Classroom Strategies for Simulation-Based Collaborative Inquiry Learning

Tom Murray, Larry Winship, Neil Stillings,
Esther Shartar, Ayala Galton

Hampshire College School of Cognitive Science, Amherst, MA 01002
tmurray@hampshire.edu, http://helios.hampshire.edu /~tjmCCS/

Abstract. Computer-based simulations can provide an excellent context for collaborative inquiry learning. However, there has been little research to identify and characterize classroom teaching strategies in this context. In this paper we report on an analysis of an expert teacher in inquiry-based methods using SimForest, a simulation-based learning environment in the domain of forest ecology. We identify a number of strategies and important pedagogical factors, including these strategies for distributed classroom problem solving: alternating convergent and divergent activities, additive knowledge, breadth search, simulated annealing, jigsaw method state space search, and collaborative hypothesis confirmation. We also describe how these strategies were introduced in a professional development workshop which lead to classroom implementations of the software and associated curriculum materials.

Introduction

Progressive educational theories stress the importance of student-active learning and inquiry-based science education (McNeal & D'Avanzo, 1996; National Research Council, 1996; AAAS, 1993). Instructional methods called inquiry-based, problem-based, case-based, project-based, and discovery-based share many of the same features and address many of the same skills. The 'classic' scientific inquiry learning cycle can be described as including these steps/skills: posing good questions and hypotheses, planning how to answer the question or test the hypothesis, observing and gathering information, systematically analyzing information, and communicating one's conclusions, which inevitably points to more questions which starts another inquiry cycle (Tabak et al. 1996, Collins & Stevens 1993, White & Frederiksen 1986, 1995). Inquiry-based science experiences conducted in relevant, meaningful contexts have been shown to develop higher order thinking skills and more sophisticated epistemological understandings (Roth & Roychoudhury, 1993; Stillings et al. 1999, 200; Smith et al. 2000). Using inquiry methods to support learning in more authentic, realistic, meaningful, and context-rich situations can enhance motivation, retention, transfer, and depth of learning (Blumfeld et al. 2000; Haury 1993; Krajcik et al. 1998; McNeal & D'Avanzo 1996). Though usually discussed in terms of science learning, these skills are important to almost all subject areas, including the humanities (Prince & Kelley 1996).

Social constructivist theories emphasize the importance of collaborative knowledge building, and inquiry learning is often prescribed in collaborative learning contexts. Inquiry involves many sub-skills, each of which must be practiced with appropriate feedback in order to be mastered. For example: posing valid (clear, confirmable) questions and hypotheses ,and dealing with errors, noise, and outliers in data (for a more complete list see Murray et al. 2003A). Students need to practice these skills numerous times to gain proficiency.

Computer-based simulations can provide an excellent context for collaborative inquiry learning. Though many educational computer-based simulations have been developed, they are not frequently used as intended in classrooms. The existence of the simulation is not enough, as appropriate curriculum and classroom pedagogies must be developed and used. Instructors must use skill in the selection of learning tasks and in classroom pedagogy and social management techniques. Most teachers are not sufficiently skilled in these areas, so professional development training is essential. In the case of using simulation-based learning environments used to teach inquiry skills and collaborative problem solving skills, there has been little research to identify and characterize classroom teaching strategies.

This paper reports on some of the results of a research project involving these development and implementation phases: the development of a sophisticated simulation-based learning environment, development of curriculum materials and activities surrounding the software, software evaluation in college biology classrooms, a summer professional development institute teaching secondary school teachers how to implement the software and curriculum, and a study following these teachers as they used the software in their class over two semesters. In this paper we focus on one aspect of this project: the characterization of diverse pedagogical strategies used by an expert teacher to support simulation-based collaborative inquiry learning.

The SimForest Software

The use of computer simulations for education, training, and performance support is widespread (Strafford 1997, Gery 1991). Simulations may be used to emphasize subject matter skills and concepts and to promote generic skills such as inquiry, problem solving, and metacognition. In particular, computer simulations and learning environments provide unique opportunities to practice scientific inquiry skills (see Alloway et al. 1996; Edelson et al. 1999; Gomez et al. 2000; White & Frederiksen 1995; Wilenski & Resnick 1999; Perkins 1986). For this project, a significant potential benefit of simulation-based learning is that, compared to "wet labs," more "inquiry cycles" can be practiced in a given time period. Since, as mentioned above, it takes many iterations of exposure to learn the subskills of inquiry, simulations have the potential to accelerate the learning of inquiry skills and other higher order skills. In addition to allowing more repetitions of the inquiry cycle, each cycle is more compact and thus feedback on the success of the entire cycle can be more immediate. Note that we strongly advocate that students experience phenomena in the real world first if possible before simulating it on a computer, so that the relevance and limitations of the computer simulation are grounded. We incorporated this philosophy into our curriculum material and professional development workshop be providing and modeling sample outdoor activities along with the computer-based activities.

