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## EDUCATING SCHOOL TEACHERS

By now I suspect that most who have an abiding interest in teacher preparation have heard of the recommendations authored by Dr. Arthur Levine in *Educating School Teachers* and released by the Education Schools Project. While many of his criticisms and recommendations are valid, I have a number of concerns not the least of which is that institutions and law makers might take these recommendations to heart without carefully thinking about their implications or consequences. In my opinion, many of Dr. Levine's recommendations seem elitist. Others of them seem to be based on a flawed perception of reality. Others still seem to be impractical.

When I first began to review the findings and recommendations contained within the Executive Summary of *Educating School Teachers,* I was immediately struck by the remark, "The measure of a teacher education program's success is how well the students taught by its graduates perform academically." Using school student performance to assess to quality of university-level preparation is naïve. It assumes a process-product approach which has never been shown to exist in the academic setting, and for which evidence is tenuous at best. While there is some connection between the quality of teaching and student learning, the two are not necessarily linked. For instance, if the best teacher education program in the world prepares teachers to teach in urban settings where students have a low socioeconomic status, the test scores of school students would in all likelihood be suggestive that the teacher program is of little worth in preparing teachers. On the other hand, a poorly prepared teacher might receive accolades for excellence if he or she is teaching in an affluent community where students are strongly motivated and high scores on mandated testing are the norm. The same would hold true for the teacher's college education program.

In addition, to make the suggestion that it would be best to pattern all teacher education programs after "exemplary teacher education programs" studied for the report is simply not practical. I have studied firsthand and in some considerable detail "quality" education programs such as that at Alverno College, and have even implemented some of their instructional strategies - especially their assessment as learning policy. Many of their strategies work well in programs with small teacher education populations, but when the processes are expanded to the "large university model" where there might be many dozens of students in a single classroom, things might not go as anticipated.

To suggest that students (assumed here to be elementary school teachers) should have a content major is a reasonable idea. Still, to suggest that all teacher preparation programs should become five-year programs overlooks the fact that many secondary education programs include a content major already. Is the implication that a 5-year plan of study would make even secondary school candidates better teachers by having them take more content courses? I'm not convinced that taking advanced courses in physics has ever done much to improve the quality of introductory-level teaching. If that were the case, the Ph.D. would be the best teacher, and we know that this is not always the case.

The cost of a 5th year of education would be exorbitant, and would result if fewer, not more teachers. A fifth year will be very expensive not only for the cost of another year of schooling, but the loss of what would have been the first-year income. The cost to the teacher candidate can be $50,000 or more. Is this a reasonable price for anyone to pay for another year of schooling of doubtful worth - especially for secondary school teachers?

Clearly, improving the quality of teacher candidates admitted to teacher education programs would be a great thing; it would great if all teacher candidates were straight-A students. However, should we restrict our programs to only the best and brightest, I dare say that there would be considerably fewer teacher education candidates. The most unfortunate thing about this elitist approach is that it has been my experience that sometimes those who were not straight-A students have turned out to be the better teachers. What really seems to matter is whether or not new teacher are predisposed to long-term professional development which all so often makes a major difference between poor and excellent teachers. This often has little to do with grade point average.

I am all for Levine's recommendation to close failing teacher education programs, and to strengthen promising ones, and expanding excellent ones. Our experiences here at Illinois State University have shown that if an excellent education program can be developed, it will attract the best and brightest candidates, and help increase the number of teachers so desperately needed. This sort of program development takes a clear vision, a tremendous amount of hard work, and years of effort.

While the discussion about *Educating School Teachers* has just begun, teacher educators should carefully consider what Levine has to say. We should not discount much of what is, I feel, justified criticism of the teacher education process. Only by examining our own successes and failures can we hope to develop teacher education programs worthy of the name.

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*JPTEO* EDITOR-IN-CHIEF



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**REVIEWERS**

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# A post participation review of the University of Virginia's on-line graduate credit physics course for teachers *PHY 605: How Things Work I*

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*The University of Virginia (UVa) Physics Department offers a series of on-line graduate credit courses intended for physics teachers who are pursuing their master's degree, or who want to expand their physics content knowledge as part of their professional development. Here I present a post participation review of PHY 605: How Things Work I, which I took in Fall 2005 for credit toward my M.S.Ed. (Physics) degree from Buffalo State College. I found PHY 605 very worthwhile in both increasing my Physics content knowledge and teaching me simple and relevant demonstrations and concepts that I could directly use in my own high school physics classroom.*

In Fall 2005, I was teaching both High School Regents and General Physics classes in Rochester, New York, and working toward obtaining my M.S.Ed. (physics) from SUNY- Buffalo State College [Ref 1], that satisfies the masters' degree requirement for my NY professional teacher certification. The ninety-minute commute from Rochester to Buffalo for evening classes was fairly discouraging during the school year (particularly in winter), so I chose to take PHY 605 from the University of Virginia (UVa) on-line offerings.

I had a couple of courses to choose from and I chose *PHY 605: How Things Work I* for a variety of reasons. In my General Physics course I felt that it was particularly important to connect what the students do in class to real life experiences and I thought that this course would help me make more of those connections. I also chose this course because I had heard of the text *How Things Work* before. This was a very popular book and I figured that something this popular was probably worthwhile.

The University of Virginia Department of Physics course *PHY 605: How Things Work I* was described in the department online literature [Ref 2] as:

"... a practical introduction to physics and science in everyday life. The course considers objects from our daily environment (baseballs, frisbees, roller coasters, vacuum cleaners, rockets, clocks and much more!) and focuses on their principles of operation, histories, and relationships to one another. This course emphasizes motion, mechanics, liquids, heat, gases, and sound. The demonstrator and lecturer is professor Lou Bloomfield, who has originated and developed the courses *How Things Work I and II* at UVa." [Ref 2]

Half of all students taking these online UVa graduate physics courses for teachers [Ref 2] find out about them by searching online; courses with similar intentions are also offered through the NTEN network [Ref 3]. At the UVa web site there are pages offering detailed information about each course that UVa offers, as well as links to each course's home page, and explanation for how to register for courses. Course prerequisites are a four-year degree and a teaching license; however this information is not verified when registering for the course. [Ref 2]

My total cost for the three credit PHY 605 as an out of state student in Fall 2005 was just over $900. In state students received a price break of $300. In addition, the textbook *How Things Work: the Physics of Everyday Life [Ref 4]* by Louis Bloomfield of UVa physics costs about $80. After registration, I received access to the UVa *Blackboard Learning System, WebAssign* (an online homework system)*, the Horizon Wimba Audio Chat Room* (hereafter referred to as chat room), and a UVa e-mail address. [REF 5,6,7] Students also received by mail ten CDs of videotaped lectures by Professor Louis Bloomfield teaching his undergraduate "How Things Work I" course. These were shipped upon registration for the course and reached most students in two weeks, however some students received their CDs late because they registered late for the course.

To succeed in this course a student needed a fairly modern computer with Internet access, an e-mail account, Acrobat Reader, and RealPlayer (to watch the CD lectures). It was also helpful to have a DSL, cable modem or other fast internet connection (dialup is too slow), computer speakers and a computer microphone for the chat room. The instructions to get to everything else needed for the course was available on the course web page and the instructor e-mailed separate, more detailed, access instructions to each student.

There were several components to the course including biweekly reading and homework assignments, the ten discs worth of lectures to watch, and thee exams plus a final. The first two exams were multiple choice and the final was multiple-choice, however the third exam was different. Instead of answering multiple choice questions, students were asked to write multiple choice questions that were then graded on a rubric. As an option students could also participate in an asynchronous online *BlackBoard* [Ref 5]

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forum which students could post questions or ask other students questions about the course. Once a week there was also audio/ internet help sessions led by the instructor using *Horizon Wimba Chat Room* [Ref 7].

My instructor of record for the course was Dr. Richard Lindgren, (not Prof. Bloomfield the CD lecturer). The instructor wrote the homework work assignments, tests, and led the on-line chat room. There were on average three hours worth of CD lectures to watch each week, plus about fifty pages of textbook reading. A typical homework assignment consisted of three demanding conceptual questions with six parts each such as the following question:

"Two identical toboggans leave the top of a steep hill at the same time. Imagine that you are in one of them, by yourself. The other is occupied by six people.

a. Neglecting the effects of air resistance and friction, which toboggan will reach the bottom of the hill first? Defend your answer.
b. During the descent, your toboggan brushes up against the six-person toboggan. Which toboggan will experience the largest change in velocity as the result of the impact? Defend your answer.
c. You decide to take a steeper route down the hill. How will your speed at the bottom of the hill be affected?
d. Before each downhill run, you must pull the toboggan back to the top of the hill. Explain how the toboggan's gravitational potential energy changes on the way up the hill and on the way down.
e. When are you doing (positive) work on the toboggan?
f. When is gravity doing (positive) work on the toboggan?" [ref 8]

Each part of the question required a couple of sentences for an answer. On *BlackBoard* there was a space to discuss each part of the question with your peers taking the course. The instructor would also answer questions, but more often it was students answering other students questions.

Although this course was very similar to PHY 105, taught by Professor Louis Bloomfield, there were some key differences that made this course appropriate for an upper level physics course. Many beginning physics teachers have difficulty conceptually understanding physics, and the homework sets in the PHY 605 course were designed to challenge students' conceptual knowledge. These questions were more difficult than those questions asked of the PHY 105 students. Another key difference between the two courses is that PHY 605 had the students write their own conceptual questions, this is something that teachers would be doing in their own courses. Blackboard also allowed some collegiality between new teachers. Lesson plans, good books, and other ideas were exchanged through this forum. I must admit that some of the homework questions stumped me and I had to post messages to *BlackBoard*.

*BlackBoard* was organized particularly well. The instructor created a separate spot for discourse upon each homework questions, so students could immediately find the information they were searching for. It was very helpful to be able to read and reread responses from both the instructor for the course and the other students. The downside was that sometimes it took a day or two to get a response. This meant that completing homework at the last minute sometimes left me with little or no help. A procrastinator's only hope was that someone more responsible asked the same questions and that a discussion of the homework question he or she was struggling with had already ensued.

