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The Development of the Concept Mapping Tool and the Evolution of a New Model for Education: Implications for Mathematics Education[1]

***Joseph D. Novak,* Cornell University,**
Institute for Human and Machine Cognition

Introduction

When I began my graduate studies in 1952 at University of Minnesota, the only psychology of learning presented was *behavioral psychology*, based largely on research with rats, cats and other animals. The only philosophy of knowledge, or epistemology, I was taught was *logical positivism*, for which the Philosophy Department at Minnesota was world famous. I did not see much value in behavioral psychology as a theory to guide research on human problem solving and ways to enhance this ability, which was the subject of my PhD thesis. Nor did I see value in a view of knowledge creation that centered on proving axioms and logically deriving new knowledge from basic premises, a view that did not appear to apply to the work I was doing in laboratory research in the Botany Department.

Although there was the work of Barlett (1932) theorizing on how cognitive learning takes place, and the extensive work of Piaget beginning in 1926 describing how children's cognitive operations advance over time, I was taught none of this. I did, however discover the writing of Conant (1947) and his ideas on how the sciences create new knowledge. Later his protégé, Kuhn (1962) would expand Conant's ideas in his enormously popular, *The Structure of Scientific Revolutions*. Lacking a psychology of learning that made sense to me, I chose to base my research on Wiener's (1948) *cybernetic* ideas, and we continued with these ideas until our research data failed to fit the theory. Most fortunately for us, Ausubel's (1963) *cognitive* psychology of learning was published about this time, and we embraced this as a founda-

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[1] Based in part on earlier papers, Novak (2004a, b), and Novak (In press).

tion from 1963 onward. Today cognitive learning theories have essentially replaced behavioral theories, although much school learning still proceeds on behavioral learning principles, such as repetition and reinforcement. This is also evident in the common drill and practice observed in mathematics classrooms.

One of the issues debated in the early 1960s was the extent to which children could profit from instruction on abstract, basic science concepts such as the nature of matter and energy. The dominant thinking in science education and development psychology was centered on the work of Jean Piaget (1926), particularly his ideas about cognitive operational stages. Piaget had devised some ingenious interviews administered to children, the results of which could be interpreted to support his theory of stages of cognitive operational development. It was widely assumed that children could not profit from instruction in such abstract concepts, such as the nature of matter and energy, before they reached the formal operational stage of thinking at ages 11 or older. Similar misperceptions are common with math educators who do not think young children can understand the basic concepts behind math procedures, or they may not even be aware of these concepts.

The fundamental questions that concerned me and my research group were:

1. Are these claimed cognitive operational limitations of children the result of brain development, or are they at least partly an artifact of the kind of schooling and socialization characteristic of Piaget's subjects, and those commonly tested in US and other schools?
2. With appropriate instruction in basic science concepts such as the nature of matter and energy, can six to eight year-old children develop sufficient understanding to influence later learning?
3. Can the development of children's understanding of science concepts be observed as specific changes in their concepts and propositions resulting from the early instruction and from later science instruction?
4. Will the findings in a longitudinal study support the fundamental ideas in Ausubel's (1963) assimilation theory of learning?

Answers to these questions could only be obtained by first designing systematic instruction in basic science concepts for 6-8 year-old children, and then following the same children's understanding of these concepts as they progressed through school, including later grades when formal science courses were taken. This was the instructional development and research project we set out to do.

To avoid problems associated with elementary school teacher's limited knowledge of science and limited time for instruction, we developed audio-tutorial instructional materials in which children were guided by audiotapes that we had developed and that were supplemented with pictures, film clips and equipment. The audio-tutorial lessons were based on ideas in the National Science Teachers Association report, *Importance of conceptual schemes for science teaching* (Novak, 1964), and an elementary science textbook series, *The World of Science* (Novak, Meister, Knox, & Sullivan, 1966). Twenty-eight lessons were developed that dealt with the particulate nature of matter, energy types and energy transformations, energy utilization in living things, and other related ideas. For the most part, these kinds of concepts are rarely presented to elementary school children, especially to 6-8 year olds in grades one and two. Figure 1 shows an example of an early lesson on energy transformations. All lessons provided audio-guidance through manipulation of materials in the carrel and other observations, including occasional “loop films” showing animations or time-lapse photography.

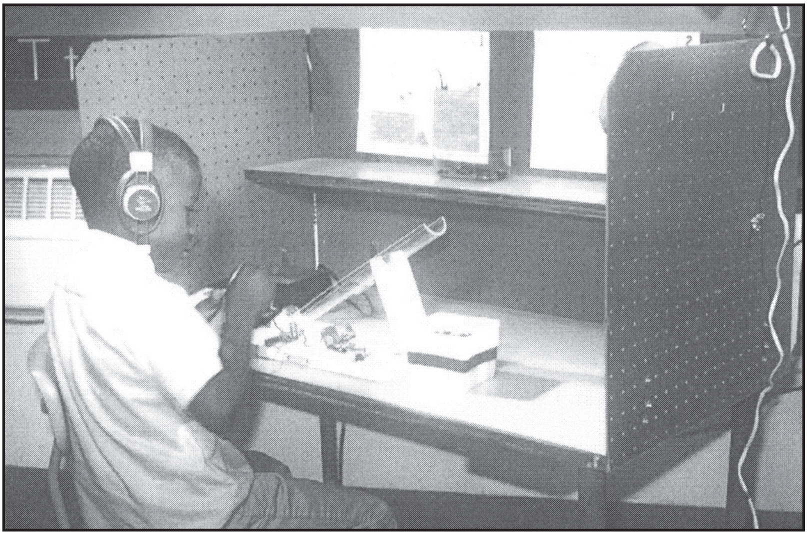

Figure 1. A 6-year old student working with an Audio-Tutorial lesson on transformation of electrical energy.

The key principle of the Ausubelian learning theory we considered in the design of our lessons is stated in the epigraph to his 1968 book:

> *If I had to reduce all of educational psychology to just one principle, I would say this: The most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly.*

As my graduate students and I developed an idea for a new lesson, we would interview 6 to 8 primary grade children in an open ended interview, usually using some of the “props” we were planning to use to teach the central concepts of the lesson, such as pictures, materials to be manipulated, loop films or apparatus we were considering. These interviews gave us some idea of what anchoring concepts most of the children already had, and also gave some preliminary feedback on how they were interpreting or using the props. This process was often repeated several times, and again after lesson prototypes were developed. On average, each lesson underwent 6 to 8 revisions before it was deemed ready to use in classrooms. We also considered Ausubel's ideas of *progressive differentiation* and *integrative reconciliation* in designing the lessons and lesson sequences (see the section on concept mapping for further discussion of these ideas). The idea of progressive differentiation requires that students build upon their prior relevant concepts, and elaborate concepts in earlier audio-tutorial lessons in a sequence as they study later related lessons. This required that some students needed to experience earlier lessons in a sequence before we could use these students to help develop later lessons. Furthermore, many concepts were revisited in later lessons, but with different examples or props to effect greater differentiation of concepts introduced earlier, and thus also to achieve integrative reconciliation of concepts that may have been initially confusing to a child or where meanings acquired may have been somewhat distorted. Photos and loop films were selected or constructed in many cases to serve as *advance organizers*. That is, we would use things that were familiar to the students, and we would build on the familiar to point them to see new aspects or dimensions of the new materials observed, much of this through the audio guidance.