SimForest is a simulation-based learning environment in the domain of forest ecology that simulates tree and forest growth, the succession of tree species over time, and the effects of environmental and man made disturbances on forest growth (see Figure 1).[1] The simulation is based on the Gap Phase Model of Botkin (1993). With the simulation students can set environmental parameters such as rainfall, temperature, soil fertility, soil texture, and soil depth; they plant (or load in from a file) a plot of trees from a list of over 30 species; and they "run" the simulation and observe the trees as they grow and the forest evolves. A forest plot's sensitivity to natural and man-made disturbances can be evaluated, and emergent properties such as species succession can be observed. The model is complex enough to allow for interesting and relatively accurate emergent phenomena. For instance, if one removes all the trees of a particular species (as if from a blight) or size (as in timber harvesting) one might observe that 50 years later the character of the forest changes, with certain other species disappearing and new one's emerging (as compared to what would have happened 50 years later without that disturbance).

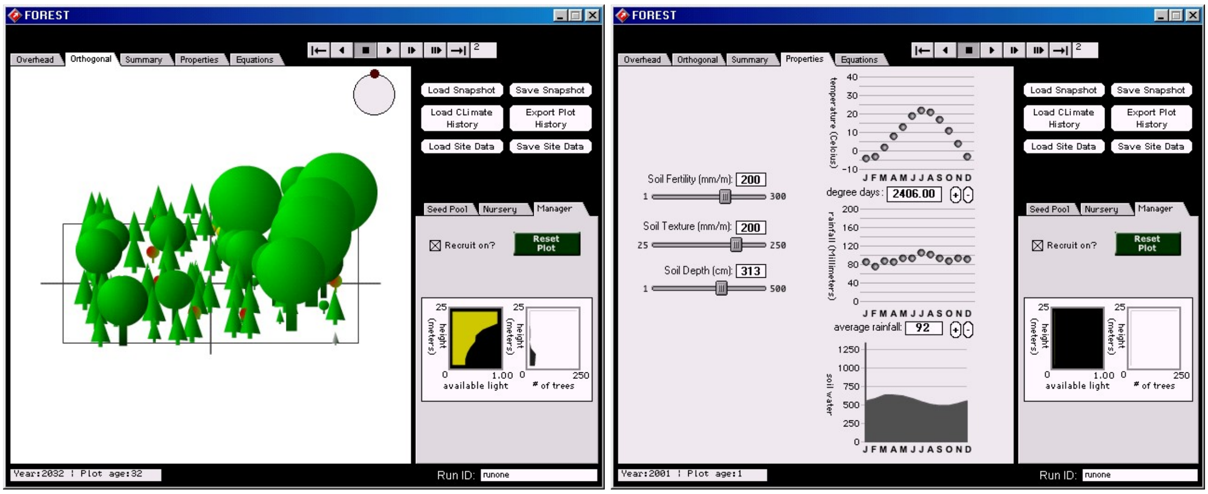

Figure 1 SimForest Orthogonal View and Site Properties Window

SimForest can be used for a wide variety of engaging learning activities, applicable to many grade levels and related subject areas. We have tested it in grades 7, 8, 10, and with college freshmen, and we have designed activities that would provide appropriate learning challenges for grades as low as 4th and as high as first year graduate school. It is applicable for High School biology and ecology courses; and College ecology, botany, forestry, forest ecology, and land use planning courses. The interface itself is simple and highly usable. However, unlike many other educational simulations, there are a large number of both input parameters (initial conditions of trees and site conditions) and output properties (what can be observed or measured). This diversity provides both flexible

[1] The software is available for download at http://helios.hampshire.edu/~tjmCCS/simforest/

opportunities and challenges for students and teachers. Students with an initial question such as "what are the effects of global warming?" must refine this question in terms of what parameters they will manipulate to answer their question in order to specify a clear hypothesis and experimental plan. Then they must decide which of the many output properties (number of trees, species diversity, average height, weight, or diameter of each species, etc.) they will measure.