Besides posting to blackboard, struggling students could get help with homework assignments and test material in the audio chat room every Wednesday. The chat room was not required for the course, but it was helpful to get to have verbal conversations with classmates and the professor. In order to be able to properly use this technology a student needed speakers and a microphone for their computer. Although it was possible to participate in the chat room without a microphone (by listening to the voice chat through the computer speaker and typing in a response), the instructor suggested he would require students to have a microphone and audio in order to participate in the chat room for future course offerings. Dr. Lindgren strongly felt that students without these tools could "not put enough information down fast enough" by typing. [Ref 9]

Chat room sessions were held every Wednesday at eight in the evening and lasted about an hour. I found the on-line audio chat to be extremely helpful, and the software very ingenious. A student could have a conversation on the computer like talking on the phone. Students took turns to speak by raising their hand (pressing a button), and the teacher could ask open-ended questions in which all students could write a response and anonymously post it to open up the question for class discussion. Teachers could also post pictures and diagrams for students to look at. However, the chat rooms were poorly attended with at most seven people showing up out of sixty-seven students. The instructor did not make attendance to the chat room mandatory, preferring that only students who really needed help attend the chat room session. The instructor also commented that the chat room sessions were more popular in his spring 2006 semester classes. Lindgren intends to keep chat room sessions on a voluntary basis. [Ref 9]

Three of the four exams, including the final were multiple-choice format consisting of approximately fifty questions. Each three hour exam had to be taken without notes or other resources, and students had to nominate a proctor for each exam. The instructor of record took considerable pains ensuring the security of the exam taking process. The exams were very different from the homework, and extended beyond homework topics -- on several occasions topics or ideas that weren't discussed in the homework appeared on exams. It was important that a student read the text, watched all the lectures, and memorized the formulas from the book. Students were expected to memorize formulas for exams, and had to be particularly careful when reading exam questions.

 

One word may make a difference between a correct answer and an incorrect one.

I really enjoyed the third exam, in which students were asked to write an exam with fifteen multiple-choice questions. The grading rubric was very well defined and I learned a lot trying to make up interesting and conceptually challenging questions. I felt this assignment really tested my understanding of the material and not just trivial facts that I may or may not have learned. It was also directly relevant to my profession as a teacher.

The material in the course was difficult for students who did not have a physics background, and relatively simple for those students such as myself who did have a physics background. I was able to do the first assignment without reading the book or watching the videos. However, I had had relatively little experience in the later topics of Fluid Mechanics and Heat, and I found that I learned a great deal conceptually from these classes. This course definitely is not for those who are computer neophytes or phobic; however, I consider myself functional in being able to use the computer and I only had one minor difficulty with the technology.

The class also helped to build my conceptual knowledge quite a bit. This was a physics course, not an education course. The classes on the CDs were at a college freshman physics class level, so I was able to do other things like laundry, dishes, grading papers, etc. while I watched the videos. The videos were worth watching however as Professor Bloomfield had several creative and entertaining ways of explaining concepts along with many intriguing demonstrations that I have since been using in my classroom. One such example was a demonstration of tying a banana to a string and hanging it from the ceiling. The banana can be cut with a knife even though the banana is not pressed against another object, like a cutting board. Bloomfield used Newton's first law to explain this concept. My students really enjoyed this demonstration and it helped engage them. I am also planning on using some of Professor Bloomfield's lectures on fluids in my General Physics class. Any graduate class that I can turn around and use in my classroom later that week was well worth the time spent taking it. I recommend this course to teachers even those not interested in graduate credit for this very reason.

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Ref 5:
More information on Blackboard can be found at: http://www.blackboard.com/us/index.aspx Blackboard is a registered trademark of Blackboard Inc., © 1997-2006

Ref 6:
More information on WebAssign can be found at: http://www.webassign.net/. WebAssign is a registered trademark of North Carolina State University under license to Advanced Instructional Systems Inc. © 1997-2003 North Carolina State University © 2003-2006 Advanced Instructional Systems Inc.

Ref 7:
More information about Horizon Wimba Audio Chat Room can be found at: http://www.horizonwimba.com/ Horizon Wimba Audio Chat Room is a registered trade mark of Horizon Wimba, Inc. © 2005

Ref 8:
E-mail correspondence from Richard A. Lindgren to Kelly Pearson. Tuesday May 16, 2006 at 11:01 am.

Ref 9:
Private correspondence and interview with Dr. Richard Lindgren by Kelly Pearson on May 12, 2006 at 3:30 pm

# A proposed model for planning and implementing high school physics instruction

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*Among the numerous factors that impact student understanding of physics, mathematically modeled concepts continue to be cited by the majority of secondary students as the most challenging. Mathematics is also one of the key factors influencing high school students' decisions regarding careers in the field of Physics. While physics instructors recognize the importance of mathematics in understanding physics concepts, there is evidence that teachers seldom make deliberate efforts to provide remedial lessons in relevant math topics. These issues compelled the author to propose a "School Physics Instruction Model" (SPIM) for improving high school physics instruction.*

Many high school students struggle to understand physics concepts that are modeled mathematically (Nashon, 2005; Nashon & Nielsen, In press; Sherin, 2001; Tao, 2001). I have had many opportunities to examine why this might be the case through my long and varied experience in science education – as a physics and mathematics teacher, teacher educator, curriculum developer, editor of curriculum materials in science and mathematics, and science education researcher.

In a recent piece of research, we looked into the perspectives of several groups, including teachers and students in selected schools and pre-service science teachers on low enrolment numbers in senior physics courses (Physics 12) in British Columbia (Nashon & Nielsen, In press). The study revealed mathematics as one of the key influencing factors in students' decisions to take senior physics courses. In other words, there is a math phobia among many high school students that deters them from pursuing physics beyond the basic graduation requirement.

However, in my view, mathematics should not prevent many of these students from taking senior physics, since many of the topics at this level of physics do not require very complicated mathematics (Tao, 2001). This is not to say that mathematics is unimportant for understanding physics. Indeed, there are some physics concepts that necessarily need to be illustrated mathematically for deeper understanding.

According to von Weizsäcker and Juilfs (1957), "Physics is rooted in experiment, in active, inquisitive and skillful intercourse with nature … [All] experiments are blind if they are not guided, or at least interpreted subsequently, by theoretical considerations" (p.11). That is, according to von Weizsäcker and Juilfs, physics-related experiences could be useless without some kind of theory oriented observations and interpretations. Theory in this case is anchored in what has already been learned. On this account, mathematics has been an important and successful tool within physics over the last four centuries. von Weizsäcker and Juilfs further underscore the importance of mathematics in supporting learners' understandings of physics concepts, saying, "The tool of conceptual thought in physics is mathematics, for physics treats the relations measured, which is numerically determined, magnitudes" (p.11). This point is echoed by Kline (1980), who argues that, "Science must seek mathematical description rather than physical explanation. Moreover, the basic principles must be derived from experiments and induction experiments" (p.51). Newton and Galileo operated on this principle and the same sensibility underpins contemporary thought in physics. One can only expect that mathematics would be seen as important in physics classes, and the point is evident in physics instruction and in curriculum materials.

Do physics instructors find out what prior mathematics knowledge their physics students possess for application in intended concept development? In fact some research (e.g., Sherin, 2001) has shown that in some cases, physics is viewed as synonymous with mathematics. In short, mathematics is important as far as physics is concerned (Sherin, 2001). Indeed, mathematics constitutes a large portion of the language of physics. Most instructors are probably aware of the need for the prior math learning, but the required action could be overlooked in many cases. What is troubling, though, is that some of the physics instructors might recognize the importance of mathematics in the understanding of physics and still make no deliberate effort to sharpen their physics students' mathematical knowledge when it is needed. It is this background that compels me to propose an instructional model that I call "School Physics Instruction Model" (SPIM). The model is still evolving, but it is my hope to present it in a compelling way to the community of practitioners and other scholars engaged in the teaching and learning of science. Before discussing SPIM, it is important to acknowledge some of the important existing models that have given grounding to SPIM.

**Existing key models**

Though not specific to physics, the conceptual change model (CCM) by Posner, Strike, Hewson, and Gertzog (1982), provides a framework for understanding learning and planning instructional activities in science. The model comprises four steps through which learners develop new conceptions:

 

1) A learner's experience of discrepancy between what he/she knows and what the empirical experience shows and the feeling of the inadequacy of the knowledge they possess to explain the empirical evidence. This state of affairs makes the learner search for a new satisfactory explanatory model;
2) The new explanatory model must be intelligible. In other words, the learner must see sense in the new explanation;
3) The new model must be plausible – it must be reasonable; and
4) The new explanatory model must be fruitful. I take this to mean that the new explanation must lead to a resolution or clearer understanding.

Although the authors have not explicitly stated that the learning will always follow these steps in a linear manner, the model has been criticized for conveying this impression, and that the social-cultural background of the learners is in a way ignored (Duit & Treagust, 1998, 2003). Although Jegede (1995) does not explicitly challenge the Posner et al.'s model, he points to the fact that students from non-Western cultures tend not to abandon their already held culturally rooted views (as Posner et al.'s model seems to convey). Instead, according to Jegede, the non-Western students have these ideas (cultural and science) coexisting side-by-side (collateral learning) and they only use one or the other depending on circumstances. The important point conveyed here is that learning is not linear and that abandonment of explanatory models is not easily achievable. Despite these criticisms, Posner et al.'s model offers insight and guidance on how students learn.

Although Driver and Oldham (1986) provide what they call "constructivist teaching practice" (CTP), in essence, what they provide is a model for planning and implementing instruction. The model comprises five steps:

1) Orientation: students are offered opportunities to develop a sense of purpose and motivation for learning;
2) Elicitation: learners make explicit their current ideas on the topic;
3) Restructuring of ideas: involves clarification and exchange of ideas, construction of new ideas, and evaluation of new ideas;
4) Application of ideas: learners are given opportunities to use the learned ideas; and
5) Review of learned ideas.

These five steps are general in nature, irrespective of the fact that Driver and Oldham have offered suggestions regarding the interpretation of the model. This model provides a general framework for planning and implementing constructivist lessons. It can be argued that Posner et al.'s model is a subsection of the model proposed by Driver and Oldham, as it is relevant to steps 2 and 3.

A model that appears to have responded to propositions conveyed in the CCM and CTP models is the Predict-Observe-Explain (POE) model (White & Gunstone, 1992; Gunstone, 1994), which provides a framework for eliciting and challenging student understandings of scientific principles or phenomena. It formulates situations that require students to respond to questions such as: "What would happen if…?" and "What if …?" These are predictive questions. As suggested in this model, the event is enacted and the observation is checked against the prediction to see if there is agreement or disagreement. If the observation agrees with the prediction, then the student's understanding is validated, but, if there is a discrepancy between the prediction and observation, then the student experiences a state of cognitive conflict leading to the desire to look for satisfactory explanations, hence POE.

It is not explicitly stated in the model that predictions can be guesswork, which is not the intent of POE. POE procedures aim to assess or elicit students' prior knowledge that constitutes the framework for predicting and explaining the predictions. Explaining predictions can reveal gaps in a student's knowledge, misconceptions or alternative frameworks that require attention or reinforcement following the observation of the actual event. This model is quite effective at eliciting and challenging student alternative conceptions or counter science frameworks.