Methodology of the 12-year Study

Ithaca Public Schools had 13 elementary schools, and for logistic reasons we chose to work with first grade teachers in five schools that were representative of the school district. A carrel unit was set up in the corner of the classroom of each of the participating teachers and 191 students in all took turns doing the lessons. These were our experimental or "Instructed" students, so called since very little science is taught in primary grades in Ithaca schools. In the second year of the study, we began to interview 48 students in the same classrooms and with the same teachers as the previous year, but these students did not receive the lessons. This was our control or "Uninstructed" sample.

The lessons were placed in carrel units, usually in a corner of the classroom. The class teacher determined the time provided for student involvement with the lessons, but most often this was during "seat-work" times, or when the teacher was working with small reading groups. Students, one at a time, could take turns doing the audio-tutorial lesson. Some students observed others doing the lessons, and many students repeated lessons one or more times, often during recess, lunchtime, or other free time. Each lesson required approximately 20 minutes for a student to complete; thus the 28 lessons provided some 10-20 hours in carefully designed instruction over the two-year span of the instruction. Those teachers who included science in their instruction (a minority) usually dealt with topics such as seasons, clouds, and plant growth, but only in a descriptive manner and not including the basic science concepts such as energy transformations and the particulate nature of matter.

Each teacher we worked with reported excellent student response to the audio-tutorial lessons, and some of the teachers also noted their value for their own learning. None asked to be dropped from the study and most wanted to continue to use the lessons in future years.

Early in the study we developed various forms of paper and pencil tests, including tests with pictures that students marked with crayons following oral questions. We found in subsequent interviews with children that these paper and pencil tests were not valid indicators of the conceptual understanding of students. We subsequently chose to use modified Piagetian interviews as primary evaluation tools, with procedures as described elsewhere (Novak & Gowin, 1984, Ch. 7).

We designed interviews to use some of the materials that were in the lessons and other materials that were different but illustrated the same concepts. We prepared interview kits, and these were used by a number of different graduate students, with some instruction on how to do the interviews. Interviews were done with the Instructed students several times during the first year, including interviews on topics other than the nature of matter and energy. However, we found we did not have the staff resources to continue interviewing all Instructed and Uninstructed students on several domains of science, and chose to interview students only on concepts of matter, energy, and energy transformations. The same interview kits were used as the students progressed through school, and over the years. We also did not have staff to interview all students each year, and we had to choose a random sample from the Instructed and Uninstructed groups for later years of the study. All interviews were tape-recorded and some were also video-recorded. Ithaca has two junior high schools (grades 7-9) and one high school (grades 10-12). This made it easier to do follow-up interviews, especially in their high school years. We made a concerted effort to interview all students remaining in both the Instructed and Uninstructed samples during their senior year and succeeded in interviewing 85 of 87 students remaining in high school. Many children have parents who are students at Cornell or Ithaca College, and they leave Ithaca when their parents complete school. With the high attrition rate, we were perhaps a bit lucky that the remaining Instructed and Uninstructed students had almost identical SAT scores, indicating we could consider these samples to be comparable in general ability.

A single investigator could not carry out the large number of interviews, so throughout the project I was assisted by my graduate students. Graduate students do not, however, stay forever. The long period of time meant that over the 13 years of the study (counting the final year of data gathering from the Uninstructed students), 24 different graduate students and staff persons participated in the interviews and interview interpretations. This feature of the study may be unique. I patterned my research group after the models I had come to know as a teaching and research assistant in the Botany Department at the University of Minnesota. Our research group worked with a common, explicit theoretical foundation, we held seminars regularly to discuss our research, our instructional development efforts in several projects in addition to the work reported here, and where we found difficulties in or new insights in our work. This teamwork was essential to maintain the momentum and consistency in methodologies as our work progressed.

The Invention of "Concept Mapping"

As we continued interviewing children in our study, we were accumulating hundreds of interview tapes. When we transcribed the tapes, we could observe that propositions used by students would usually improve in relevance, number, and quality, but it was still difficult to observe specifically how their cognitive structures were changing. Our research team considered various alternatives we might explore, and we also reviewed again Ausubel's ideas regarding cognitive development. Three ideas from Ausubel's Assimilation Theory emerged as central to our thinking. First, Ausubel sees the development of new meanings as building on prior relevant concepts and propositions. Second, he sees cognitive structure as organized hierarchically, with more general, more inclusive concepts occupying higher levels in the hierarchy and more specific, less inclusive concepts subsumed under the more general concepts. Third, when meaningful learning occurs, relationships between concepts become more explicit, more precise, and better integrated with other concepts and propositions. The latter involves what Ausubel calls *progressive differentiation* of conceptual and propositional meanings, resulting in more precise and/or more elaborate ideas, and *integrative reconciliation*, or resolution of conflicting or ambiguous meanings or concepts and propositions. In our discussions, the idea developed to translate interview transcripts into a hierarchical structure of concepts and relationships between concepts, i.e., propositions. The ideas developed into the invention of a tool we now call the *concept map*. We now see the development of organized frameworks of knowledge not only the product of meaningful learning, but also the basis for creative thinking and the production of new knowledge (Novak, 1993).

We were somewhat surprised to find that we could rather easily transform the information in an interview transcript into a concept map. Figure 2 shows examples of concept maps we drew from interview transcripts for one above-average Instructed student at the end of grades 2 and 12. Note that while new concepts such as “atom” are assimilated into her cognitive structure, she also has acquired some new misconceptions. This is characteristic of students who learn sometimes by rote and sometimes at relatively low levels of meaningful learning. The mean quality of maps for Instructed students was substantially better than for Uninstructed students as will be shown below. We found that a 15-20 page interview transcript could be converted into a one page concept map without losing essential concept and propositional meanings expressed by the interviewee. This we soon realized was a very powerful knowledge representation tool, a tool that would change our research program from this point on.

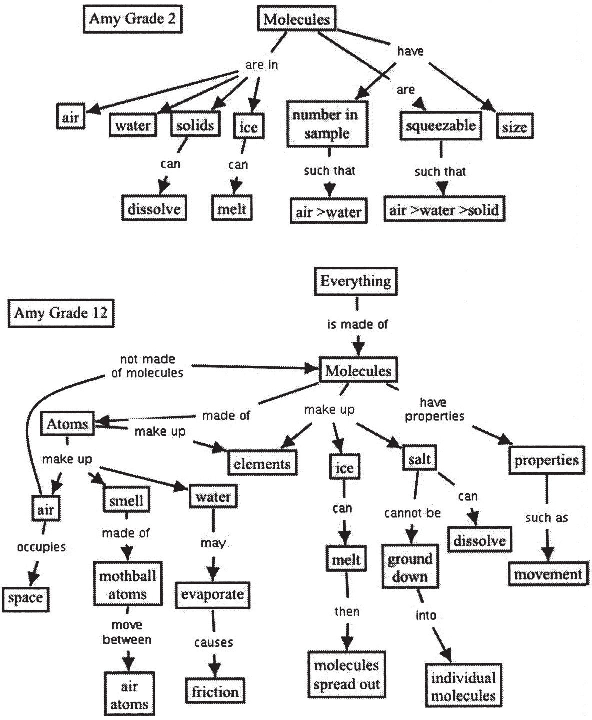

Figure 2. Two concept maps drawn from interviews with an above average Instructed student at the end of grade 2 and at the end of grade 12.

