary
  - o Identify and communicate sources of unavoidable experimental error
  - o Identify possible reasons for inconsistent results such as sources of error or uncontrolled conditions
- Using available technology, report, display, and defend the results of an investigation to audiences that might include professionals and technical experts.

Table 1. *A limited framework defining scientific inquiry skills as a part of scientific literacy. This framework is intended to be suggestive, not definitive.*

theory development, but that typically data are collected for the purpose of formulating principles or developing empirical laws. Finally, this listing was prepared with the understanding that not all inquiry processes will be experimental in nature. Sometimes evidence and logic alone will be used to draw scientific conclusions. Additionally, not all scientific inquiry skills will be used in any one investigation. Scientific inquiry based on observations will likely differ significantly form scientific inquiry based on experimentation. Geologist, biologists, chemists, and physicists, for example, all have different approaches to conducting scientific investigations and will use various elements of the listing to different degrees.

A Framework for Teaching Scientific Inquiry Skills

A framework must be provided if science teachers are to teach scientific inquiry skills systematically and a level appropriate to the intellectual maturity of their students. For instance, the approaches used for teaching early elementary children will differ remarkably from techniques used at the high school level. Teaching scientific inquiry skills effectively requires definitions of both the stages *and* levels of scientific inquiry suitable for students. Table 1 describes, roughly speaking, the levels of scientific inquiry (Wenning, 2005a). The most important features of the levels-of-inquiry spectrum are shown in Figure 1.

Using the stages and levels of inquiry sequences, teachers can implement inquiry practices in the science classroom. Teachers thereby help students learn inquiry skills by modeling successively more sophisticated forms of inquiry. Students develop increased understanding by moving through progressively more sophisticated levels of inquiry and carrying out various stages of inquiry repeatedly. As the level of intellectual sophistication required to conduct the various levels of inquiry grows, the locus of control shifts from teacher to student. For instance, during discovery learning the teacher directs students to make specific observations and guides them to draw specific conclusions using "funneling" questions (Wood, 1998). Inquiry lessons require the teacher to use a think aloud protocol to explain various scientific practices. While the teacher maintains control of equipment and the experiment, students are encouraged through "focusing" questions (Wood, 1998) that help them understand the nature of the scientific process. With inquiry labs, students take greater

Discovery Learning	Interactive Demonstrations	Inquiry Lessons	Guided Inquiry Labs	Bounded Inquiry Labs	Free Inquiry Labs	Pure Hypothetical Inquiry / Applied Hypothetical Inquiry
Low			<= Intellectual Sophistication =>			High
Teacher			<= Locus of Control =>			Student

Figure 1. *The levels-of-inquiry spectrum. As students become more intellectually sophisticated, the level of inquiry utilized by teachers correspondingly can become more sophisticated. At the same time, the locus of control shifts gradually from the teacher to the student.*

control of the entire learning process, from answering a series of questions and developing problems, to designing experimental procedures and drawing conclusion on their own. Lastly, during the advanced levels of hypothetical inquiry, students identify their own problems, develop hypotheses or models, make predictions, conduct experiments or observations, and draw conclusions on the basis of logic using empirical evidence. Interested readers are referred to the article *Levels of inquiry: Hierarchies of pedagogical practices and inquiry processes* (Wenning, 2005a) for additional information and examples associated with each of the levels within the inquiry spectrum.

Scientific Inquiry Literacy Test (ScInqLiT)

Eight steps were followed in the development of the Scientific Inquiry Literacy Test *(ScInqLiT)* using general procedures outlined by DeVellis (1991). The first step was to develop a framework that clearly defines what is to be measured. The framework for *ScInqLiT* can be found in Table 1. This framework operationally defines what constitutes literacy in scientific inquiry at a level appropriate to the understanding of high school science students. This framework gave a clear statement about what needed to be included in the assessment that came to be based upon it. The framework was reviewed by several physics teaching majors, scientists, and educators to provide reasonable assurance of content validity.

A pool of 40 questions was then generated for possible inclusion in the final assessment instrument. Each item consisted of a multiple-choice question with four possible answers. One or more questions were generated for each of the specifications presented in the framework. A team of six reviewers consisting of senior level undergraduate physics teacher education majors then reviewed the items for accuracy and clarity. Each of these reviewers had a good understanding of scientific inquiry as demonstrated by multiple and varied assessments completed as part of their physics teacher education course work at Illinois State University.