**SPIM**

CTP, CCM and POE models have been key in the framing and development of SPIM. Specifically, SPIM is aimed at alleviating the challenges that physics teachers and students confront in concepts that involve mathematical modeling. The model embraces constructivist ideals (Driver, 1989) and comprises seven steps of planning and implementing physics instructions:

1) *Elicit students' prior knowledge of topic*
Research has continued to underscore the role of prior knowledge in new knowledge construction (Driver, 1989).
2) *Identify students' counter physics preconceptions*
Identifying students' prior counter physics ideas about a topic intended for instruction alerts the physics teacher to undesirable preconceptions that his/her students possess in order to plan to challenge them.
3) *Plan practical activities challenging counter physics conceptions*
The best pedagogical approach to confront counter physics preconceptions is to prove them inadequate by providing experiences in which the ideas get challenged. Such ideas are targeted by presenting experiences that may likely cause cognitive conflicts. This puts the students in a state of anxiety that leads them to search for more satisfactory and meaningful explanations to the discrepant events - consistent with Posner et al.'s (1982) model that spells out conditions necessary for conceptual change.
4) *Qualitatively discuss the activity findings as a prerequisite to developing mathematical models*
This arises from the concern expressed by some participants in my study (Nashon, 2005; Nashon & Nielsen, In press) regarding the casual manner in which physics teachers treat students' prior mathematical knowledge. In other words, there is some sense in starting with qualitative aspects, while realizing that in other cases quantitative and qualitative aspects

 

are intertwined and difficult to separate. However, a deliberate effort should be made to progressively move from qualitative to the integration of both qualitative and quantitative aspects of physics content.

5) *Identify key mathematical concepts within the topic and provide remedial lessons*
Mathematics is considered part of students' prior knowledge in this paper since it is a tool of physics. Studies have shown how the majority of students are put off by the mention of mathematics related terminology in physics. This inevitably calls for a deliberate effort during planning and implementation of physics instructions to provide remedial lessons in the appropriate mathematics concepts for use in the physics class. In other words, "sharpen the tool" before use.

6) *Progressively ease the students into the quantitative aspects of the topic.*
Easing students into the quantitative aspects of physics is probably one way of ensuring that students see the link between the ideas they learn in mathematics classes and the application of the same in physics. Furthermore, one does not want a situation whereby the mathematics being used obscures the understanding of the intended physics concepts.

7) *Provide application problems and questions for practice.*
Application of any ideas to a real life situation is one way of ensuring relevance, mastery and meaningfulness on a personal level. And, practice is in many ways an appropriate strategy for developing proficiency and competency.

**Example** *(The superscript numbers in the example indicate where SPIM steps are applied)*

Let me use an example to illustrate this procedural model. The example comes from the many examples that I have encountered during my teaching career. One difficult concept that I have often come across is about "Floating and Sinking Bodies".

There are students who perceive the relationship between the weight of a floating object, its volume and the volume displaced as dependent. For instance, grade 11 students in one of my classes offered that an object floats if the displaced volume of the fluid in which it is floating is less than its (object's) own volume[1]. This is sensible as far as floating is concerned, however, when asked to develop a similar statement with regard to objects that sink, they offered this: "an object sinks when the displaced volume of the fluid in which it is placed is greater than its (object's) own volume"[1].

Based on the first statement, this latter one seems to make logical sense to many students and yet it is flawed[2]. If a teacher is confronted with this kind of situation the prudent thing to do is to provide experiences that challenge this perception. One approach would be to give the students a hands-on activity whereby they determine the volume of a small rectangular steel bar by measuring the length, breadth and height and calculating its volume (this is basic knowledge that most high school students would have had since grade 6 or 7)[3]. This step is then followed by immersing the bar in water in a measuring cylinder to determine the volume of the water displaced and compare this volume to the calculated volume of the steel bar (block)[3].

Certainly, the outcome of the above activity will challenge the students' perception that a sinking object displaces more volume than its own. Does this mean that objects that displace their own volumes are considered to be sinking? A major misconception that arises from this activity is that objects that are just submerged in a fluid are considered as having sunk[2]. This can be addressed by placing a hard-boiled egg in concentrated saline water[3].

The egg is submerged but does not get to the bottom of the container despite displacing the same volume of saline water as its own[3]. Also, a qualitative discussion of swimming and how the swimmers float at various depths is illuminating to the students regarding the misconception[4]. This prepares students for discussion of the following concepts and skills: density, relative density, upthrust (buoyancy), determining the density of irregular sinking objects, determining the density of floating objects, and Archimedes principle in general. These are qualitatively[4] as well as mathematically modeled.

Of course there are mathematical concepts employed in the development of these topics: setting (forming) and solving equations with one unknown, isolating the unknown (or making the unknown the subject), translating word statements into algebraic expressions (for this topic it is translating into equations)[5].

It is prudent for a physics teacher to provide remedial lessons on these math topics prior to starting the work on the density and related concepts and skills as outlined above[5]. If these math topics have relevance to other physics topics then, a remedial lesson may not be necessary but reference should still be made to them[5]. This is important as it makes it easier for students to concentrate on understanding the physics concepts instead of struggling with understanding the math. At this point it is opportune to model mathematically the concepts of density, relative density and determination of density of irregular objects, density of floating objects, and upthrust (buoyancy)[6].

To deepen the students' understanding of these physics concepts, it is useful to give them practice problems and questions that require them to apply the qualitative as well as mathematical models developed during instruction[7].

The seven steps or stages of the proposed model – SPIM - provide the minimum requirements for planning and implementing instructions, success of which may also depend on a variety of other factors. Appropriate instructional tools, such as analogies (Glynn, 1991; Zeitoun, 1984; Nashon, 2004) and concept maps (White & Gunstone, 1992) and recognizing students' preconceptions (Driver, 1989) can also add to the tool kit for successful instructional planning and implementation in physics and other science subjects, especially at the high school level.

Instructional strategies such as SPIM, CTP, CCM and POE can be used in physics teacher education programs to enhance the pre-service teachers' ability to process students' learning difficulties in physics. It is important that teacher educators make deliberate efforts to sensitize science teacher candidates to the challenges that physics students confront. This can be achieved by encouraging teacher candidates to carefully plan physics curricula and instructions in ways that address the learning difficulties their students experience - especially those that fall within the locus of their (teachers') control.

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# Engaging students in conducting Socratic dialogues: Suggestions for science teachers

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*While students are often involved in classroom discussions, it is more often in the role of responder rather than questioner. Socratic dialogues – which are designed to enhance academic discourse – often take place with students providing responses to a teacher's questions only. One of the goals science teachers should have for Socratic dialogues is to develop within students a disposition for and skill in questioning. Indeed, students should learn to question all information provided them. What better way to get students to adopt a skeptical attitude than to have them become actively involved as questioners in the process of scientific discovery? The authors offer suggestions for engaging students in the questioning process.*

Many of the 42 Modeling Method physics teachers involved in the *Chicago ITQ Science Project* over the past two academic years have indicated to the Project's director (CW) that it is difficult to engage students as leaders in the process of Socratic dialoguing. Students are willing responders to questions posed by teachers, but reticent to take the lead by posing their own questions to peers. This problem persists even when teachers follow traditional guidelines for Socratic dialoguing (Wenning, 2005). Why might this be so?

Perhaps it has to do with the fact that students so often have been treated by teachers not as active inquirers but as passive recipients of information. They do not question because they have not been expected to question. They do not question because they have not been taught to question. They do not question because they lack the skill to question. These problems are closely associated with a didactic form of instruction where a teacher is seen as the fount of all knowledge and students as empty vessels to be filled. In the Modeling Method, and other forms of inquiry-oriented instruction, students are seen as anything but passive recipients of information. Rather, they are expected to become actively involved in the construction of knowledge based on careful observation, data collection and analysis, logical reasoning, and questioning.

Because students are not often encouraged to or informed how to question in a classroom where teaching by telling is taking place, they frequently are reticent to do so in novel inquiry-oriented classroom settings. Many students respond to hundreds of questions each year, but they often fail to pick up the art of posing meaningful questions as a result of these experiences. This is clear evidence that students don't learn the skill or habit of questioning by "osmosis." Unfortunately, teaching effective questioning skills is rarely seen as part of a traditional course. As it is true of teachers who are attempting to use Socratic questioning for the first time, so it is will be with students who are expected to question others. If they are to become engaged in Socratic dialogues as active inquirers, they would benefit from explicit guidance in asking questions.

Many students are at a loss when it comes to developing the wide variety of probing questions commonly asked by teachers during Socratic dialogues. Teachers have an advantage. They know the difference between divergent and convergent questioning. They know the subject matter and the misconceptions that students often bring into the classroom. They know the processes and assumptions, principles and values of science. In addition, teachers might subconsciously turn to Bloom's taxonomy of educational objectives (Bloom, 1956) as a guide to formulating questions.

As almost any first-year teacher can explain, there are categories of question types associated with each of the six cognitive domains in Bloom's taxonomy: knowledge, comprehension, application, analysis, synthesis, and evaluation. While Bloom's taxonomy is a rudimentary guide to developing questions, its cognitive domains do not depict the much wider range of question types that might be posed during a Socratic dialogue – especially one associated with scientific discovery. Rhodes' typology of questions (Rhodes, 1995) is a more powerful guide to formulating questions in this situation, and science teachers should be as familiar with it as they are with Bloom's taxonomy.

**The Rhodes' Typology**

The Rhodes' typology of questions is a comprehensive treatment of content-directed question types, and is extremely well suited for use in Socratic dialogues based upon observation and/or experiment. All content-based questions in this typology are classified into one of eight categories: informational, interpretive, explanatory, procedural, relational, verificational, heuristic, and evaluational. Each category has subcategories, but these will not be dealt with here for the sake of simplicity. A sampling of questions from each category and sub-category will be provided, however, to show the great variety of questions that can be posed when involved in Socratic dialogues.

**Informational questions** – the questioner seeks knowledge concerning a particular fact, circumstance, or conclusion derived through observation or experimentation:

- What is it?
- How does it work?
- What does it do?
- What happened?

**Interpretive questions** – the questioner seeks to understand the meaning of an observation or a conclusion:

- What does that mean?
- What do you mean by that?

**Explanatory questions** – the questioner seeks clarification; asks for things to be made understandable:

- Why does it work that way?
- What is the reason for that?
- Why did you do that?

**Procedural questions** – the questioner seeks clarification of methods or processes:

- What was done?
- How is that done?
- Is it done this way?

**Relational questions** – the questioner seeks clarification of the connections between various elements:

- Which is the most important?
- Which is largest?
- Which came first?
- How do these compare or contrast?

**Verificational questions** – the questioner attempts to confirm the validity of an observation or procedure:

- What are the facts to support it?
- Where are the data?
- Where is the proof?
- What is the reasoning?
- How do you know that?

**Heuristic questions** – the questioner attempts to stimulate interest as a means of furthering investigation:

- What would happen if?
- What could we find out?
- How could we find out?