In the history of science, there are many examples where the necessity to develop new tools to observe events or objects led to the development of new technologies. For our research program, the necessity to find a better way to represent children’s conceptual understandings and to be able to observe explicit changes in the concept and propositional structures that construct those meanings led to the development of what has now become a powerful knowledge representation tool useful not only in education but in virtually every sector of human activity. It should be noted that although there were other knowledge or semantic structure representations prior to our development of concept maps, most of these are not hierarchically organized, do not contain explicit single concept labels in the "nodes", and usually do not have "linking words" between the concepts that are necessary to represent propositional meanings. Other forms of knowledge representations have been described by Jonassen, Beissner, and Yacci (1993), as well as others.

For our research project, the use of concept maps drawn from structured interviews became the primary tools we used to ascertain what learners know at any point in their educational experience. While it does take an hour or two for an experienced person to make a concept map from a 20-30 minute interview transcript, the precision and clarity of the learner's cognitive structure represented this way made it relatively easy to follow specific changes in the student's knowledge structures as she/he progressed through the grades. We also used concept maps made by our research staff to identify valid and invalid notions held by students. It should be noted that these concept maps were made by many different graduate students over the span of the study, but still the consistency in the patterns observed for each student was remarkable. This illustrates in part the robustness and validity of this form of knowledge representation, as well as consistency in interviewer elicitations over time.

In our study, the researchers constructed the concept maps from the transcripts of the interviews with the children. Later, and not in the study, we got students to construct maps directly, by giving them key terms which they had to arrange in meaningful patterns and then connect with lines that they labeled with the nature of the relation between the terms. When students are taught how to do this direct form of concept mapping, it is possible to use the concept maps they draw to observe the initial state of the learner's knowledge in a given domain, as well as to monitor changes in their cognitive structure. Edwards and Fraser (1983) have shown that students' concept maps can be as revealing of learners' cognitive structures as clinical interviews. We have found student concept maps to be good indicators of their knowledge when learners have sufficient skill in concept mapping and motivation to construct their own concept maps. We did not attempt to have students in our samples construct concept maps, since the technique was not developed until after the study was underway, and training in the use of concept maps was not feasible. While our longitudinal study was in progress, we made little effort to encourage the use of concept maps, since this may have confounded our study results. There were a few of the teachers in Ithaca schools interested in the use of concept maps, but most preferred to continue with their usual teaching practices. As Kinchen (2001) has observed, it is difficult to "fight the system."

It is important to note that these explicit changes were observed in different interviews done by different graduate students over the span of 12 years. We were careful to have graduate students draw concept maps without knowing whether the interviews were with Instructed or Uninstructed children. The consistency with which the same valid or faulty knowledge structures were shown in concept maps drawn by different researchers illustrates the robustness and reliability of the technique of representing children's understandings in the form of concept maps. Subsequently other investigators have also found concept maps to be reliable, valid indicators of conceptual understanding and changes in relevant concept and propositional structures over time (Kankkunen, 2001; Ruiz-Primo & Shavelson, 1996; Shavelson & Ruiz-Primo, 2000).

Major Findings of the Study

Using the concept maps drawn from interviews as the primary source of information, we extracted valid and invalid propositions or notions evidenced in the concept maps. It was clearly evident that Instructed children had fewer and fewer misconceptions as they progressed through school, when compared with Uninstructed students. Conversely, the Instructed students had an increasing number of valid ideas or notions as they progressed through the

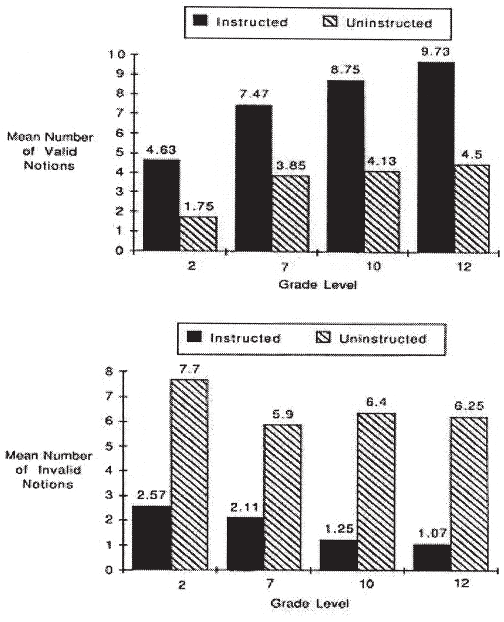

Figure 3. Mean number of valid notions held by Audio-tutorial Instructed students and Uninstructured students (top graph) and mean number of invalid notions held by students (lower graph).

grades. The results are shown in Figure 3. We see that by the end of grade 2 the Instructed students significantly outperformed the Uninstructed students in their understanding of energy and molecular kinetics ideas. When students begin the formal study of science in grade 7, both Instructed and Uninstructed students improve in their understanding of energy and molecular kinetics concepts, but a highly significant ($p<.001$) superiority of Instructed students compared with Uninstructed students was observed, both for valid and invalid ideas. Moreover, the Instructed students showed steady improvement as they progressed through high school sceince courses, whereas improvements for Uninstructed students were small. This significant difference in performance over the years for the Instructed and Uninstructed groups led to a significant interaction variance for years in school. Other statistical results have been reported elsewhere (Novak & Musonda, 1991). Clearly the students who were helped to form basic science concepts in grades one and two had developed their cognitive structure (their *subsumers*, in Ausubelian terms) for energy and molecular kinetics ideas in a way that continued to facilitate their meaningful learning, further developing their understandings and reducing their misconceptions. Such remarkable results shout for replication, but to my knowledge, no one else has attempted a 12-year longitudinal study of children's science concept development.

It would appear in retrospect that we were successful with the great efforts we made to devise the right kind of experiences and sequences of experiences in the audio-tutorial lessons, and to provide the necessary concrete-empirical props most of the students needed to acquire the concepts presented meaningfully and substantively. In fact, the data suggest that many of the junior high school science courses failed to do this and hence many of the Uninstructed secondary school students did not progress substantially in their understanding of basic ideas about energy and the structure of matter. Limitations of Piaget's ideas on the capability of children to develop abstract ideas have been pointed out by others (Cf. Flavell, 1985).