Teachers, in their attempts to develop clear activities, pose driving questions, and provide scaffolding, must make similar decisions. This is the case for many simulation-based learning situations (and most wet-lab situations as well). Our approach to dissemination and teacher training was a combination of constructivist professional development and a-la-carte curriculum materials (see Garet et al. 2001; Howe & Stubbs 1996; Simon 2000). We:

- exposed teachers to various lessons and instructional methods by demonstrating these with them taking the roles of both students and, later, teachers;
- provided activity examples and templates (these were indexed by goal topic and skill); and
- provided teaching hints and pedagogy-based explanations to help them adapt the materials and methods that we offered to their own situations.

In order to do this we first had to articulate the activities and teaching methods ourselves. The development of driving questions and activities was a brainstorming and trial and error process that came relatively directly from the nature of the simulation, the learning goals, and past teaching experience of team members. But articulating general pedagogical strategies and classroom management techniques was more difficult. As mentioned above, there is little previous research in this area for collaborative simulation-based inquiry learning. What we decided to do was to document and analyze the teaching behavior of one of our project team members, who was an acknowledged practical expert in inquiry-based and collaborative classroom methods. We later introduced these methods to other teachers who adopted them to successfully use in their own classes (see Murray et al. 2003B), but this paper focuses on the evaluation of the expert teacher's behavior.

Method

As mentioned, the method that we focus on in this paper is that of studying the behavior of an expert in order to discover and make explicit certain modes of action and action structures. We report on a multi-case study of a single expert teaching a number of classes. A primary goal of this phase of our research was to document a variety of inquiry-based methods for using simulations in the classroom. In the fashion of "action research" (Cobb 2000; Feldman & Minstrell 2000) the instructor was both a subject of study and a participant in developing the study. In planning each learning session (classroom and clinical) he varied the methods that he prepared to use, often adapting the lesson plan based on what was learned in previous sessions, thus allowing us to observe a variety of activities and "driving questions" (Soloway et al. 1997). However, though some pre-planning was involved, much of each session involved responding and adapting dynamically to the needs of the students as they engaged in open ended tasks. To situate the cases study, and to provide evidence that the sessions we observed provide reasonable data for "best practice" recommendations, we briefly describe the instructor.

Description of the case study instructor. All of the college level sessions were lead by Larry Winship, a Hampshire College Professor of Botany who has substantial familiarity with computers (in past decades he found himself writing Fortran code as part of his botany research). He had not used simulation-based software very extensively in his teaching in the past (though spreadsheets and web searches are commonly used). However, he was the content expert on SimForest design team, and thus he knew the SimForest software intimately and had been considering how it could be used in instruction for some time. This professor (who we will usually refer to as "the instructor") is considered an expert in inquiry-based science teaching methods, as are many of the Natural Science professors at Hampshire College. In a later Section we discuss the extend to which the observed teaching strategies of this instructor could reasonably be expected transferred to other instructors.

Overview of case study sessions. Over five semesters (3 years) we completed five rounds of qualitative evaluation of the SimForest-B software with college students. The sessions lasted from 1.5 to 2 hours. Three of the sessions were in a Hampshire College 100-level course titled "The Ecology of Old Growth Forests" which was taught by Winship, and was attended by a mix of college freshmen and sophomores. The other two sessions were in clinical settings in which we observed students using the software (the subjects were paid for participating). The clinical sessions were set up like classes, sometimes starting with Winship giving an introduction to important botany concepts, and continuing in a way similar to his classroom teaching style. Data gathered included: observational notes, transcribed video tapes, focus group observation notes, and student feedback questionnaires. Table 1 summarizes these trials (Trials 4.1 and 4.2 were done in the same week, but the participants were split into two groups due to scheduling difficulties). In all sessions students worked in pairs or threes (except for an occasional classroom student who wanted to work on his or her own). All trails involved a minimum of "lecture style" and a series of open-ended tasks to be done using the simulation, punctuated with periods of bringing the entire class together to discuss and harvest what they had discovered. During the exploratory tasks the instructor walked around the class to answer questions and give hints when students were stuck or at a "teachable moment." Occasionally the instructor interrupted the independent exploratory work to share with the entire class some information that was inspired by an individual's question. After each session or series of sessions students were asked to give general feedback on their experiences in a focus-group fashion. In several of the sessions one or two video cameras were set up, each observing one pair of students and the computer screen.