**Evaluational questions** – the questioner attempts to determine the worth of an observation or conclusion:

- Is it any good?
- How good is it?
- What difference does it make?
- So what?

**Fully Engaging Students in Socratic Dialogues**

One of the student complaints that *Chicago ITQ Science Project* Modeling teachers frequently report is that, "The teacher doesn't tell us anything." This often stems from the fact that students fail to see the importance of their own questions in getting the answers they seek. Because students have yet to learn to question and then, in turn, trust the findings of their own work and that of their peers, they often feel they are being left without guidance. They retain a strong tendency to rely upon the word of their teachers who are seen as absolute authorities of the subject matter. Students, if they are to be at all confident of the credibility of their own conclusions and those of other students, first must learn to skeptically question these observations, processes, and conclusions. Only then can they take confidence in their own work and that of their peers, and see nature itself as the final arbiter. In so doing, they come to understand one of the critical elements of the nature of science (Wenning, 2006).

If teachers are to effectively engage students in Socratic dialogues as questioners as well as responders, student must be made aware of the nature of the question-generating process. Teachers can share what they know about the question formulation process with students in an effort to enhance the quality of classroom discourse by developing students as questioners. Even a small amount of instruction can be helpful in this area. For instance, it might be very helpful if the teacher were to speak explicitly about questioning procedures. While it is doubtful that most students would care at all about a formal typology of questions, they probably would be inclined to learn about how to ask appropriate questions.

For instance, one of the authors of this article who is an expert in the Modeling Method of Instruction (JS) defines two groups of questions students might want to ask during whiteboard discussions. Sample questions (see Table 1) are posted in front of the classroom on a whiteboard for all students to see. These question forms then become part of the traditional "toolbox" that teachers often refer to in the Modeling process. The "toolbox" consists of pre-lab notes, lab results summaries (sketches of graphs, mathematical representations, general conclusions, etc.), post-lab notes, handouts, worksheets with original attempts at solutions, final solutions, and alternative solutions. These cumulative materials, and neither the teacher nor the textbook, become the source of authority for the students during classroom discussions. Each student is responsible for bringing his or her "toolbox" to class each day.

I. Clarification Questions
   a. How do you know…?
   b. Where did you get…?
   c. Why did you do…?
   d. What does…tell you?
   e. What does…mean?
   f. Where on your (graph, motion map, diagram)…?

II. Extension Questions
   a. What if we changed…?
   b. How is this problem different from…?
   c. How is this problem similar to…?
   d. Is there another way to do this?
   e. What is key to solving this problem?
   f. How does…compare to…?

Table 1. *Providing two types of questions to get students started with the questioning process.*

**Additional Suggestions**

Before students will become fully engaged in Socratic dialogues as active questioners, they need to be comfortable with the process. In an earlier article, the lead author (CW) summarized a list of guidelines for conducting Socratic dialogues (Wenning, 2005). As an adjunct to that article, the current authors provide procedures to be followed in order to enhance student comfort with Socratic dialogues – especially when the basis of that discussion is a whiteboard presentation:

- *Allow students to present without interruption.* Let presenters do the bulk of the talking at the outset. When students are making a presentation, it is time for the teacher and all others to be good listeners. Listen intently and patiently to what the presenters are saying; try to understand things from the speakers' viewpoint as novice scientists. Avoid interrupting the presentation. Wait until after they have completed their overview before allowing comments or questions. To interrupt before students are finished making their initial presentation is suggestive of presenter error or audience impatience. The listening approach might well reveal the cause of student error if any is revealed. This might include important preconceptions that students are prone to bring into the classroom.

- *Promote peer questioning.* After students have learned about formulating and posing questions, the teacher should encourage students to ask questions. Teachers should use wait time effectively to get students to start asking questions. Indeed, it is best to allow audience members to begin the questioning process because they can then ask the easier and more obvious questions. If students fail to note an error or oversight, this is where the teacher can contribute most to the questioning process.

- *Show respect for student conclusions.* Many times students will be absolutely correct in their findings and assertions. When this is the case, it is best to have the class acknowledge that this so. On the other hand, student errors should be addressed by asking questions rather than by providing a direct critique. A central tenet of the Socratic approach is to avoid telling presenters directly that they are mistaken. Questioners should work to make visible students' intellectual processes and, thereby, lay bare the source of student misunderstanding. If presenters are found making a mistake, it is best to allow them to redeem themselves by identifying that mistake and drawing the proper conclusion through the Socratic questioning process. This will allow them to save face, and make them more amenable to the presentation format. If other students have made this same mistake in the past, the teacher should draw attention to this fact in a general fashion.

- *Get students to agree.* Another of the central tenets of the Socratic approach is to achieve a consensus using evidence and logic. Student errors should not be ignored. Agree only on that which is correct and proper. When misunderstandings and preconceptions are identified, they must be confronted and resolved through questioning so that they might be overcome. When something is seen that is in need of correction, point out first those things upon which everyone agrees. Keep the discussion moving forward with an open, accepting attitude. If resolution cannot be achieved through the process of the Socratic dialogue, throw down the challenge of conducting another observation or experiment. Avoid resolving any scientific problem by fiat or by voting. These are not acceptable forms of conflict resolution in the scientific community.

- *Maintain a positive atmosphere.* Avoid criticizing student errors; this potentially could humiliate presenters and place them on the defensive. Teachers should make a point of stopping any discussions where "sniping" is going on or threatened. Nothing will shut down productive discourse quicker than negative comments – making "fun" of a presenter or attempts at retaliation for a real or perceived attack. Taking the time to explicitly express the "we're-in-this-together" attitude, and to openly discuss why negative comments cannot be tolerated is critical to setting a positive atmosphere. Students are very perceptive, and are usually able to articulate why a positive climate is crucial for the class's success. Once they have expressed the need for a positive tone in the classroom, they take ownership of it. The enlightened despot known as the teacher hasn't dictated it.

 

- *Let students feel that a new idea is theirs.* Students will have greater knowledge and understanding of concepts that they develop on the basis of experience and insight rather than in ideas provided to them by teachers on the basis of authority. It is far better to ask questions and make suggestions and let students think things through for themselves. A great way to end a dialogue is to have students summarize their finding. This allows them to develop and have a sense of ownership, and help students distinguish between what is known with certainty, and what is not known.

- *Make the students feel that they have contributed.* When students have done a good job, be certain to acknowledge that fact honestly and sincerely. Conclude a Socratic dialogue by praising even the slightest improvement in understanding, and do so with sincerity. Make any fault seem easy to correct. It is most appropriate to have a round of congratulatory applause following student presentations.

Only after students become comfortable participating as responders in Socratic dialogues will there be any hope of them becoming actively involved as questioners. Not only must teachers educate the intellect if students are to become actively engaged in the questioning process, they must also help students understand that they are expected to question, and that developing critical questioning skills is a valuable part of the educational process. It is critical that the teacher model appropriate questioning strategies, explain the process of question formulation, and then fade from the scene so that students will become actively engaged as questioners in the process of Socratic dialogues.

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

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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 field of cognitive science can and should have an impact on the development and refinement of physics education curricula. However, cross references between these research areas are rarely made. The Modeling Method is an example of a curriculum whose efficacy can be better understood by studying the pertinent cognitive science research. In order to refine a curriculum it is extremely useful to have an understanding of why students might be exhibiting the exit skills shown. This paper will attempt to demonstrate how an understanding of previous research in knowledge organization and problem-solving behavior can inform the practice of modeling educators. This paper is divided into the following three main sections: modeling efficacy research; problem-solving behaviors and strategies; and knowledge organization and schemas. In addition, research articles in the area of problem-solving strategies are further sub-divided by studies that are exploratory in nature and studies that researched the efficacy of methods developed to improve student learning based upon the exploratory studies findings.

**The Efficacy of the Modeling Instruction Pedagogy**

Modeling Pedagogy is one of the few physics reform programs that have been shown to substantially improve students' conceptual understanding of physics and their ability to solve problems. Since the majority of misconception research dealt with isolated concepts, Halloun and Hestenes (1985a) decided to design an instrument that would allow one to assess the knowledge of students before and after physics instruction specifically in the area of the force concept. The subsequent instrument, called the Mechanics Diagnostic Test (MDT), focused on concepts shown to be deficient in the previous misconceptions research in the domain of mechanics. A later version of the MDT was called the Force Concept Inventory (FCI). The MDT was written in language that students without physics training could easily understand. The instrument was administered to college and high school students both pre and post instruction. Halloun and Hestenes (1985a) discovered that the qualitative knowledge gain in conventional physics instruction was extremely poor and independent of the professor. This meant that at the end of the instruction not only were basic Newtonian concepts lacking but misconceptions about mechanics remained firmly in place. In subsequent research Halloun and Hestenes (1985b) were able to develop a taxonomy of common sense beliefs which was based upon item selection on the MDT and student interviews. They classified these alternative beliefs in terms of specific Newtonian concepts so that the taxonomy could act as a guide when assessing instructional interventions.

The MDT clearly demonstrated that there was a need for the development of a radically different teaching approach that would help students to develop a clearer understanding of Newtonian concepts and help to remove their misconceptions. Halloun and Hestenes developed an instructional intervention centered on model-based reasoning that could improve students' grasp of Newtonian concepts. Hestenes (1987, 1992) argued that an analysis of the structure of scientific knowledge indicates that development and deployment of models is the main activity of scientists. The models in mechanics are highly developed and can provide a coherent structure that can be easily learned by students. This structure should allow students to refine their common-sense beliefs into a more coherent scientific structure of the physical world. Initially, Hestenes (1987) defined a model as "…a conceptual representation of a real thing" (p. 441) but later refined this definition by explicitly stating that models are coherent representations of the physical system studied (Hestenes, 1992).

The first attempt made to improve physics instruction using the modeling theory of instruction was researched by Halloun and Hestenes (1987) within the context of college-level instruction. During lectures, modeling theory was discussed and "modeled" via paradigm problems. When solving paradigm problems in lectures the students were guided to think in terms of the relevant information and its associated models. Two recitation sessions were taught using the deployment of the modeling pedagogy to solve additional example problems (one of these recitation sessions required an extra two hours of instruction per week). It was demonstrated that the MDT's pre to post gain for all of the students attending the modeling lecture was greater than that of a control group of conventional students (roughly 0.42 vs. 0.23). However, the students who practiced the modeling pedagogy in recitation sessions showed even greater gains from 0.52 to 0.4 depending upon time spent on task.