An initial pilot test consisting of the 40 questions was administered to 425 high school science students enrolled in five different central Illinois high schools during early February 2007. The population generally consisted of freshmen enrolled in introductory lab science, biological science, or general science courses, sophomores and juniors enrolled in chemistry courses, and juniors and seniors enrolled in physics courses. The range of scores on the pilot test was 0 to 36 out of 40 possible. The test mean was 18.78 (46.95%) with a standard deviation of 7.90 and a standard error of measurement of 2.79. The KR20 reliability coefficient was an unexpectedly high 88%. An analysis was conducted of each test item examining difficulty, discrimination, and suitability of foils. The mean item difficulty for 4-response multiple-choice questions was 0.469, which is a bit low for multiple-choice questions with four responses each. To maximize item discrimination, desirable difficulty levels are slightly higher than the midpoint between random guessing (1.00 divided by the number of choices) and perfect scores (1.00) for the item. The ideal mean difficulty for the four response multiple-choice questions used in this test therefore should not deviate much from a value of 0.625.

Five poor performing (very high or very low difficulty and/or small to negative discrimination) and somewhat redundant test items were removed, and one non-redundant but poor-performing test item was revised. This question was rewritten for increased clarity, and better alternative answers were prepared. The revised pilot test was administered a second time during mid to late April 2007 to 61 entirely different high school students. It is believed that these students – four classes from among two teachers – were highly motivated, and the groups relatively homogeneous. The high/low scores were 12/31 out of 35 possible. The mean test score of these students was 23.7 (67.6%), which is slightly higher than expected for a test designed to produce the maximum possible spread among scores. The standard deviation of the sample was 4.62, and the standard error of the mean 2.49. The mean item difficulty was 0.68 meaning that, on average, 68% of students completing a question gave the correct response. This exceeds the ideal mean item difficulty for a test of this format and did so, ostensibly, due to the fact that this latter pilot group was both motivated and homogeneous. The mean item discriminability was 0.32. These facts, plus the fact that the frequency distribution of scores was positively skewed, support belief in the motivated/homogeneous assumption. This is an important factor in interpreting item analysis data. The KR20 reliability coefficient was 0.71, not unanticipated given the nature of the second pilot group.

Following the second pilot study, and as part of the final review process for publication, one question was replaced and several others had their wording revised for improved clarity. It is expected that the finalized version of *ScInqLiT* has increased validity and reliability as a result of these changes.

Administering ScInqLiT

ScInqLiT is an un-timed test requiring typically about 40 to 50 minutes for nearly all high school students to complete. *ScInqLiT* probably is best employed under pre-test, post-test conditions; it generally should not be used as an achievement test. Due to its nature as a diagnostic test, the results from any testing situation probably will be unacceptably low. Questions have been developed and selected to provide a maximum dispersion of scores. As can be seen from the pilot study samples, average scores on these tests hover in the vicinity of 47% to 68% for high school students. *ScInqLiT* is best used primarily for the purpose for which it was created – to serve as a research instrument for identifying weaknesses in student understanding, improving instructional practice, and determining program effectiveness in relation to teaching scientific inquiry skills. *ScInqLiT* can be used readily for educational research or during professional development workshops for both elementary- and secondary-level teachers to show learning gains among participants.

The author encourages widespread use of *ScInqLiT,* and urges that test results be forwarded to him along with participant demographics so that the test can be normed using a variety of study groups. Users are requested to keep the instrument secure as with other standardized tests, and collect copies from students following testing. Use of the names *Scientific Inquiry Literacy Test* and *ScInqLiT* should also be avoided with students to help prevent them searching the Web for background information.

Limitations of ScInqLiT

Ideally, assessing procedural knowledge will be done use ing performance tests. *ScInqLiT* is a paper-and-pencil test. As such, it is limited in its ability to authentically assess student abilities to conduct scientific inquiry. Ideally, a test of scientific inquiry abilities would include materials with which a student would create and conduct a scientific experiment and draw legitimate conclusions. Alternatively, observational data could be provided to students who would then interpret that data to draw scientific conclusions. As a paper-and-pencil test, *ScInqLiT* should be thought of as only an indicator of student ability to conduct scientific inquiry. Researchers would do well to develop authentic tests including manipulatives that might be used to more fully assess student ability to conduct scientific inquiry in each of the various science disciplines.