The results reported here and in the published paper (Novak & Musonda, 1991) were initially met with some skepticism, since they fly in the face of the commonly accepted dogma. There remains in the science education literature an overwhelming commitment to the idea that only discovery or inquiry approaches to learning science can result in meaningful literature. Of course, most classroom teachers continue to use lecture and "cook book" laboratories in their teaching, and assessments requiring primarily recall of specifics, with the result that they confirm the limited value of this kind of instruction. What we achieved in our audio-tutorial instruction, and what we propose to do in future projects utilizing computer technologies and the Internet very significantly departs from the common form of classroom science instruction. While my position remains largely a minority position in science education circles, I have every confidence that the validity of the idea that young children can learn to a significant degree basic, abstract science concepts necessary for developing understanding of the wide array of concepts in all of the science disciplines will be validated in the next decade or so, perhaps in Latin countries if not in the USA. One only has to look at where we were in this country for half a century as *behavioral* psychology diminished, at best, and prevented, at worst, progress in developing a *cognitive* understanding of human learning. We have made great strides in better understanding what is required for science teaching to effect student understanding in science (Mintzes, Wandersee, & Novak, 1998; Bransford, Brown & Cocking, 1999). We have also made progress in identifying better ways to assess students' understanding of science (Mintzes, Wandersee & Novak, 2000). What is needed now is a new longitudinal study utilizing the latest technology resources to provide the kind of instruction and guidance to teachers and students that could only be done rather crudely with audio-tutorial instruction, albeit the latter was shown to be effective in our work and the work of others (Fisher & MacWhinney, 1976). This new kind of program is described below.

Another significant outcome of the study was to illustrate the power of carefully designed, technologically mediated instruction. While admittedly we dealt with only a limited domain of science, we chose to focus upon the domain of molecular kinetics and energy transformations since this is a notoriously difficult area of instruction in science, especially at the elementary school level. Furthermore, an understanding of these ideas is essential to understanding almost all science phenomena.

There was in our data strong support for the principal ideas in Ausubel's Assimilation Theory of cognitive development and general support for the value of cognitive over behavioral psychological theories. Here again the psychological landscape has changed quite dramatically since the 1960s, with virtually all educational psychologists moving to embrace *cognitive* theories of learning by 1990. In short, the cognitive learning and development ideas that were the foundation of our 12-year longitudinal study are now generally accepted, albeit much of this acceptance was based on hundreds of mostly short term "experiments" done by psychologists and educators, and many of these studies were driven by essentially positivistic epistemological assumptions. Nevertheless, there remains considerable debate in science education circles on the cognitive limitations of young children, and therefore what science should be taught in early grades. In my view, the American Association for the Advancement of Science's *Benchmarks* (1993) and *Atlas* (2001) and the National Research Council's *Standards* (1996) grossly underestimate the conceptual learning capability of younger children and unnecessarily and unwisely recommend postponement of instruction in basic energy and molecular kinetics ideas until the middle school years. This precludes the early development of these fundamental concepts needed to understand almost any of the concepts in science, and relegates the early years largely to descriptive studies of biological and physical phenomena. Our 12-year study, and the research of others noted earlier, would argue against postponing instruction in molecular kinetics concepts, as well as other basic science concepts.

Implications for Mathematics Education

We believe that our work in science education has important implications for mathematics education. First, it was clear that children's ability to operate materials and interpret events could be shown to be dependent on the development of appropriate concept and propositional frameworks and these defined the meanings for science concepts the children were building over the years. These meanings and their progressive development could be observed from interviews using the concept map tool. We believe the same kind of results could be shown for the development of mathematics concepts, since we believe the same psychological and epistemological factors operate in mathematics and other disciplines as well. The tragedy we see is that most school mathematics teaching focuses on drill and practice of *procedures*, rather than on developing conceptual understanding. To illustrate, consider the very fundamental ideas associated with understanding the concept number. Figure 4 shows some of the key concepts that need to

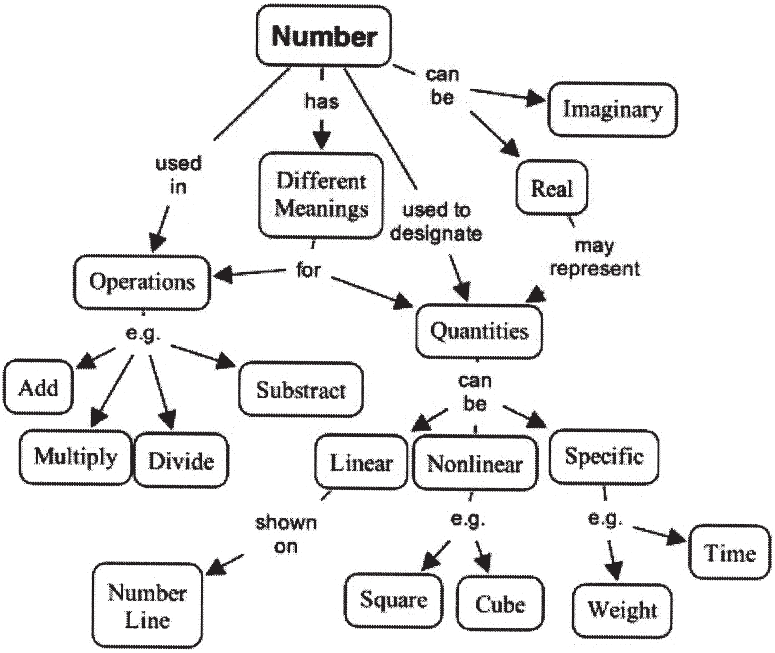

Figure 4. Some of the key concepts that are needed to understand the nature of numbers.

be understood and related to understand the nature of numbers and operations using numbers.

Many elementary school classes introduce the idea of number using rods, marbles, strips of paper, etc. Such hands-on activities function to integrate thinking freely and acting to construct meanings. However, most of the time such activities are not accompanied by introduction of appropriate concept labels and concept relationships. The result is that students learn to manipulate the objects according to some procedural rules, but they fail to build an understanding of the mathematical concepts. For example, Tzur and Simon (2004) discuss the "The Next Day Phenomenon" illustrated when students partition strips of paper into either 6 or 8 pieces. They subsequently easily recognize that 1/6 is greater than 1/8 because they saw that the latter strips were smaller than those cut into sixths. However, when asked the next day which is larger, 1/5 or 1/7, they usually fail to transfer their learning to give a correct answer. Tzur and Simon attribute this failure to develop to an *anticipatory stage* in cognitive development, following ideas of Piaget and other mathematics educators. From an Ausubelian perspective, the learners simply have failed to develop a concept of division as it applies to a linear object. They do not recognize fractions as representative of a kind of division example, nor are they developing their concept of division. These students would be even more frustrated when asked to compare 3/5 with 3/7 or 21/35 with 55/77. Needless to say, they are unlikely to relate any of these fractions to subtraction or multiplications operations. If instead, the concept map shown in Figure 4 was used as a scaffold for student learning and then various activities such as cutting paper strips were to be represented on this scaffold as students progressed in their work, we could anticipate learning that more closely followed what we are finding in science when this kind of learning facilitation is provided along with appropriate hands-on activities and problem exercises. Yang, Hsu, and Huang (2004) found that engaging sixth grade students in real world experiences significantly increase their number sense. The kind of activities they describe, together with the use of concept maps could be especially effective. David Ferrer in Mexico has found concept maps helpful in teaching vector analysis, and examples of his work can be seen at http://www.geocities.com/dmacias_iest/Conceptual.html