A key feature in the success of the pedagogy is the structuring of physics knowledge so that it is no longer a list of equations to memorize but a coherent body of knowledge organized into a number of models. The models contain a number of distinct representations that allow the students to flexibly apply their knowledge in a variety of situations and to check internal coherence in the models developed. For example, students have both algebraic and graphical representations chunked with each model which can allow for more flexibility during problem solving. The internal coherence of the models developed is tested whenever students demonstrate that the same prediction occurs no matter what representation utilized. While this type of lecture style deployment of the modeling theory did allow for physics knowledge to be presented in a coherent structure, it did not allow for the empirical development of model representations via laboratory experimentation. During the same time frame the high school version of Modeling Pedagogy was developed. Central to the high school version was the development, revision and application of models in physical situations (Wells, 1987 and Hestenes, 1992).

This enhanced modeling method has been tested extensively. The MDT was redesigned by Hestenes, Wells and Swackhamer (1992) and renamed the Force Concept Inventory (FCI). This test was given to a number of conventional college, conventional high school and modeling method high school classes. The modeling courses showed significant gains over those from conventional classes both in high school and college. Hake (1998) compared the FCI scores for over 6,000 students based upon the degree of interactive engagement (i.e., the amount of student involvement in hands-on activities usually associated with immediate feedback from peers and instructors). Hake (1998) discovered that students in highly interactive engagement courses had normalized gain factors of about 0.7 whereas conventional courses (i.e., low interactive engagement) had normalized gain factors below 0.3. The modeling method courses in Hake's survey had normalized gains approaching 0.7. The ability of the modeling method to improve conceptual understanding as measured by the FCI continued to be demonstrated by a number of researchers (Brewe, 2002; Desbien, 2002; Vesenka, et al, 1992).

The Modeling method's efficacy to improve problem solving has also been proven. Hestenes and Wells (1992) detail the construction of the Mechanics Baseline Test (MBT). The MBT was designed to be used by students who had prior knowledge of physics and looks like a normal quantitative physics problem-solving test. While the MBT is quantitative in nature it was also designed to test for qualitative understanding (i.e., the problems cannot be solved by simply plugging numbers into formulas) and graphical application. Hestenes and Wells found that a good posttest score on the FCI was necessary but not always sufficient to produce a high score on the MBT as the correlation between the two was 0.68. Wells et al (1995) showed that modeling students produced posttest MBT scores that were roughly 21% higher than that of students in conventional courses. Hake (1998) confirmed this result when he plotted his data in the same way and found a correlation of 0.91. Therefore, Hake (1998) and Hestenes and Wells (1992) determined that problem-solving ability was actually enhanced by highly interactive classes where the concepts were emphasized. These findings were replicated by several other researchers in the following years (Desbien, 2002 and Vesenka et al, 2002). These findings demonstrate that Modeling Instruction is a method that one can use to greatly enhance a student's conceptual understanding and their problem-solving abilities.

**Studies of other Modeling-Based Curricula**

Modeling Instruction has demonstrated its efficacy through the use of paper and pencil tests focused on conceptual understanding and problem-solving ability. However, the cognitive advantages of the pedagogy have not been explored in terms of the topics reviewed in this paper. A review of the literature for other modeling-based pedagogies such as the middle school MAR's project might determine if other research groups might have assessed additional consequences of modeling based pedagogies such as the cognitive and metacognitive advantages.

White (1993) studied the efficacy of a course designed to develop models using the inquiry cycle and a computer microworld, known as ThinkerTools, at the sixth grade level. The entire curriculum is referred to as ThinkerTools curriculum. The curriculum was tested against a control group of naïve sixth graders and a high school physics class using a post-test transfer task consisting of 17 problems involving the concepts and principles addressed. The curriculum uses a similar approach to Palincsar and Brown's (1984) reciprocal teaching method such that initially the students were guided in a highly structured format that gradually faded away while more of the elements of the inquiry process were turned over to the students. The curriculum emphasized the development and need to translate between different representations of motion and forces. The students in the experimental group significantly outperformed both control groups on the final test. The mental models constructed by the students were explored via interviews. The interviews involved students solving out loud a series of qualitative problems. The students who did well in the ThinkerTool curriculum were able to give the correct Newtonian response (i.e., responses based on the use of an understanding of Newton's Laws of Motion) to the problems and to transfer their model to more difficult questions. However, when asked to answer far-transfer questions that covered unique situations not dealing with those specifically in the curriculum many students reverted to Aristotelian answers (i.e., answers based upon ideas such as all motion has a cause). One disadvantage of this curriculum is that while it seems to focus on models of motion and forces, which this paper is specifically researching, it does not mention how the curriculum attempts to organize the models or how the models are specifically developed. The curriculum was redesigned by White and Frederiksen (1998, 2005) to incorporate a high level of self-assessment in order to enhance metacognitive skills. They demonstrated that the metacognitive addition did enhance students' achievements on some of the assessed tasks. This curriculum design will be discussed further in part II of this paper.

Schwarz and White (2005) redesigned the ThinkerTool computer software to allow for more exposure to model development such that students would test their models by changing the computer's environment. For example, students had the ability to change the gravitational force exerted in the microworld. After testing their models the students would debate and present the models to the rest of the class. They found that the modeling assessment posttest developed by Schwarz demonstrated that the students did develop a better understanding of the nature and purpose of models but had not promoted an understanding of how models were created, evaluated and revised. No comparison between the two curriculum forms was conducted for student understanding of modeling. No differences were found between the Modeling ThinkerTools and the original ThinkerTools curriculum in the development of scientific inquiry skills and physics knowledge. It seems that the non increase might be caused by the fact that the original ThinkerTool curriculum built models implicitly so that the only new item in the modeling version was that the students were able to change some of the computer parameters to produce non-Newtonian environments. Schwarz and White (2005) did find that the modeling posttest score was highly correlated with the physics posttest thereby demonstrating a link between knowledge of modeling and the learning of science content. The link between modeling and science content shown by Schwarz and White (2005) has been seen in the Modeling Instruction research through the higher gains on the FCI for modeling vs. non modeling students. In Hake (1998) the data demonstrated that non-modeling inquiry classes do not often produce the same gain factors as modeling classes.

Another recent middle school modeling curriculum is called MARS (Modeling Assisted Reasoning in Science). This curriculum spans the three years of middle school and utilizes computer programs with which to build scientific models that have different interlinked representations. Raghavan, Sartosi, Schunn, and Scott (2005) demonstrate that the MARS students develop a better understanding of what models are and what they are used for after exposure to the curriculum. This finding is similar to that of Schwarz and White (2005). Lawson's Test for Scientific Reasoning was administered to both the MARS students and to a control group and the MARS students demonstrated significantly higher scores. In addition, the knowledge gain of the students was tested using a mixture of FCI, TIMMS and NAEP questions. MARS students post test scores were significantly higher than that of the control group. The MARS program found a similar link between modeling and increased conceptual understanding.

An elementary teacher pre-service course at San Diego State University was developed that uses inquiry activities and computer simulations that helps students construct powerful conceptual models to explain physics phenomena. The materials developed for that course are currently called Constructing Physics Understanding (CPU). Galili, Bendall and Goldberg (1993) completed a project looking at the effects the instructional units had on the students' knowledge state in the area of image formation. Galili et al (1993) conducted interviews with students after the course using a number of tasks that included the drawing of a ray diagram and follow-up questions keyed specifically to each task. Half of the tasks used equipment that the students had used previously in the course while the other half included unfamiliar equipment. The experimenters inferred the state of the students' knowledge from their comments and their ray diagrams. They argued that the results demonstrated that the post-instruction students' knowledge about image formation represented a well-defined intermediate state of knowledge that was more expert-like thereby showing that the students using these materials were developing more expert-like knowledge structures. Galili et al (1993) concluded that since the postinstruction students' state of knowledge is well-defined but a hybrid between the preinstruction state and that of the expert state that strong restructuring was necessary to achieve an expert state. However, there was no direct comparison in this study between the CPU students' state of knowledge in this domain and that of students in more traditional classes. However, over the course of the several years students were interviewed in order to document their understanding (Goldberg and Bendall, 1995). Students were asked to explain a novel prism and concave mirror task. Similar tasks were included on the course final exam for comparison over a period of two years. It was determined that the number of major errors committed by the students when performing the tasks dropped from 79% in the 1988 interview to 24% on the 1993 exam. Goldberg and Bendall (1995) felt that these tasks "provided some evidence of the effectiveness of the approach" (p. 988). In the area of electric circuits the students were asked a question identical to one produced by McDermott and Shaffer (1992). McDermott and Shaffer (1992) found that only 10% of students in an algebra based college physics course and 15% of students in a calculus based college physics course were able to answer the question correctly. The CPU students over the course of four semesters answered the question correctly 72% to 80% depending upon the semester.

The evidence seems to indicate that modeling based curriculums at the middle school, high school and college levels promote a greater conceptual understanding than that of conventional or other inquiry courses. Only the high school group has shown the effects of the curriculum on problem-solving ability. Problem-solving ability has been shown to be greatly enhanced over that of exiting students in conventional or other inquiry based curriculums. For most of the modeling based curricula, researchers have not looked at the knowledge structures and problem-solving strategies developed by the students. One of the curricula discussed above did look at the knowledge states of the exiting students but did not directly compare them to that of exiting students in more traditional courses. In addition, little work seems to have been done on how students use metacognitive behaviors to further problem solving in modeling classes. The question becomes: Why might the problem-solving ability be better and why might the conceptual understanding be enhanced? In order to discover what cognitive and metacognitive traits the modeling students might be developing one must look at the research from the domain of cognitive science.

 

## Problem-Solving Research

There have been many ways that the research community has defined problem solving over the years. Since this paper deals with problem solving, a definition of what is meant by that term in this context is needed. Polya (1968) said that problem solving was "finding a way out of a difficulty, a way around an obstacle, attaining an aim that was not immediately attainable." (p. ix). Hayes (1981) defined a problem as "whenever there is a gap between where you are now and where you want to be, and you don't know how to find a way to cross that gap, you have a problem" (p. i). Likewise, Newell and Simon (1972) described a problem in the following manner: "A person is confronted with a problem when he wants something and does not know immediately what series of actions he can perform to get it" (p.72). For most researchers in physics, a problem is usually defined as the tasks listed at the end of the each chapter. These tasks are considered problems by physics researchers since there are "givens" and a question (or goal) to solve for. It is the students' job to answer the question or achieve the goal from the "givens". The problems are at the end of the chapter since the students must first obtain an initial knowledge state that will allow them to know the actions needed to solve the problems. These tasks are usually very specific, well-defined problems and may not seem to fall in line with the definitions of the psychologists above. However, for a novice in many cases the tasks at the end of the chapters are very much problems since they do not immediately know how to start nor what methods to use to reach the final goal. This seems to fall very much in line with the psychological definitions above. Of course, it is always possible that experts might consider the end of chapter tasks very trivial and not in the least problematic. In order to determine why novices experience difficulty solving problems and how we as educators might help them become better at the task, researchers designed studies that contrasted the problem-solving behavior of novices to that of experts. In the sections below I will review the pertinent problem-solving studies, focusing on those in the fields of physics and mathematics as there are many similarities between the two fields. A review of this area of the problem-solving literature will allow for a better understanding of the nature of good problem solving and why the modeling pedagogy might help students become more superior problem solvers. In addition, the review will highlight the problem-solving trajectory from novice to expert in order to determine if the problem-solving abilities of modeling students are more in line with those of an expert rather than those of a novice.