The Importance of ScInqLiT

The No Child Left Behind Act of 2002 requires that all 50 states develop challenging goals in science and assess student progress toward the goals outlined in the *National Science Education Standards.* The required assessment in science must be in place for the 2007-2008 school year. States are now working toward developing their responses to the Federal mandate. The problem before them is to prepare and implement quality science assessments by the deadline. In an effort to provide assistance with this effort, the National Science Foundation asked the National Research Council to formulate guidelines for this work. The NRC responded by producing *Systems for State Science Assessment* (NRC, 2005). This work was predicated on the fundamental position of the *National Science Education Standards:* scientific literacy should be the goal for all K-12 science education. Any science assessment should therefore include not only content knowledge assessment, but also the critically important idea that it is important "...for students to understand science as a specific way of knowing..." (p. 1). As can be seen from a review of the historical development of a definition for scientific literacy (Wenning, 2006), one of the central themes has almost always been an understanding of how one conducts scientific inquiry.

If the main goal of science education is indeed the attainment of scientific literacy, then understanding the processes of scientific inquiry is critically important to achieving the stated goal. A scientific inquiry literacy assessment instrument – an instrument for measuring a fundamental dimension of scientific literacy – could have a significant impact on both curriculum design and instructional practice. For instance, assessments and their frameworks provide important data required for informed decision making, for holding schools accountable for meeting achievement goals, and for determining program effectiveness. Additionally, such assessments and their associated frameworks can help classroom teachers, school administrators, and educational agencies to exemplify their goals for student learning. *ScInqLiT* is currently being used as part of a *Student Teacher Effectiveness Reporting System* at Illinois State University that will be the subject of a future article.

Teachers, teacher educators, and science education researchers wishing to obtain a copy of the *Scientific Inquiry Literacy Test* (*ScInqLiT*) may download it as a password-protected portable document file (PDF) from the *Journal of Physics Teacher Education Online* Web site at the following URL: http://www.phy.ilstu.edu/jpteo/ScInqLiT.pdf. The associated *Nature of Science Literacy Test* (*NOSLiT*) is similarly available at http://www.phy.ilstu.edu/jpteo/NOSLiT.pdf. The passwords for both tests may be obtained directly from the author of this article by e-mailing him at wenning@phy.ilstu.edu.

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Cognitive variables in science problem solving: A review of research

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This paper provides an overview of research into cognitive variables that are involved in problem solving and how these variables affect the performance of problem solvers. The variables discussed are grouped together in: prior knowledge, formal reasoning ability and neo-Piagetian variables, long-term memory and working memory, knowledge base, and metacognitive variables.

Introduction.

During the 1960s and 70s, researchers develop general problem-solving models to explain problem-solving processes (Bransford and Stein, 1984; Newell and Simon, 1972; Polya, 1957). The assumption was made that by learning abstract (decontextualized) problem solving skills, one could transfer these skills to any situation. Under the influence of cognitive learning theories, the last 25 years have seen a great deal of work in the study of problem solving and there is a growing consensus about the kinds of mental processes involved and the kinds of difficulties problem solvers have. Today we know problem solving includes a complex set of cognitive, behavioural, and attitudinal components. Mayer and Wittrock (1996) defined problem solving as a cognitive process directed at achieving a goal when a solution method is not obvious to the problem solver. Palumbo (1990) supports problem solving as a situational and context-bound process that depends on the deep structures of knowledge and experience. Garofalo and Lester (1985) indicated that problem solving includes higher order thinking skills such as visualization, association, abstraction, comprehension, manipulation, reasoning, analysis, synthesis, generalization, each needing to be managed and coordinated.

In the realm of cognitive psychology, problem solving has a dual identity as a basic cognitive function and also an activity of educational importance (Elshout, 1987). In a matrix with rows representing basic cognitive functions and columns representing important educational activities, Elshout showed that problem solving, as a basic cognitive function, is involved in all educational activities and as an activity, involves all the basic cognitive functions.

Problem solving plays a crucial role in the science curriculum and instruction in most countries (Gabel and Bunce, 1994; Heyworth, 1999; Lorenzo, 2005). It is a much-lamented fact that students often do not succeed in applying knowledge that they have acquired in lessons at school or in everyday contexts. This circumstance seems to apply especially to science lessons (Friege and Lind, 2006). As a consequence, improving students' problem-solving skills continues to be a major goal of science teachers and science education researchers. In order to achieve the ability to solve problems in science, there are two concerns (Lee et al., 2001): to develop in students problem-solving skills through science education, and to look at the difficulties faced by students in this area and find ways to help them overcome these difficulties. Modeling Instruction has demonstrated its efficacy in improving students' ability to solve problems (Malone, 2006). This author attempts to explain why modeling pedagogy might help students become more superior problem solvers by means of a review of the pertinent literature investigating the differences in problem-solving and knowledge structure organization between experts and novices. Evidence from the research literature suggests that a variety of cognitive factors is responsible for science problem-solving performance.