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Development of a New Model of Education

Vygotsky (1928 in Russian; 1978 translated) introduced the idea of the "zone of proximal development" (ZPD), implying understandings a child has that can be built upon for further cognitive development. He anticipated Ausubel's idea that meaningful learning must begin with what the learner already knows. One of the values of concept maps is that when children construct their own concept maps for a question or problem in any domain, they reveal with considerable specificity what is their developmental potential for the topic of study. Thus we are provided with a clear view of "what the learner knows" and we can design instruction to build upon this. We generally recommend that children build concept maps in small groups, since the exchange that occurs between children can often serve to correct faulty ideas and promote meaningful learning. In part this results from the fact that the cooperating students are at approximately the same level of understanding, much more so than teacher and student. Cooperative learning confers an advantage to students over the usual independent, competitive teaching approaches (Cañas, Ford, Novak, Hayes, Reichherzer, & Suri, 2001; Qin, Johnson, & Johnson, 1995).

Another use of concept maps is to provide maps made by experts to serve to "scaffold" learning of students (O'Donnell, Dansereau & Hall, 2002). The idea of "scaffolding" learning goes back to early studies by Vygotsky where he described his studies showing that language and the social exchange using language can significantly enhance children's cognitive development. Through proper use of language, adults can "scaffold" the learning of concepts by children. Although we were not aware of the scaffolding and ZPD ideas when we designed the audio-tutorial lessons, we were doing things congruent with these ideas. When we were designing our audio-tutorial lessons, we interviewed children to see what their thinking was about a particular concept or problem and then designed experiences that would build on what they knew and would extend their ideas by providing hands-on experiences and appropriate scientific vocabulary to explain the events they were observing. Perhaps one of the reasons the relatively brief instructional experiences children had in audio-tutorial lessons in grade one and two had such a sustained impact on their later learning in sciences was that we were on the right track in working within children's ZPD and using activities and appropriate language to scaffold their learning. The audio-tutorial lessons could also be considered a kind of "coaching" as students studied and manipulated materials. In general, the literature on coaching students using various approaches shows significant facilitation of learning (Bransford, et al., 1999). Given the extraordinary range of learning activities that can now be facilitated and integrated using Cmap Tools, we believe that even greater advantage of Vygotsky's ideas and ideas from the literature on coaching can be incorporated into instruction.

Over the years that our longitudinal study was in progress, we became increasingly aware of the extent to which school learning programs lead most students into predominantly rote models of learning. Some children, for reasons of their genetic make-up or early childhood experiences, resist the effect of school instructional and assessment practices that push students towards rote learning patterns. We have found that interviews and questionnaires can be used to assess individual's proclivities to learn by rote or meaningfully, with most people falling somewhere along a continuum from very rote learners to highly meaningful learners (Bretz, 1994; Edmondson & Novak, 1993). We wish now we had been more aware of the problem of commitment to rote learning and had made assessments of our students in grades one and subsequently of their preferred learning approach. It is likely that such data would have tracked well those students who progressed in their conceptual understandings over the 12 years, and those students who made little progress in their conceptual understanding. While it may be wishful thinking to consider that the audio-tutorial program would have shifted some children's patterns toward meaningful learning, it would have been wise to at least monitor their subject's disposition to learn with greater or lesser commitment to meaningful learning.

We have also found in our more recent research that it is useful to assess individuals' commitments to constructivist versus positivistic epistemological views (Chang, 1995; Edmondson and Novak, 1993). In general, we observe that learners who are more constructivist in their epistemological orientation are also more likely to employ meaningful learning strategies than learners who are more positivistic in their orientation. In recent years there has been a large increase in papers published in the *Journal of Research in Science Teaching* dealing with epistemological issues, including a recent paper by Sandoval and Morrison (2003) that deals with the relationship between learning approach and epistemological views held by students. I would urge researchers doing future longitudinal studies to include measures of learners' epistemological ideas, as well as their learning approach.

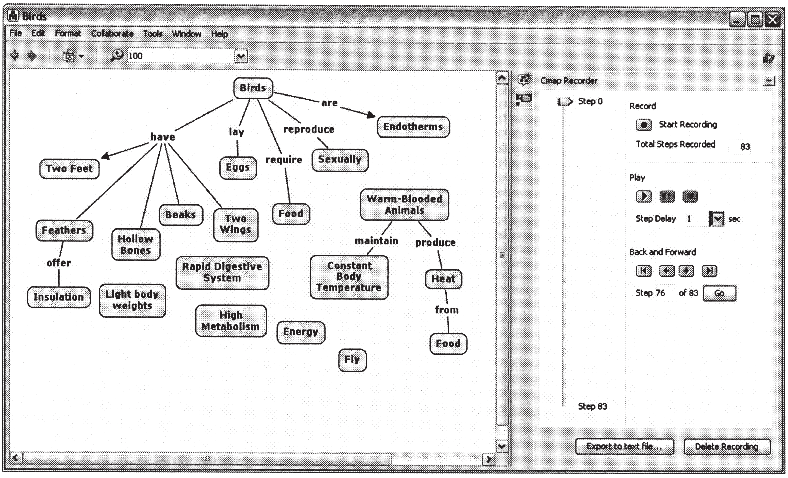
Audio-tutorial technology is now obsolete, and we have vastly more opportunity to facilitate learning in the sciences as well as in other fields using computer guided instructional strategies and excellent software available for concept mapping, such as the Cmap Tools (Cañas et al., 2004) software available to schools at no cost from the Institute for Human and Machine Cognition (www.ihmc.us). I see great promise for instructional strategies that combine the use of "expert" concept maps to scaffold student (and teacher) learning using the Internet in conjunction with Cmap Tools software, inquiry activities and collaborative learning, as I have described elsewhere (Novak, 1998, 2003). These new tools and approaches should provide some very exciting research opportunities for future longitudinal studies that show the potential that young minds possess that are not being developed adequately in schools today.

Cmap Tools supports the construction of *knowledge models*: sets of concepts maps and associated resources about a particular topic (Cañas, Hill, & Lott, 2003). Through simple drag-and-drop operations students can link all types of media (images, videos, text, web pages, documents, presentations, etc.) and concept maps, whether theirs or constructed by others, to their maps. These resources can be located anywhere on the Internet.