## Problem-Solving Differences between Novices and Experts

The initial research defining the differences between experts and novices began in non-academic domains such as chess (de Groot, 1965 and Chase and Simon, 1973), taxi driving (Chase, 1982) and bridge (Charness, 1979). Researchers soon moved into academic domains such as computer programming (McKeithen, Reitman, Rueter and Hirtle, 1981) and physics (Simon and Simon, 1978). The definition of an expert in these studies was loosely defined to mean a subject or subjects who had more experience in the field or better problem-solving expertise as evidenced by grades than others. The majority of the novices were college undergraduates and the experts were graduate students or full professors. Simon and Simon (1978) studied two subjects, one expert and one novice (college undergraduate), solving physics problems via talk aloud protocols (also known as verbal protocols). The problems used were taken from typical college physics textbooks. The subjects were asked to solve the problems while saying everything they were thinking till they finished the task to their satisfaction. The subjects demonstrated several similarities: both read the problem, selected appropriate equations, and solved them after plugging in the unknown values. Simon and Simon (1978) found that the main difference between the two was the type of strategy they employed. The expert used a working forward strategy while the novice chose a working backward strategy. The difference between the two strategies dealt with where the two subjects started the problem-solving journey. The expert chose to work with variables generating a series of equations till they reached the solution (hence the term working forward) while the novice considered first and foremost the ultimate goal. The novice first defined the goal (i.e., what they were searching for) and then hunted for an equation that contained the unknown to be solved for. Hence this strategy became associated with the term working backward. Simon and Simon (1978) also discovered that there was a 4:1 difference in solution speed favoring the expert subject. The difference in the speed might have occurred since the experts seemed to use fewer equations and had shorter solution procedures than the novice subjects. In addition, at times the experts seemed to immediately recognize which equation was needed. They concluded that it seemed like the expert's solution path was guided by a type of "physical intuition" (p.337). They believed that this intuition probably meant that the expert was referring to physical principles in order to solve the problem and that this was a major reason for the success observed. However, since the problems used in this study were obtained from a standard first-year college physics textbook the expert might have simply recognized the solution to the problems. The last difference that Simon and Simon (1978) mention is that the expert made only one metastatement per problem while the novice made five such statements on average. The metastatements were usually about planning the solution, the meaning of the equation chosen, observing errors made, and self-evaluations of progress. These metastatements will be discussed later in more detail as this observation was quite discrepant from later studies.

In the Simon and Simon (1978) study they make no reference to the expert completing an analysis of the problem situation. However, McDermott and Larkin (1978) reported that in a verbal protocol study their expert chose to complete a qualitative analysis of the problem while the novice in the study consistently avoided doing so. Larkin (1979) continued to work with expert/novice differences and found that during a talk aloud protocol study that experts paused for shorter amounts of time between retrieving equations than did the novices. Larkin (1979) attributed this finding to the possibility that the experts had the equations linked or grouped together in cognitive chunks allowing for the quick activation of other linked equations. She also said that the chunk seemed to be linked to a fundamental principle as the experts mentioned the principle when conducting the qualitative overview. Larkin (1979) hypothesized that the qualitative overview served two functions:

1. It allowed for an easy way for the expert to check the equations used against the original physical situation thus reducing errors.

2. It was a method by which the expert obtained an easy to remember overview of the problem's main features.

The imagery used to represent a problem may be crucial to the ability to reach a correct solution. McDermott and Larkin (1980) reported that experts also used diagrams representing the problem statement during their solutions. They reasoned that experts use diagrams to such a large extent because it minimizes the likelihood that they might become confused and it allows them to quickly determine if a particular solution approach is appropriate. In addition, research has shown that experts in economics use graphs as place holders of information so that it can provide cues to the next steps in a specified line of reasoning (Tabachneck, Leonardo, and Simon, 1994).

Other studies continued to find convergent results when comparing physics experts with novices such as the experts' consistent use of principles to work forward towards a solution via a qualitative analysis of the problem and the novices' tendency to work backwards via an equation that contains the unknown they are solving for (Larkin, 1981; Larkin, McDermott, Simon and Simon, 1980a, 1980b). The main focus for the novice during problem solving was the status of the unknown variable. In a number of cases the researchers designed computer models based upon skilled physics experts and novices (Larkin, 1981; Larkin, 1980; Larkin, McDermott, Simon and Simon, 1980a, 1980b; Reif and Larkin, 1979). One of these models was a hierarchical planning model that worked by first reading the problem, noting the quantitative relations mentioned, planning a solution by qualitatively constructing the relationships between the major aspects of the problem, selecting quantitative equations based upon the principles generated in the qualitative construction, and then checking the solution by using a variety of different techniques (Larkin, 1980). These computer models were able to demonstrate that by following these "expert-like" procedures the expert performance empirically observed could be duplicated.

The finding that experts seem to work forward while novices work backwards was brought under question by a study of 79 subjects in a study designed by Priest and Lindsay (1992). These researchers found that novices and physics experts used a similar amount of forward and backward inference. Anderson, Greeno, Kline and Neves (1981) noted that subjects performing geometry proof generations often worked forwards as well as backwards. However, the selection of problems used in the studies may have influenced this finding. If the problems selected are relatively easy then even novices may be able to work forward in order to solve them. Therefore, in the case of difficult problems the novices may not have the necessary knowledge to enable them to work forward. This limitation of the studies was clearly pointed out by Singh (2002) when she found that experts given very difficult problems behaved more like a novice although they still approached the problem solution in a more systematic way.

The initial study by Simon and Simon (1978) found that novices made more metastatements about planning and checking their solutions while Larkin (1979) found the opposite. There is a possibility that the reason for the differences is that the Simon and Simon (1978) study utilized regular end of chapter problems which would have been quite straightforward for the expert. Dhillon (1998) completed a verbal protocol study similar to past designs and his findings supported Larkin (1979). His findings led him to the belief that checking the solution strategy was an inherent part of the strategy for experts as they consistently checked their work and logic as they progressed towards the solution. If a novice did check their solution it was only superficially. His subjects were allowed to use a physics text as a reference if they wished. Dhillon (1998) discovered that novices consistently referred to the text for examples while the experts did not.

Schoenfeld (1985, 1987) demonstrated similar findings with math experts and college age novices. He discovered that when the novice selected an initial path they rarely deviated from it and continued down that path no matter how unsuccessful it was shown to be. The good problem solvers and math experts were goal-directed and constantly evaluated the status of their solution approach by evaluating problem-solving approaches as they were generated. These studies also implied that there seemed to be a link between better problem-solving abilities and more "expert-like" behavior.

Researchers began using high school age subjects in an attempt to determine what differences existed between good and poor problem solvers. Finegold and Mass (1985) based a study on the decision that students who obtained grades higher than 90% in their high school advanced placement physics course would be considered good problem solvers while those with a grade lower than 60% would be considered poor problem solvers. The students completed five problems while thinking aloud and the good problem solvers were able to arrive at a good solution for all of the problems while only two poor problem solvers did so. Finegold and Mass (1995) found many findings similar to the initial research such as that good problem solvers decoded the problem statements in more detail, planned their solutions, completed all five problems in less time, spent more time on problem translation and planning, and used physical reasoning more often. The poor problem solvers were more likely to deploy physical laws incorrectly and do little or no planning out of the solution method. No significant difference between the two groups in how often they checked their final answers was found but three out of eight good problem solvers checked their solution paths while only one out of seven poor problem solvers did. The difference in the numbers that checked their solutions seems to definitely favor the good problem solvers. A number of these findings were replicated in the field of electrostatics by McMillan and Swadener (1991) and college physics by Zajchowski and Martin (1993).

Santos (1995) conducted a study with ninth grade math students. Thirteen students solved math problems via think aloud methods. Their problem-solving efforts were characterized by high, medium and low level problem-solving ability based on the number of correct solutions. While this study had similar findings to the other studies in this section, Santos (1995) also demonstrated that flexibility in problem solving via the use of different representations allowed the high level students to be more successful. The lower level students who only chose a numeric representation were not able to determine the qualitative structure of the problem thereby being less likely to solve it correctly. In a study of analogy use by experts, Clement (1991) also demonstrated that experts were more flexible in reaching a solution path and usually choose to check their solutions via alternate paths. A similar good/poor problem solver design was conducted by Hegarty, Mayer and Monk (1995) with college undergraduates using inconsistent-compare problems in the domain of arithmetic. A compare problem is characterized by relation statements in which the value of one variable in the problem is defined in terms of another variable in the same problem. Inconsistent versions of a compare problem contain relational keywords (such as less) that prime an incorrect mathematical operation (subtraction rather than addition). Hegarty, et al (1995) found that successful problem solvers spent less time solving the problems, seemed to take the time to base their solution plan on a model of the situation described in the arithmetic problem, and made fewer errors. As a part of their methodology they utilized eye fixation data to determine how often and what problem elements subjects focused on. They found that the unsuccessful problem solvers referred to the problem statement more often and focused on the numeric terms of the problem while the successful problem solvers were more balanced attending not only to numeric terms but also to the problem situation as a whole. It was found that these behaviors on the part of the unsuccessful problem solvers led to their not being able to recover nor detect reversal errors (i.e., students would add when they should have subtracted or vice versa). The results of the eye fixation data seemed to be supported by the fact that in a retrospective interview the poor problem solvers remembered more details concerning the numbers in the problem while the good problem solvers remembered more about the context of the problem situation. Savelsbergh, de Jong and Ferguson-Hessler (1996) in another good/poor problem solver design but with the addition of experts discovered a continuum of strategies with decreasing use of the methods detailed above as the subject's problem-solving skill lessened. In addition, they might have discovered a clue as to why good problem solvers are able to remember more of the context of the problem since the good problem solvers and experts in this study produced detailed elaborations of the elements in the problem. These elaborations could lead to greater understanding as shown later in part two of this article.

It is possible that the problem-solving differences shown above might be affected by how the expert and novice use procedural and declarative physics knowledge. Reif and Allen (1992) investigated the differences in the use of domain specific knowledge specifically in the area of acceleration. They found that while both groups invoked the concept the same number of times the novices often misapplied it especially in complex cases and did not invoke the concept components that should have been linked to the basic concept. Further, when a novice was able to invoke the components they were unable to apply them correctly. In addition, experts were able to use supplemental knowledge that seemed to be linked to the problem concept such as forces but novices did so only moderately. A large difference was noted when it came to special cases. Experts would use case specific knowledge about the acceleration concept on familiar cases whereas the novices incorrectly applied them ignoring the case specificities. Reif and Allen (1992) felt that the novice's concept of acceleration was not coherent and lacked the knowledge of when to apply special cases which means that the knowledge used in problem-solving situations between the two groups was very different. Actually, in the special cases, the novices seemed to always apply their knowledge about special cases regardless of the specific situation. The differences in the coherence of the concept should lead to the production of more errors on the part of the novice students. This study suggests that the knowledge organization of the two groups might be different.