The purpose of this paper is to present an overview of a number of cognitive variables involved in problem solving in science and how these factors mediate the performance of problem solvers. The variables discussed are grouped together in: prior knowledge, formal reasoning ability and neo-Piagetian variables (mental capacity, field-dependence/field-independence, mobility/fixity dimension, and convergent/divergent characteristic), long-term memory (LTM) and working memory (WM), knowledge base, and metacognitive variables. This exposition could suggest some directions for classroom instruction to facilitate more effective problem solving.

Prior knowledge.

According to Ausubel's theory, if students are meaningfully to incorporate new knowledge into existing knowledge structure, then the existing structure is an important factor in what they learn (Ausubel et al., 1978). In the psychology of Ausubel, that lays great stress upon the internal mental networks that a student develops for himself rather than upon external teaching networks. In this is the implicit idea that every student constructs his own knowledge in his own way. To learn, the student has to *unpack* what he is taught and then *repack* it in a way that suits his previous knowledge and his own learning style. The central idea in Ausubel's assimilation theory is that of meaningful learning, which defines as nonarbitrary, substantive, nonverbatim incorporation of new knowledge into cognitive structure. Cognitive structure is the framework stored in our minds that grows and develops from chilhood to senescence. Ausubel's concept of meaningful verbal learning which has gained wide currency stresses the importance of prior knowledge as the most important factor influencing learning (Novak, 1980). Emphasis is placed on the comprehension of concepts and the inter-relations among concepts; as links between prior knowledge and new knowledge are established, meaningful learning is said to occur. The implication is that students with the appropriate prior knowledge will be able to comprehend more and achieve better.

In terms of this theory, we would expect to see relationships between prior knowledge and post knowledge and achievement. Entwistle and Ramsdem (1983) have shown that the level of students' prior knowledge and factors associated with course and teaching affect the way students approach their studies and subsequently what they learn. They found that prior knowledge was a particular concern in the sciences.

Concepts maps can be constructed to examine students' starting points before instruction. The maps will do more than identify the range of concepts and ideas that students hold before instruction; they will also reveal the students' alternate conceptions (Ebenezer, 1992). Hegarty-Hazel and Prosser (1991) have used concept-mapping tasks as a way of obtaining information about how students see the structural relationships between the major concepts included in the topic they are studying. The tasks used in this study asked students to describe briefly the relationship between concepts included in a list that had been previously identified from a analysis of the curriculum.

Much of the published work in science education has focused on the relation between prior knowledge and post knowledge, and the difficulties in changing and developing students' conceptions. Several studies shows that prior knowledge is statistically significantly related to variation in science achievement (Lee et al., 2001; Chandran et al., 1987; Hussein, 1989; Lawson, 1983; Solaz-Portolés and Sanjosé, 2006). They indicate that prior knowledge is good predictor of problem-solving performance.

Formal reasoning ability and neo-Piagetian variables.

Piaget taught us that young children are fundamentally different kinds of thinkers and learners from adults –that they think in concrete terms, cannot represent concepts with structure of scientific concepts, are limited in their inferential apparatus, and so forth. His stage theory described several general reorganizations of the child's conceptual machinery –the shift from sensorimotor to representational thought, from pre-logical to early concrete logical thought, and finally to the formal thinking of adults. In Piaget's system, these shifts are domain independent (Carey, 1986). Developmental level is a Piagetian concept and refers to the ability of the subject to use formal reasoning (Lawson, 1985). Psychological tests are research tools used more often to determine students' level of reasoning and neo-Piagetian variables.

Most of the discussion of Piaget's work among science educators has focused on the transition between the concrete operational and formal operational stages and ways in which instruction can be revised in light of this model (Bodner, 1986). A great deal of attention has been given to the work of Piaget, pointing out that there may be a connection between age (maturity) and the complexity of thinking of which a learner is capable. Thus, Piaget's followers (Herron, 1978; Lawson and Karplus, 1977) argue that students who have not attained formal operational ability will not be able to comprehend meaningfully abstract concepts and principles of science.