Novak and Gowin (1984, Chapter 2) have decided the act of mapping as a creative activity, in which the learner must exert effort to clarify meanings, by identifying important concepts, relationships, and structure within a specified domain of knowledge. Knowledge creation requires a high level of *meaningful learning*, and concept maps facilitate the process of knowledge creation for individuals and for scholars in a discipline (Novak, 1993). Educators have recognized that it is the *process of creating* a concept map that is important, not just the final product. However, in many cases the teacher cannot accompany the students during the process of concept mapping, whether it is because there are too many students, the student is doing the work at home, or the learning is taking place at a distance. Cmap Tools provides the capability of "recording" the process of constructing a concept map, allowing for a graphical "playback" at a later time, controlling the speed and moving forward or backwards as needed. Figure 5 shows at the right the pane that allows the user to control the recording. In this example, the student has taken 83 steps to reach this point in the map construction, and pressing on the playback button will start showing step by step the complete process of map construction. The recording is saved with the concept map, so if it is copied or moved the recording is not lost. The playback also identifies which user performed each step, which is essential to support collaborative work. In effect, the playback of concept maps created by an individual reveals the processes by which meaningful learning was occurring.

Despite the free-style format that concept maps can take, specific characteristics of well-constructed maps (structure, semantics, context, etc.) provide an abundance of information on which to develop smart tools that aid the user in the process of constructing concept maps (Cañas & Carvalho, 2004). One such tool allows the user to select a concept in a map and search the Internet and Places (CmapServers) for information (including concept maps) that are related to the concepts selected, taking into account the context of the concept map itself (Carvalho, Hewett, & Cañas, 2001). That is, the program tries to determine "what the concept map is about" and performs a query accordingly. Researching a topic can begin by constructing a small map and using the research to locate information related to the map. The information retrieved can then be used to improve the map, and the cycle continues. By linking relevant resources found onto the map itself, the concept map becomes the centerpiece of the research endeavor. Figure 6 illustrates how many of the activities in learning can be integrated through the structure of a concept map built with Cmap Tools.

The program contains other features that support the user, whether a student, teacher or instructor, in the use of concept mapping in an educational environment, such as a map-comparison module and automatic generation



Total Steps Recorded 83

Step Delay 1 sec

Step 76 of 83

Figure 5. The Recorder feature of CmapTools allows the graphical playback of the steps in the construction of a concept map. This feature can be used by map makers to review their progress, or by teachers and researchers to study contributions by individuals over time.

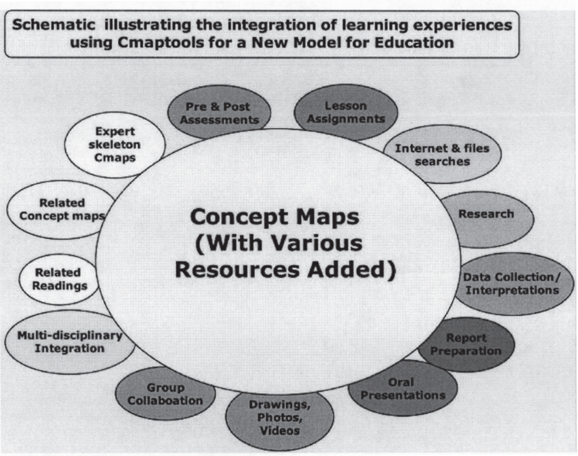


Figure 6. The whole spectrum of learning activities can be integrated using Cmap Tools, incorporating various learning activities recorded via the software creating a digital portfolio as a product of the learning.

of an HTML version of the concept map when stored in Place. For the purpose supporting the ideas presented in this paper, we consider that the combination of the collaboration tools, the knowledge model construction features, and the search mechanism provide a strong foundation on which to build on the "expert" map scaffolding ideas in the New Model for Education described in the following sections. Using "expert skeletal" concept maps to scaffold student and teacher earning, Scardamalia and Bereitere (1993) have suggested how technology might be used by students or other learners to help build their knowledge, and we believe that Cmap Tools greatly extends this capability.

During the last 20 years of teaching at Cornell University, I taught a course called "Learning to Learn". The book, *Learning How to Learn* (Novak, & Gowin, 1984), derived in large part from experiences teaching the course. One of the techniques I found most helpful to students was to prepare concept maps showing key ideas and their relationships. These were not complete maps, just the key concepts. Students were asked to add concepts to the professor's maps and restructure the map in ways that would make the most sense to them. The exams in this course typically provided the students with a list of 20-25 concepts, and they were asked to build a concept map using these concepts and additional concepts they wished to add. Students were also asked to select a "learning partner", since considerable research supports the value of cooperative learning (Qin, et al., 1995). It was impractical in terms of student schedules to form learning groups larger than two, although sometimes the students took the initiative to meet in groups of 4 to 6, usually comprising 2 to 3 learning partner teams. Course evaluations repeatedly commented on the value of the learning partner arrangement, and in fact a few of these led to later marriage of the learning partners. Examples of the kind of concept maps that were used with students can be seen on the Cmap Tools Network[2].

In general, the literature on coaching students using various approaches shows significant facilitation of learning (Bransford, et al., 1999). Given the extraordinary range of learning activities that can now be facilitated and integrated using Cmap Tools, we believe that even greater advantage of Vygotsky's ideas and ideas from the literature on coaching can be incorporated into instruction.

Our plans are to begin developing expert skeletal concept maps in the area of science, since science is universal and it is also a subject poorly taught, especially at the elementary school level. The same could be said for mathematics, and this might be the second area to be developed. We estimate that the project would require some 300 expert concept maps to provide reasonable coverage of all areas of science for grades one through twelve, or ages 6 through 18. Similar expert concept maps for mathematics may require less than 200 to cover most of the field of school mathematics. One reason that we see child prodigies in mathematics but not in the sciences may be that they do not need the years of study to build up the large array of concepts and propositional structures necessary for understanding science (history, literature or other more conceptually complex disciplines). There are many scientists who have already prepared concept maps for specific disciplines, so this would be an easy starting point, although many of the maps might need some revisions to make a better fit with the project. Unfortunately, there are far fewer experts in mathematics using concept maps at this time. Also, we would need to prepare some "global" concept maps to give a broad conceptual overview of science or sub-domains of science, and similar global concept maps for mathematics. Figure 7 is an example of one such global concept map. Figure 8 shows a concept map dealing with the kind of energy transformation we call photosynthesis, and could represent a sub-map for Figure 7.

Pérez et al. (Pérez, Suero, Montanero, & Fernández, 2000) report on using concept maps to scaffold university and high school student's learning of physics for more than a decade. Although their students did not use computer software, their feedback indicated better understanding of physics concepts with the use of concept maps. They are now moving towards leveraging the use of Cmap Tools and technology (Pérez, Suero, Montanero, & Pardo, 2004). O'Donnell, et al. (2002) report on a study where a kind of concept mapping was used successfully to scaffold learning. A number of other school and university teachers have reported on using scaffolding approaches with

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[2] Place: IHMC Public Cmaps (2), Folder: JDN's LCKKnowledge.