## Summary of Problem-Solving Differences between Experts and Novices

In the review above I have detailed the commonalties and differences in the problem-solving methods used by experts and novices. In addition, I have highlighted the discrepancies between studies and attempted to explain why they might exist. A summary of these problem-solving behaviors can be seen in Table 1.

In a number of cases researchers mentioned that coherence of an expert's knowledge, their "physical intuition", and the equations and principles used might be chunked together and this might be associated with the observed differences. This leads one to ask what is different between the knowledge and its organization to allow for these observed differences in problem-solving behaviors. The differences between how the two groups organize their knowledge will be discussed in detail. There is one significant finding that is mentioned briefly in a number of the studies described in this section - the qualitative differences in the planning, monitoring and evaluation completed by the two groups. These differences fall under the general category of metacognition. The question becomes: when you do undertake the time to make these metastatements, what does it buy the user? In order to further this finding the research conducted in this area is discussed in detail.

## Problem-Solving Strategy Training Studies

A number of research teams between the late 70's and 80's have attempted to teach problem-solving strategies to students to determine if they produced improvement in problem-solving

| EXPERT BEHAVIORS | NOVICE BEHAVIORS |
|---|---|
| • Typically use a working forward strategy except on more difficult problems | • Typically use a working backward strategy |
| • Performs an initial qualitative analysis of the problem situation | • Usually manipulates equations discovered via equation hunting |
| • Constructs diagrams during solution process | • Rarely constructs or uses diagrams |
| • Spends time planning approach sometimes via models of the physical situation | • Rarely plans approach – simply dives in |
| • Uses fewer equations to solve the problem | • Uses more equations to solve problem |
| • Usually solve problems in less time | • Usually takes more time to solve the problems |
| • Refers to the physical principles underlying the problem | • Refers to the numeric elements of the problem |
| • Concepts more coherent and linked together | • Concepts not coherent and lack applicability conditions for special cases |
| • Fewer errors – concepts usually deployed correctly | • More errors – concepts usually deployed incorrectly |
| • Can use more than one representation to solve problems – which usually allows them to deviate to other solution paths when stuck | • Usually only utilize a numeric representation to solve problems – once they become stuck rarely can free themselves |
| • Checked solution by a variety of methods (i.e., more flexible) | • Superficially check solution if at all |
| • Rarely refer to problem statement or text | • Frequently refer to problem statement and textbook (especially examples) |

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

ability. The strategies taught included the behaviors used by experts and many seem to be based on a four part strategy described by Polya (1968) – understand the problem, devise a plan, carry out the plan and finally look back. I divided the studies between ones conducted in a lab setting and ones conducted in an actual classroom setting. All of the studies mentioned were conducted with college age students.

## Problem-Solving Strategy Studies Conducted in a Laboratory Setting

In the late seventies two studies, Larkin (1979) and Larkin and Reif (1979), reported that they taught an "expert-like" problem-solving strategy based upon an analysis of expert and novice verbal protocols. Five students were taught to conduct a qualitative analysis of problems based on fundamental principles and associate problem information such as equations with seven specific electricity and magnetism principles by chunking. Larkin and Reif (1979) believed that the chunking of equations would give the students an easily remembered overview to use during a qualitative analysis of the problem. Five additional students were not given any chunking or qualitative analysis trainings. All ten students then talked aloud while solving 3 direct current circuit problems. In the control group only 4 out of 5 students could solve one problem while the experimental group solved a majority of the problems (2 students solved 2 problems and 3 students solved all 3 problems). These findings demonstrated that teaching students to behave similar to experts seemed to improve their ability to solve problems. Larkin and Reif (1979) went one step further and hypothesized that this might mean that expert knowledge was organized via coherent chunks rather than into lists of principles or equations.

Heller and Reif (1984) developed an efficient hierarchical problem-solving procedure that did not exactly reproduce the procedure shown to be used by experts but seemed to be similar to it while being more efficient. The procedure contained three stages: problem description, solution search, and solution assessment. A number of the elements they included in the different stages were a theoretical description of the physics involved, exploratory analysis of the problem, and some metacognitive processes. They thought a hierarchical problem-solving structure would be best with the top levels containing basic ideas and the bottom levels elaborating on the topmost levels. They tested the effectiveness of the procedure using 24 undergraduates divided into three conditions: experiment procedure, modified procedure developed from that used normally in textbooks and no procedure group. They assessed the solutions on post task problems for all students based upon adequacy of motion and interaction information, equations used, and correctness of the final answer. The solutions were assessed based on the written work of the students and the accompanying verbal protocol record. The experimental procedure group performed significantly better than the other two groups on all measures tested (Heller and Reif, 1984).

Lewis (1989) designed his problem-solving strategy to force novices to adopt the expert-like use of multiple representations for problems. He conducted a study using almost 100 math students to test if training students to first use a diagrammatic representation then convert it to an algebraic statement would improve their problem-solving skills. He had three experimental groups: the diagram group received problem-translation training as well as the diagrammatic integration training; the statement group received only the translation training and the control received no training. The diagram group produced significantly fewer reversal errors (i.e., selecting the inverse of the proper algebraic operation) on inconsistent-compare problems (described previously) from pre to post-test and was able to transfer the newly learned skills to more complex problem situations that were similar to the training problems (i.e., near transfer tasks).

## Problem-solving Strategy Studies Conducted in a Classroom Setting

Since the lab studies demonstrated a decided ability to increase the students' problem-solving ability via the training of expert-like problem-solving strategies, the question now became: Could these types of problem-solving strategies that are effective in the lab be scaled up for a classroom setting with continued success even without randomly assigned subjects? Wright and Williams (1986) developed and taught a procedure called WISE to community college physics students. The WISE method had students initially identify the principles involved in the problem, draw a sketch; isolate the unknown; substitute values; and then evaluate the answer. Students who used the procedure had significantly better classroom performance than other students. In addition, these students seemed to feel that the strategy made their problem-solving process better. These results were encouraging and did not require a restructuring of the course.

At the University of Minnesota, Heller, Keith, and Anderson (1992) developed a five step problem-solving approach called the Minnesota Problem-Solving Strategy for use in algebra based university physics classes employing a cognitive apprenticeship model. This strategy required a restructuring of the introductory course since the problem-solving strategy was modeled in practice sessions and lectures. The instructors in the practice sessions slowly turned the process of instruction over to the students as they become more competent. The efficacy of this type of cognitive apprenticeship pedagogical approach has been shown in numerous studies (Collins, Brown and Newman, 1989). The problem-solving strategy had the students visualize the problem, describe the physics terms, plan the solution, execute the plan, and then check and evaluate the solution. The practices made use of context rich problems that forced the students to use the developed strategy since normal novice strategies seen in some of the studies previously reviewed would not allow for success. Based on a scoring rubric developed by the group it was discovered that group solutions were consistently better than individual solutions especially in the areas of the qualitative analysis but they did not compare results to students not using the Minnesota Problem-Solving Strategy in order to determine the effects on problem-solving success. Huffman (1994, 1997) did test this idea with high school students where one subset of students was taught using the Minnesota Problem-Solving Strategy and the other using a general textbook strategy. While Huffman did find the quality of solutions better with the Minnesota group, especially problem representations, there was no difference in conceptual understanding or solution organization between groups. This study does seem to suggest that it may be very difficult to train large numbers of students in the classroom setting.

The ability to utilize multiple representations to solve problems seems to be a skill which can be taught in a large scale classroom. Kohl and Finkelstein (2006) concluded that students in reform lecture classes were learning more representational skills than those students in a more traditional physics course. The researchers then analyzed both courses for the representational content used in all aspects of the course which thus allowed them to perform more consistently across a wide range of representatial tasks. They determined that the reform class made use of a boarder range of representations during all aspects of the class: lecture, homework, quizzes and exams. Kohl and Finkelstein (2006) inferred that the source of the broader representational skills demonstrated by the reform students was the difference in instructional emphasis.

## Summary of Classroom and Lab Studies

It is interesting to note that the commonality between the problem-solving studies is that in all cases they have demonstrated that student performance in some way was improved by explicit instruction in problem-solving strategies. One major difference between these studies was that only Larkin and Reif (1979) utilized verbal protocols in order to directly observe the differences while the rest mostly focus on group administered paper and pencil tests and/or intense analyses of the students written problem solutions. Therefore, the majority of the studies and most importantly the classroom studies did not determine if the students actually internalized the strategy and were exhibiting expert-like problem-solving skills in the classroom such as working forward but could only infer that this might be what happened due to the performance on written assessments. In addition, representational skills seem to be able to be taught to students in the context of a large lecture format class.

## Schema and Knowledge Structure Research

The problem-solving studies referred to the use of principles by experts and that these principles seemed to have algebraic representations and other knowledge linked, chunked or connected in some fashion. These findings allowed researchers to postulate that the experts seemed to have developed a coherent set of knowledge that helped them perform better. Reif and Allen (1992) definitely showed that while novices and experts use the same concepts to solve problems the knowledge in the case of the novice lacks coherence. It has been suggested that the difference in problem-solving abilities might be due to the greater amount of knowledge that experts possess (de Jong and Ferguson-Hessler, 1986). However, there is some evidence for the assertion that the structure of one's knowledge may play an important role. This evidence was uncovered when Hinsley, Hayes and Simon (1977) demonstrated that competent problem solvers in algebra did indeed utilize schemas and that these schemas seemed to direct their problem-solving strategy. A schema is a mental structure that allows one to organize their knowledge. For example, in math a problem schema would consist of interrelated sets of knowledge about particular problems that unite the problems on the basis of some type of underlying feature or features. Hinsley et al (1977) asked math students to categorize a set of algebra word problems by problem type. They found that students did indeed categorize problems into type and this categorization occurred very quickly sometimes after reading only the first statement in the problem. They went on to explore if the students used these categories to solve problems. They discovered that they did indeed utilize them to help solve problems and that the categories included information about "useful equations and diagrams and appropriate procedures for making relevant judgments" (p. 104). They also found that if the student did not recognize the problem type then they used a general problem-solving procedure which would lead to a working backward approach. Hinsley et al (1977) concluded that this research did support the idea that people form schemas which are knowledge structures that can powerfully and flexibly represent an individual's knowledge. The card sort procedure designed by Hinsley et al (1977) was used quite extensively to study the differences between knowledge structures constructed by novices and experts in a number of domains.