The neo-Piagetian theory of Pascual-Leone argues that formal reasoning alone cannot explain student success, and provides explanatory constructs for cognitive development by postulating: a) the M-operator or M-space, which accounts for an increase in students' information processing capacity with age (Pascual-Leone and Goodman, 1979); b) the field factor (field-dependence/field -independence), which represents the ability of a subject to disembed information in a variety of complex and potentially misleading instructional context, thus, the learners who have more difficulty than others in separating *signal* from *noise* are classed as field-dependent (Pascual-Leone, 1989); and c) the mobile/fixed cognitive style, that arises from a combination of mental capacity (M-space) and disembedding ability, fixity characterizes consistency of function of field-independent subjects in a field-independent fashion, while mobility provides for variation according to circumstances (Pascual-Leone, 1989).

Positive linear relationships between formal reasoning activity (developmental level) and achievement in science problem-solving have been described by a number of authors (Lawson, 1983; Chandran et al., 1987; Níaz, 1987a; Hussein, 1989; Bunce and Huchinson, 1993; Tsaparlis et al., 1998, Demerouti et al., 2004). More general studies by Staver and Halsted (1985) and by Robinson and Níaz (1991) also support this relationship.

In science, mental capacity (M-space) is associated with students' ability to deal with problem-solving (Níaz, 1987a; Tsaparlis, Kousathana and Níaz, 1998; Tsaparlis, 2005). However, students with higher information processing capabilities (higher mental capacity scores) do not always perform better than students with lower mental capacity scores (Chandran et al., 1987; Robinson and Níaz, 1991).

Studies by Níaz (1987), Tsaparlis (2005), Danili and Reid (2006), Tsaparlis, Kousathana and Níaz (1998), Johnstone, Hogg and Ziane (1993), and by Demerouti, Kousathana and Tsaparlis (2004) have indicated that students with better disembedding ability (i.e. field-independent students) are more successful solving problems than students with lower disembedding ability scores (i.e. field-dependent students). However, studies by Chandran, Treagust and Tobin (1987), and by Robinson and Níaz (1991) have shown that this cognitive variable played no significant role in science achievement. Overall, the field dependent/independent test is considered by some researchers a very powerful instrument to predict academic performance of individuals (Tinajero and Paramo, 1998).

The results of various works (Níaz, 1987b; Níaz et al., 2000; Stamovlasis et al., 2002) support the hypothesis that mobility-fixity dimension can serve as a predictor variable of students' performance in problem solving. Moreover, the most *mobile* students performed best on creativity tests whereas *fixed* students performed better on tests of formal reasoning (Níaz and Nuñez, 1991). Mobile subjects are those who have available to them a developmentally advanced mode of functioning (i.e., field-independence) and a developmentally earlier mode (i.e., field-dependence)(Níaz, 1987b).

Many researchers tended to equate divergent thinking with creativity and convergent thinking with intelligence. This has caused a great deal of controversy, with different research supporting different results (Bennett, 1973; Runco, 1986; Fryer, 1996). According to Hudson (1966), the *converger* is the student who is substantially better at intelligence test than he is at the open-ended tests; the *diverger* is the reverse. Convergent thinking demands close reasoning; divergent thinking demands fluency and flexibility (Child and Smithers, 1973). In the literature little research is reported on convergent/divergent cognitive styles and performance in science. In the work of Danili and Reid (2006) the convergent/divergent characteristic correlated with pupils' performance in assessment where language was an important factor, but not in algorithmic types of questions or in questions where there is a greater use of symbols and less use of words. In almost all the tests the divergent pupils outperformed convergent pupils and, when there were short answer or open-ended questions, the differences in the performance between the divergent and convergent groups became larger.

Long-term memory (LTM) and working memory (WM).

Information processing theory focuses on learning and learner and suggests mechanisms in the learning process (Osborne, 1985). This theory enables us to understand the learning limitations and, more important, to help the students to circumvent the problems. In terms of this theory, long-term memory (LTM) helps us to select the important from the unimportant. If we decide to act on this information, it is encoded for storage or translated into a response. The storage process is most efficient if we link the new information to something already in the LTM. The LTM seems to have almost infinite capacity for holding information, but the retrieval system is not always efficient. The more similarities and anchorages we can find for attaching the new information, the more easily it will be retrieved. The short-term memory (STM), sometimes also referred to as working memory (WM), is the space where the information derived from the LTM and from outside is brought together in mental operations and transformations. It is here where new and recalled information interacts, is linked and sequenced for a response (to learning task or problems) or for storage (Johnstone, 1993; Kempa, 1991). It is well established through psychological research that the capacity of our working memory is rather limited. Most people can hold only about 7 ± 2 information units (chunks) in their working memory. What constitutes a information unit or chunk in this space is controlled by our previous knowledge, experience and acquired skills (Johnstone and El-Banna, 1986). Thus, the size of each unit of information depends upon the way it is perceived by the person (Johnstone, 1983). Figure 1 shows one version of the information processing theory in a schematic form.