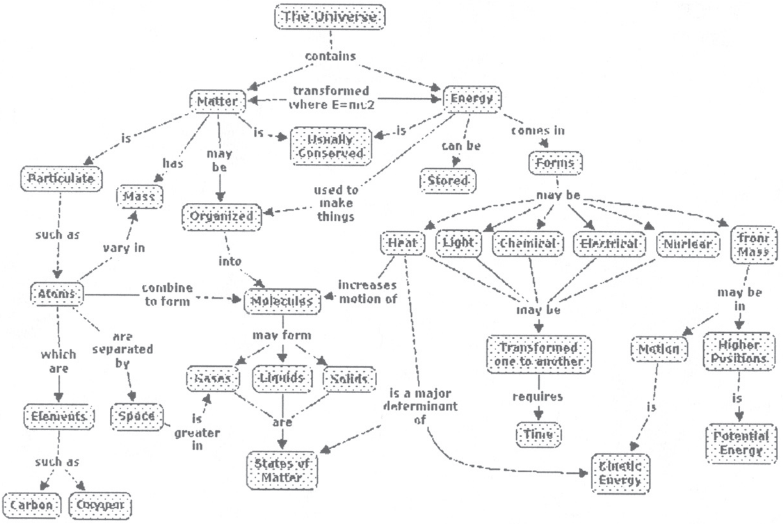

Figure 7. A "global" concept map presenting the major concepts needed to understand most areas of science. This map will need to be revised as string theory in physics gains greater acceptance.

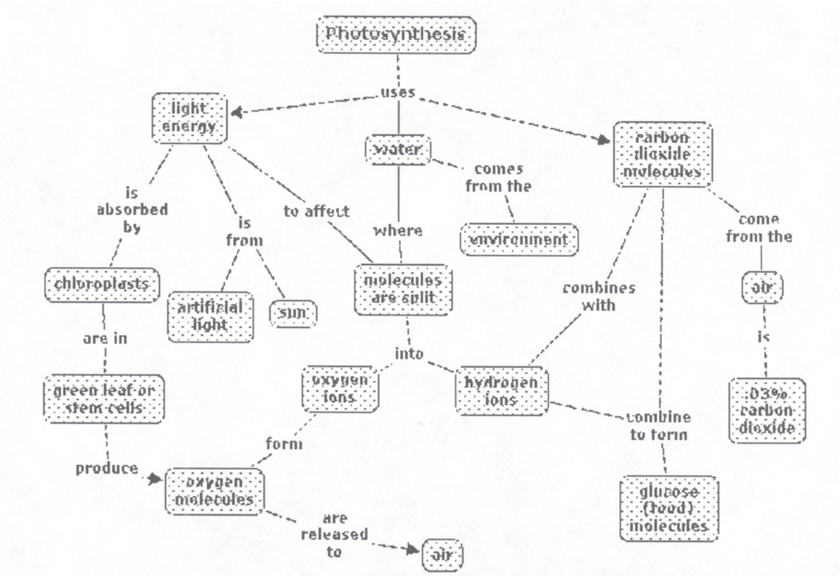

Figure 8. An example of a sub-concept map for Figure 7, dealing with one form of energy transformation done by green plants called photosynthesis. This concept map can be attached to the concept light energy in Figure 7 as an icon that opens this map when clicked.

concept maps, but little empirical data is available at this time. Therefore, we proceed with this approach with the support of underlying theoretical ideas, and indirect empirical support such as can be found in some of our research (Bascones & Novak, 1985; Novak & Musonda, 1991). The Bascones and Novak study showed approximately 100% greater improvement in problem solving scores for high school physics students using concept mapping, compared with students doing traditional exercises. The Novak and Musonda study showed that students taught with audio-tutorial methods in grade one and two achieved 100% or more improvement in understanding of molecular kinetic concepts when compared over twelve school years with students who did not receive this early science instruction. The latter study illustrates in part that technologically mediated instruction can be very effective. The two studies and other similar research show the huge unattained learning improvement potentials that currently exist for the improvement of teaching and learning. No study has looked at the learning improvement that could be attained by applying the best technology and the best pedagogy over the 12-year span of schooling, but the studies that exist suggest that such learning augmentation can approach an order of magnitude greater than that now commonly observed.

An important advantage of organizing instruction beginning with an expert concept map is that learners and teachers almost always have faulty knowledge or misconceptions in virtually every domain of knowledge that has been studied. Research has also shown that these misconceptions are notoriously difficult to overcome with traditional instruction (Novak, 1977; Novak, 2002). The use of concept maps has been shown to be effective for remediating misconceptions, especially when learners begin with a valid "expert" concept map and when they work collaboratively to construct a new knowledge model. We are currently working with a number of organizations that are building on what we know about learning, creating, and using knowledge (Novak, 1998), and developing sets of expert concept maps for training new workers and other purposes.

The World of Science Project

During the early 1960s, I wrote a series of elementary science books that had been published first by Bobbs-Merrill as The Wonderworld of Science, which was a fairly traditional elementary science book series. Most elementary school science textbooks cover many, many topics of science very superficially. None of these books present basic concepts of atoms and molecules and the nature of energy and energy transformations in early grades. Without introducing these concepts, it is essentially impossible to provide *explanations* of why things in the universe behave as they do. Wonderworld was an apt name for the early Bobbs-Merrill books as well as all other 28 elementary science series that were on the market in the 1960s, since they did little go explain why things in the universe work the way they do. Indeed, this remains the case today for most elementary school science programs! The problem of superficial coverage of science topics was also recognized by the Curriculum Committee of the National Science Teachers Association and their plan to build science instruction on "basic conceptual schemes" (Novak, 1964). Ausubel's (Ausubel, 1963, 1968) cognitive learning theory was published in 1963, and this became a foundation for final writing in the books for The World of Science. I sought to take many of the good illustrations, activities and ideas in the Wonderland of Science books to rewrite the books to include information and activities that would illustrate the particulate nature of matter, energy and energy transformations, and the interplay of energy and matter in living and non-living systems. After 4 years of writing and editing, the *World of Science* was published in 1966. Unfortunately, Bobbs-Merrill was sold to another company in 1968 and this company decided not to market the World of Science books, nevertheless, the books began to enjoy some success in elementary school classrooms in the USA, and later served as the primary foundation for audio-tutorial lessons designed for our 12-year longitudinal study (Novak, 2004a; Novak & Musonda, 1991). All of these books have now been scanned and we hope to make them publicly available soon at the IHMC web site (www.ihmc.us).

Our plan is to use The World of Science book as a starting point for a demonstration project for **A New Model for Education**. To begin, concept maps have been prepared for all sections of the grade two book of the World of Science entitled *The Exciting World of Science*. All concept maps are

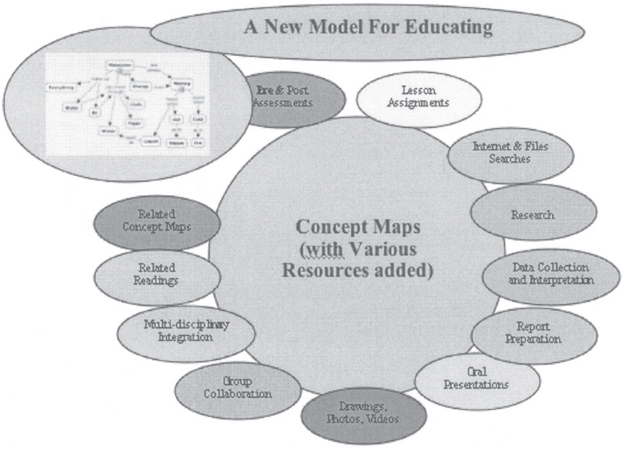

Figure 9. Schema showing the New Model for Education with a "skelton expert" concept map.