## Differences in Knowledge Organization between Experts and Novices

In physics a classic study was conducted by Chi, Feltovich, and Glaser (1981). Chi et al (1981) asked 8 students who had completed a semester of physics (novices) and 8 physics graduate students (experts) to categorize a set of problems taken from a standard college text based upon the similarity in their solution processes but were told not to solve the problems. They discovered that the novices sorted the problems based upon surface structure while the expert sorted them based upon deep structure (i.e., physics principles). A surface structure was considered "(a) the objects referred to in the problems (e.g., a spring, an inclined plane); (b) the literal physics terms mentioned in the problem (e.g., friction, center of mass); or (c) the physical configuration described in the problem (i.e., relations among physics objects such as a block on an incline plane)" (p. 125). Chi et al (1981) postulated that these categories might be used by the novices and experts to access a knowledge unit that contained information they could use to solve the associated problems (i.e., a problem schema). It was suggested that the categories used by novices and experts to access their schemas would be dissimilar with novices categorizing problems via surface features while experts used principles. They then proceeded to conduct experiments that would allow them to determine the contents of these knowledge structures by asking the subjects (2 novices and 2 experts) to describe all they could about the problems in each category and how they would go about solving them. The experts associated the principles with solution procedures and applicability conditions which were similar between experts and seemed to be replicated by the Reif and Allen (1992) findings. The novices seemed not to have many (if any) explicit solution procedures associated with the surface features. These postulated structures would lead to a top down problem-solving approach by experts whereas the novices would exhibit a bottom up approach since they initially activate the specifics about the problem instead of the overreaching principle that would guide the solution approach. This would be consistent with the problem-solving behaviors observed in the preceding sections. In addition, when Chi et al (1981) included intermediate level students they discovered the knowledge structures were based on a mixture of principles and surface features suggesting that learning is correlated with a general shift in the structure of the knowledge organization from one based upon surface features to one based upon physical principles. This is very similar to the knowledge state finding of the CPU curriculum discussed earlier (Galili et al, 1993).

Chi, Glaser, and Rees (1982) continued the above studies by asking subjects to take their original sorts and to subdivide each category. They found that many of the novices' sub-groupings included only one or two problems and that novices' had difficulty developing higher level categories. This suggests that the experts' develop a hierarchical knowledge structure which includes the physical objects in the problems at the lower levels whereas the novices' knowledge structure includes the physical objects in the higher level categories. In addition, it was discovered that both experts and novices use the same words to cue their solution procedures but that their reasoning was different. Chi et al (1982) concluded that the problem-solving difficulties demonstrated by novices must be due to inadequacies in their knowledge organization. These hierarchical knowledge structures based upon principles would lead to experts conducting a breadth first search as they would need to skim over all the principles to decide upon an initial solution approach. However, novices would select a strategy based on surface features; thereby committing to a depth first search as they tried every procedure connected with solving problems associated with that surface feature. Chi et al (1981) suggest that students taught ways to reorganize their knowledge might improve their problem-solving abilities.

Chi et al's (1981, 1982) card sort findings were later replicated and extended by a number of researchers in the area of physics (Hardiman, Dufresne, and Mestre, 1989; Snyder, 2000 and Veldhuis, 1986). All three of these studies determined that some novices categorize problems based on a mixture of surface features and principles showing that the process is not as clear cut as Chi et al (1981) may have concluded. The findings that deep structure characterizes expert categorization while surface features drive novice performance was also demonstrated in the field of mathematics (Krutetskii, 1976; Schoenfeld, 1985; Schoenfeld and Herrmann 1982; Silver, 1979 and Silver, 1981). The robustness of deep structure vs. surface feature categorization by experts and novices has been demonstrated in a number of diverse domains such as biology, computer programming, dinosaur knowledge, engineering and even aquarium usage (Chi and Koeske, 1983; Gobbo and Chi, 1986; Hmelo-Smith and Pfeffer, 2004; McKeithen, Reitman, Rueter and Hirtle, 1981; Moss, Kotovsky, and

 

Cagan, 2006; Smith, 1990, 1992; and Weiser and Shertz, 1983).

A number of studies in physics extended the original Chi et al (1981) study by looking at the knowledge structures developed by good problem solvers and poor problems solvers. Researchers hypothesized, based on the prior studies, that there should be a difference in knowledge structures between the two groups of students. In a forced choice study Hardiman, Dufresne, and Mestre (1989) found that college age novice subjects who tended to be better problem solvers also tended to categorize physics problems by principles. They were able to show that there was a correlation between problem-solving ability as demonstrated on a problem-solving task and cognitive structure based upon the percentage of problems categorized expertly. In addition, researchers soon discovered that expert or better problem solver knowledge structures were not only based more upon physics principles but that the knowledge was more coherent and that the relationship between the elements chunked or linked to the principles were explicit (de Jong, and Ferguson-Hessler, 1986; Ferguson-Hessler and de Jong, 1987; and Savelsbergh, de Jong, Ferguson-Hessler, 1996). These findings were hinted at in the original problem-solving studies.

A series of studies looked beyond the differences in categorization by using methods devised to discover the amount of cohesion in knowledge structures developed by subjects. Bagno and Eylon (1997) used free, cued and contextual recall tasks to probe the concepts formed by high school students of physics. They determined that the students did not have a global view of the concepts and failed to extract a knowledge structure based upon a global view. Robertson (1990) went further by investigating the type of cognitive structure high school novices developed specifically for Newton's second law during a verbal protocol study. He found that the score that students received based upon the number of connected elements normally contained in an expert knowledge structure (determined by a task analysis) correlated highly with their ability to perform transfer problems correctly. His conclusions were that if novices are to use their knowledge structures effectively then they needed to connect the principles and concepts to each other. This same conclusion was reached recently by Sabella and Redish, (in press) when they conducted a verbal protocol study using graduate students in physics (i.e., the experts in some of the original studies) which included a structured interview. They discovered that those subjects with globally coherent knowledge structures that linked the principles together were more flexible during problem solving. In addition, subjects who had local coherence (only certain elements of the knowledge structure linked together) could not easily handle more difficult problems that required the use of several principles simultaneously.

## Summary of Knowledge Structure Differences between Experts and Novices

It is very clear by the scope of the research discussed in this section that people do activate knowledge structures during problem solving and that not only the content but the organization of those knowledge structures correlate with success in problem solving (i.e., the more expert-like the knowledge structure the better the problem-solving ability). In addition, to be a flexible problem solver it was shown that one needs to have a global knowledge structure which links the principles together. A summary of the knowledge structure findings can be found in Table 2.

The question for researchers then became can knowledge structures be taught to students in a fashion that would produce gains in problem-solving skills since these two areas seem to be connected. Research pertinent to these types of studies will be reviewed in Part II of this article.

## Conclusion

Is it possible that Modeling Instruction could be developing more expert-like students than non-modeling methods? In order to analyze this question we need to review the basic tenets of Modeling Instruction with the express purpose of linking them to the previous research concerning problem-solving and knowledge structure organization.

During the course of study modeling students develop a model of a physical situation via an experiment. The data from these experiments are used to produce several different representations of the model consisting of verbal, diagrammatic, graphical and algebraic representations. These representations are tested by the students to ensure that they are coherent (i.e., each representation

| 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*

allows the students to obtain the same solution to a problem). This is an activity that rarely occurs in a conventional physics class. Would this type of model development allow the students to produce knowledge structures that link these representations to the principles or models being developed? By explicitly linking these representations together modeling students could be developing a more expert-like knowledge structure. Is it possible that the knowledge developed is structured hierarchically? These are gaps in the physics education research as there have not been any studies designed to determine if modeling students have a more expert-like knowledge structures nor how it is specifically structured. It is possible that the reason that the modeling students do so well on the Force Concept Inventory is that they have produced a knowledge structure in this area that is more consistent with that of an expert. Possibly a future literature review of studies that attempted to develop the knowledge structures of subjects in lab and classroom situations might give us a better idea if it is possible to develop an expert-like knowledge structure during the course of year of study.

During their course of study modeling students deploy the models constructed to new contexts via the use of deployment labs and problem sets. The problem sets are specifically designed such that the students are required to use the different representations to solve them. The students cannot simply rely on one representation to solve all problems thus they should become more versatile problem-solvers and demonstrate this quality of expert-like problem solving. A problem-solving strategy based on a qualitative analysis of the model to be utilized is scaffolded by the modeling instructors. Before every problem the students are asked to first select the physics model that can be deployed to solve the problem thereby reinforcing a qualitative analysis of the problem and a working forward strategy. These behaviors have been shown to be utilized extensively by expert physicists and proficient problem solvers. In addition, the chunking of the representations to the model should allow those representations to become available to the student for use as soon as they associate a problem with a particular model as implied by the studies conducted by Larkin and Reif (1979) and Kohl and Finkelstein (2006). The modeling method also constantly asks the students to justify their answers in terms of how they know the answer and whether the answer made sense to them. These two questions might engender the students to check their answers more often which has been shown to be an expert trait and might lead to fewer problem-solving errors. This strategy is similar to the method used by Heller and Reif (1984) which obtained significantly improved problem-solving behavior. While it has been shown that modeling students perform better on the Mechanics Baseline Test, studies have not determined if the cause could be the deployment of the consistent problem-solving strategy that consists of expert qualities as found in previous research.

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# PHYSICS TEACHER EDUCATION JOB OPENING

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The successful candidate is expected to show significant potential for scholarship, research and instruction of future and current physics teachers at both the graduate and undergraduate level. The successful candidate will join a strong interdisciplinary team already in place, and to contribute to a substantial Buffalo State College presence in physics teacher education through scholarship, through participation in relevant professional organizations such as the AAPT, PTEC, NARST, ASTE, AERA and NSTA, and through significant grant activity from the NSF, US DEd and NYSED. Exceptional candidates with an appropriate record of publication may be considered for hire at the Associate level.

The candidate must show evidence of reviewed scholarship in physics education research or teacher preparation. An appropriate doctoral degree in physics, physics education, science education or education is required, with a masters' degree in physics. We prefer but do not require the following:

* Experience working with pre-service or in-service teachers
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* Experience supervising and mentoring teacher candidates and teachers
* Experience conducting research and scholarship with undergraduate and Masters' students

Please send a letter of interest describing how your background fits the detailed position requirements, a resume, research plan, statement of teaching philosophy including any data supporting teaching effectiveness, and a list of three references by email to: DEMARCMJ@BUFFALOSTATE.EDU, or by letter to: Dr. Michael DeMarco, Chair of Physics, Physics Department, Buffalo State College, 1300 Elmwood Avenue, Buffalo, New York 14222. For fullest consideration, complete applications should be received by January 15, 2007. Buffalo State is an affirmative action / equal opportunity employer.