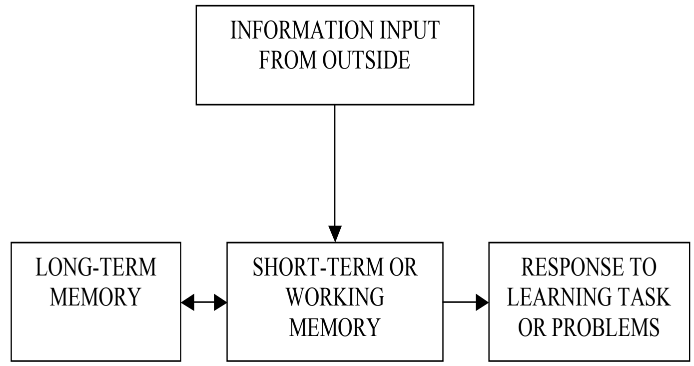

Figure 1. *Schematic representation of the information processing theory.*

In science education, cognitive structure is commonly defined as the representation of relations between elements of LTM. Cognitive psychologists posit *the essence of knowledge is structure* (Anderson, 1984, p.5). Research on the cognitive aspects of science learning has provided evidence that professional scientists and successful students develop elaborate, well differentiated, and highly integrated frameworks of related concepts (Shavelson et al., 2005) to form a static network (Hendry and King, 1994). This *static* knowledge about facts, concepts and principles (in the LTM) is called declarative or conceptual knowledge (Fergusson-Hesler and de Jong, 1990). Declarative knowledge is characterized by what people can report (knowing that) and facilitates the construction of organized frameworks of science concepts while providing scaffolding for the acquisition of new concepts (Novak and Gowin, 1984).

According to Kempa's studies (Kempa, 1991; Kempa and Nicholls, 1983), a direct connection emerges between cognitive structure (LTM structure) and problem-solving difficulties. These difficulties are usually attributable to one or more of the following factors:

1. The absence of knowledge elements from a student's memory structure.
2. The existence, in the student's memory structure, of wrong or inappropriate links and relationships between knowledge elements.
3. The absence of essential links between knowledge elements in the student's memory structure.
4. The presence of false or irrelevant knowledge elements in the student's memory structure.

In terms of Ausubel's theory, if students are meaningfully to incorporate new knowledge into existing knowledge structure, then we would expect to see relationships between conceptual knowledge after instruction and achievement (Pendley et al. 1994). Indeed, it was found that conceptual declarative knowledge is a excellent predictor of problem-solving performance (Friege and Lind, 2006; Solaz-Portolés and Sanjosé, 2006). On the other hand, expert performance seems to reside in the organization of the experts' domain knowledge. Experts possess a large knowledge base that is organized into elaborate, integrated structures, whereas novices tend to possess less domain knowledge and a less coherent organization of it (Zajchowski and Martin, 1993). The way knowledge is organised allows optimised access to the long-term memory. The borders between long-term memory and working memory of experts become fluent so that the capacity of the working memory in comparison to a novices' memory is considerably expanded (Ericsson and Kintsch, 1995).

Research on problem solving has shown that the psychometric variable working-memory can be predictive, in certain cases, of student performance (Johnstone et al., 1993; Niaz and Loggie, 1993; Tsaparlis et al., 1998). A characteristic model of problem solving is the Johnstone–El Banna model (Johnstone and El-Banna, 1986). This model is based on working-memory theory as well as on Pascual-Leone's M-space theory. It states that a student is likely to be successful in solving a problem if the problem has a mental demand which is less than or equal to the subject's working-memory capacity, X (i.e., $Z \leq X$, the authors approximated the Z value to the number of steps in the solution of the problem for the least talented but ultimately successful students), but fail for lack of information or recall, and unsuccessful if $Z > X$, unless the student has strategies that enable him to reduce the value of Z to become less than X. Simple problems have been used to study the necessary conditions for the validity (Tsaparlis, 1998), as well as the operation and the validity itself (Tsaparlis and Angelopoulos, 2000) of the Johnstone–El Banna model.

Knowledge base.