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[3] Place: IHMC Public Cmaps (2), Folder: The World of Science.

publicly available on the Cmap Tools Network[3]. The concept maps would serve as a starting point for students and teachers for each section illustrated in the book, and then students would use these Cmaps together with Cmap Tools to search the Internet for pertinent resources and ideas. Figure 9 illustrates one of the "expert skeleton" concept maps that could be used as the starting point for building a knowledge model, preferably with students working in teams and sharing ideas.

The science books provide relevant readings and suggested activities. It would be important for the teacher to help students perform these activities, and similar related activities, some of which might be suggested in Internet resources. Learners would also add their own concepts to the expert skeleton concept map, as well as resources identified in readings and from the Internet. Figure 10 illustrates a stage in this process.

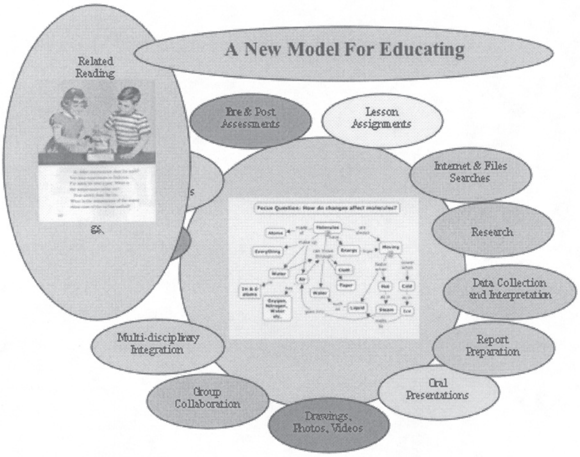

Figure 10. Schema showing the New Model for Education with a concept map and resources added to the "expert skeleton" concept map, plus a page from a World of Science book providing relevant reading and activities.

Obviously, it would be a very deficient science program that did nothing more than to have students copy and do some building on the expert skeleton concept maps provided for grade two, or for any other grade. Students need concrete, hands on experiences with real things and to observe real phenomena to put meaning into the concept labels provided in the concept maps and other resources. Figure 11 shows a concept map illustrating some of the key features of Novak's New Model for Education. When online, clicking on the icons on concepts provides additional information. Other concept maps for the New Model for Education can be found at Cmap Tools Network[4].

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[4] Place: IHMC Public Cmaps (2), Folder: Novak's New Model of Education.

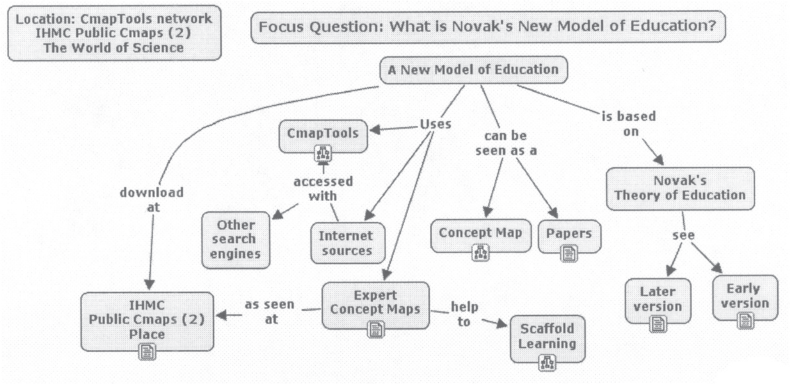

Figure 11. A concept map showing some of the key features of Novak's New Model for Education. When online, the icons below concepts lead to additional information.

A pilot program effort is already in progress in Italy, where Giuseppe Valittuti (2004) is now working to translate The World of Science books into Italian. Valittuti and his colleagues have obtained funding from the Italian Ministry of Education for teacher training and expect a number of elementary school teams to begin working with the World of Science concept maps and other resources during the year. The plan is to have four sets of schools focus on different aspects of The World of Science series and produce photos and videos of students doing projects that illustrate and utilize the various science concepts. There will be much feedback from classrooms helping the teams to refine their work, sharing "electronic portfolios" using Cmap Tools. This feedback should help us to rapidly refine concept maps, techniques and approaches for improving practice of the New Model for Education. The Cmap Tools Network may serve as a clearinghouse for some of these efforts through its Public servers in Italy and other countries. We anticipate that an abundance of both anecdotal and empirical data will flow from these efforts in a few years. Based on the solid theoretical and related research findings now available, there is every reason to be optimistic that these innovative efforts will be successful. A similar program is now underway in Panamanian schools and this work can be monitored at:

http://200.46.157.52:8001/servlet/SBReadResourceServlet?viewhtml

Problems of Implementation

The greatest challenge we may expect is to change the school situational factors in the direction of teacher as coach and learner from the prevailing model of teacher as disseminator of information. We know that we need to engage teachers and administrators in training programs that can model the new educational approaches, and we also need to seek their counsel on ways to improve on the New Model for Education. There is also the challenge of changing assessment practices that now rely primarily on multiple-choice tests that measure mainly rote recall of information, to performance-based tests that require students to demonstrate that they understand basic concepts and can use these concepts in novel problem solving, and that they can use Internet resources to grow and modify their concepts and learn new concepts. There remains in the New Model plenty of room for acquisition of specific facts and procedures, but now these should be learned within the context of powerful conceptual frameworks. Research (Bransford et al., 1999) has shown that factual information acquired in a context of meaningful learning is not only retained longer, but this information can be used much more successfully to solve new problems. In Panama, we are finding that a three week workshop is sufficient to train teachers and teacher trainers to use Cmap Tools and to begin to implement A New Model for Education.

Even with the current state of technology and pedagogical understandings, it is possible for schools, states or countries to mount a New Model for Education. In some poor countries, new technology is providing new communication capabilities. Rater than installing expensive phone lines and cables, use of cell phones is simply stepping over one hundred years of communication technology used in more affluent countries. Cell phones and cheap hard drive capacity is making possible transmission of large quantities of information including information from the Internet.
(see for example:
http://www.wired.com/news/print/0,1294,63131,00.html)

Even in these poor countries, a New Model for Education can be introduced, and the enormous problems they have with poor school facilities, lack of books and highly trained teachers and other things the affluent countries have thought as essential can be largely obviated by emerging technologies. In fact, it may be that the poorer countries will be the first to embrace that what is relatively expensive and difficult today will become an order of magnitude less costly, and more effective in a relatively few years. Furthermore, research on teaching and learning is improving, and this too will contribute to greater effectiveness. The rate and kind of new technological advances is difficult to predict, but the history of the past few decades can serve as a model of where we might expect to be in 10 or 20 years, if we begin to exploit more fully the technologies and ideas available today. The possibilities are enormous; what we need is good leadership.

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