The knowledge needed to solve problems in a complex domain is composed of many principles, examples, technical details, generalizations, heuristics, and other pieces of relevant information (Stevens and Palacio-Cayetano, 2003). The development of a knowledge base is important both in terms of its extent and its structural organization. To be useful, students need to be able to access and apply this knowledge, but the knowledge must be there in the first place. Any claim that is not so, or that knowledge can always be found from others sources when it is needed, is naive (Dawson, 1993).

Shavelson, Ruiz-Primo and Wiley (2005) present a conceptual framework for characterizing science goals and student achievement that includes declarative knowledge (knowing that, domain-specific content: facts, definitions and descriptions), procedural knowledge (knowing how, production rules/sequences), schematic knowledge (knowing why, principles/schemes/mentals models) and strategic knowledge (knowing when, where and how our knowledge applies, strategies/domain-specific heuristics). For each combination of knowledge type and characteristic (extent-how much?- , structure –how it is organized?- and others), Li and Shavelson (2001) have begun to identify assessment methods. However, while we can conceptually distinguish knowledge types, in practice they are difficult to distinguish and assessment methods do not line up perfectly with knowledge types and characteristics. For example, to measure the extent of declarative knowledge, multiple-choice test and short-answer questions are cost-time efficient and very reliable. To measure the structure of declarative knowledge concept- and cognitive-maps provide valid evidence of conceptual structure (Ruiz-Primo and Shavelson, 1996a). To measure procedural knowledge, performance assessments, not paper-and-pencil assessments, are needed (Ruiz-Primo and Shavelson, 1996b). Sadler (1998) provided evidence of the validity of multiple tests for measuring schematic knowledge (mental models). Strategic knowledge is rarely ever directly measured. Rather, it is implicated whenever other types of knowledge are accessed (Shavelson et al., 2005).

Ferguson-Hessler and de Jong (1990) distinguished four major types of knowledge for the content of an adequate knowledge base with regard to its importance for problem solving:

1. Situational knowledge is knowledge about situations as they typically appear in a particular domain. Knowledge of problem situations enables the solver to sift relevant features out of the problem statement.
2. Declarative knowledge, also called conceptual knowledge, is static knowledge about facts and principles that apply within a certain domain.
3. Procedural knowledge is a type of knowledge that contains actions or manipulations that are valid within a domain. Procedural knowledge exists alongside declarative knowledge in the memory of problem solvers.
4. Strategic knowledge helps the student to organize the problem-solving process by showing the student which stages he should go through in order to reach a solution.

Later, these authors described different aspects of quality of knowledge that can occur in all types of knowledge. Aspects of quality of knowledge are hierarchical organization (superficial vs. deeply embedded), inner structure (isolated knowledge elements vs. well structured, interlinked knowledge), level of automation (declarative vs. compiled) and level of abstraction (colloquial vs. formal) (de Jong and Ferguson-Hessler, 1996) .

Two studies of Lee and co-works (Lee, 1985; Lee et al., 1996) have shown that successful problem solving is related to cognitive variables: concept relatedness, idea association, problem translating skill and prior problem experience. Concept relatedness is a measure of the relatedness between concepts that are involved in problem solving. Idea association measures the ability to associate ideas, concepts, words, diagrams or equations through the use of cues which occur in the statements of the problems. Problem translating skill measures the capacity to comprehend, analyse, interpret and define a given problem. Prior problem solving experience is a measure of the prior experience in solving the similar problems. In an extension of the two previous studies (Lee et al., 2001), they investigated the effect of the same cognitive variables (except for prior problem solving experience) in solving other type of problems, such as the different topics and levels. The findings of these studies are consistent and link the success of problem solving to adequate translation of problem statement and relevant linkage between problem statement and knowledge.

Friege and Lind (2006) reported that conceptual knowledge and problem scheme knowledge are excellent predictors of problem-solving performance. A specific problem scheme consists of situational, procedural and conceptual knowledge combined into one. Problem schemes are a high quality type of knowledge characterised by a very profound and interlinked knowledge. A detailed analysis shows that the conceptual knowledge is more typical for low achievers (novices) in problem solving whereas the problem scheme knowledge is predominately used by high achievers (experts).

Camacho and Good (1989) described differences in the way experts and novices go about solving problems. Successful solvers' perceptions of the problem were characterized by careful analysis and reasoning of the task, use of related principles and concepts to justify their answers, frequent checks of consistency of answers and reasons, and better quality of procedural and strategic knowledge. Unsuccessful subjects had many knowledge gaps and misconceptions.

De Jong and Fergurson-Hessler (1986) have found that poor performers organized their knowledge in a superficial manner, whereas good performers had their knowledge organized according to problem schemata with each problem schema containing all the knowledge – declarative, procedural and situational – required for solving a certain type of problem. In a subsequent experiment Ferguson-Hessler and de Jong (1990) collected information about differences in study processes between students who are good problem solvers and students who are not. Good and poor performers did not differ in the number of study processes scored, indicating that both groups studied in an equally active way. They differed in the type of processes scored: good students applied more deep processing and less superficial processing than poor students. Poor performers were found to pay more attention to declarative knowledge, whereas good performers tended to pay attention to procedural and situational knowledge.

Metacognitive variables.

A classical definition of metacognition is that offered by Flavell (1976, p.232): *Metacognition refers to 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.* From the Anderson's cognitive perspective, the components of knowledge needed to solve problems can be broadly grouped into factual (declarative), reasoning (procedural), and regulatory (metacognitive) knowledge/skills, and all play complementary roles (Anderson 1980). In accordance with the work of O'Neil and Schacter (1999), to be a successful problem solver one must know something (content knowledge), possess intellectual tricks (problem-solving strategies), be able to plan and and monitor one's progress towards solving the problem (metacognition), and be motivated to perform. An article of Richard E. Mayer (1998) examines the role of cognitive, metacognitive and motivational skills in problem solving, and concludes that all three kinds of skills are required for successful problem solving in academic settings.

Several studies have investigated the relationship between metacognitive abilities and academic achievement (Leal, 1987; Pintrich and DeGroot, 1990; Pokay and Blumenfeld, 1990). One limitation in these investigations is that they relied on self reports of students to assess metacognitive strategies they use. The study of Otero, Campanario and Hopkins (1992) develop an instrument for measuring metacognitive comprehension monitoring ability (CMA) that does not rely entirely on subjects' self-reports. Their results indicated that CMA was significantly related to achievement academic, as measured by marks. In the paper of Horak (1990) were noted interactions between the students' cognitive style (field-dependence/independence) and their use of problem-solving heuristics and metacognitive processes.

The results of the work of Artz and Armour-Thomas (1992) suggest the importance of metacognitive processes in mathematical problem solving in a small-group setting. A continuous interplay of cognitive and metacognitive behaviours appears to be necessary for successful problem solving and maximum student involvement. In same way, the study of Teong (2003) demonstrates the effect of metacognitive training on mathematical word-problem solving. Experimental students, who developed the ability to ascertain when making metacognitive decisions and elicit these decisions, outperformed control students on cleverness to solve word-problems. And experimental and interview based-design was used by Longo, Anderson and Wicht (2002) to test the efficacy of a new generation of knowledge representation and metacognitive learning strategies called visual thinking networking (VTN). Students who used the VTN strategies had a significantly higher mean gain score on the problem solving criterion test items than students who used the writing strategy for learning science. To get an overview of the characteristics of good and innovative problem-solving teaching strategies, Taconis, Fergusson-Hessler and Broekkamp (2001) performed an analysis of a number of articles published between 1985 and 1995 in high-standard international journals, describing experimental research into the effectiveness of a wide variety of teaching strategies for science problem solving. As for learning conditions, both providing the learners with guidelines and criteria they can use in judging their own problem-solving process and products, and providing immediate feedback to them were found to be important prerequisites for the acquisition of problem-solving skills. Abdullah (2006) indicated that there are only a few studies looking specifically into the role of metacognitive skills in physics in spite of the fact these skills appear to be relevant in problem solving. This researcher has investigated the patterns of physics problem solving through the lens of metacognition.

Summary and conclusion.

In accordance with the results of the investigations that we have analysed, success in problem solving appears to be influenced by the following cognitive variables:

- Prior knowledge.
- Formal reasoning activity (developmental level).
- Mental capacity (M-space).
- Disembedding ability (field dependent/independent).
- Mobility-fixity dimension.
- Divergent-convergent thinking.
- Declarative knowledge (conceptual knowledge).
- Working memory capacity.
- Concept relatedness.
- Idea association.
- Problem translating skill.
- Prior problem solving experience.
- Procedural knowledge.
- Strategic knowledge.
- Problem scheme knowledge (problem schema containing all the knowledge required for solving a problem).
- Metacognitive skills.

Obviously, skill in problem solving depends on the effective interaction of cognitive variables as those discussed above. In order to improve problem-solving skills, the standard approach is to look at the cognitive variables and processes involved in skilled problem-solving performance and then to derive instructional approaches that will assist students. In this paper, we are presented cognitive variables involved in the solving of problems. In a later article we will address cognitive processes in problem solving.

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