Eval Trial	Type	# of sessions	N	Data types
1	class	2	7	O,V,Q,F
2	clinical	2	6	O,V,F
3	class	3	16	O,V
4.1	clinical	3	3	O,F
4.2	clinical	3	4	O,F
5	class	1	15	O

Table 1: Summary of SimForest College Student Trials
(O-observation notes, V-video transcripts, Q-questionnaire, F-focus group)

The five evaluation sessions followed several informal pilot tests that were used to work our some software usability bugs (small software improvements were also made between these trials). Our observations and analysis of the college sessions taught by the inquiry teaching "expert" were incorporated in to the design of curriculum activity structures and collaborative inquiry pedagogical methods that were introduced to secondary school teachers during a one week summer institute. After the summer institute we supported and evaluated the use of the software in the secondary school classrooms. The results of our evaluation of the summer institute and the secondary school classroom use can be found in (Murray et al. 2003 A, B, C). In this paper we will focus on what we learned in the college trials summarized in Table 1.

Data analysis for the characterization of pedagogical strategies was mainly through a structured analysis of observation notes, using ethnographic-style methods (Maanen 1988), supplemented by evidence from video transcripts when necessary. Data analysis was conducted by the first author, without input from the domain expert (the subject of the case study).

Sample Data

In this paper we only have room to illustrate one of the sessions. Though there was significant variation in the progression of activities among the sessions, there was commonality in the instructional strategies and principles applied, and this case is typical in that sense.

Trial 2, Session 1. In this trial six subjects used the software in pairs for a 2-hour clinical session. The instructor started out with an introduction to relevant botany principles and an explanation of some of the characteristics of the SimForest growth model (the students were volunteer subjects not in a botany class). He described the light factor and how the shading leaf weight of trees at various heights effects trees. He discussed a major factor in tree death, that as trees get older the ratio of leaf weight to tree mass becomes smaller. He described the "gap phase model" used in our simulation, which averages the effects of each tree over the entire 20 meter plot. He sketched graphs on a blackboard that illustrated a typical distribution of tree ages and diameters in a plot, to discuss the tree diversity and randomness of tree attributes. He asked the class to brainstorm about what factors affect tree growth. Cumulatively they correctly mentioned light, soil, exposure to elements, and rain. He briefly described tree species succession.

The instructor then lead the class through an experimental activity using the simulation, which also served as an introduction to the software. First he asked them to use the site properties tool to set the rain and temperature to reflect local conditions. To help with this he gave a handout that showed average monthly weather conditions for the Amherst region. He asked the students to grow a plot (run the simulation) starting from a clear-cut plot. He asked "are all of the plots the same? Why not?" This lead them to discover the stochastic nature of the simulation. He asked the class if any of them saw white pines in their plots. Few were found. The he said "see if you can get white pines to grow by playing with the site properties." As students engaged in this open-ended experiment, The instructor walked around the class and was observed giving the following advice:

- "Take baby steps in your investigation."
- "You may want to take notes."
- "That looks a little rich for our forest here. try less fertile soil."
- "Look for white pines and scarlet oaks too."
- "Remember, you have to let it run to see tree succession before you change things. White pines may not grow right away."
- "Clear the plot and start over when you change conditions."
- (when asked a question) "Try to find that out yourself."

After about 15 minutes the instructor brought the group together again. He recorded on the blackboard what they found as the best conditions for white pine, noting "we have rough agreement here." Next he suggested an exercise with the goal of teaching students about the stochastic nature of the simulation and the implications of this for data analysis. "Now everyone start with the same conditions: soil type 70, soil fertility 130, soil depth 350, average temperature 60, and average rainfall 78." "Grow the plot several times for the same length of time and compare." The ensuing class discussion illustrated that the students understood the implications of the stochastic nature of the simulation.

Next he organized a collaborative distribution of a problem solving "search space" to more precisely find the optimal conditions for white pine growth. "Let's get organized and do some experiments" he said. He asked group 1 to vary the temperature, group 2 to vary the rainfall, and group 3 to vary the soil fertility, leaving all other variables constant as in the previous experiment. "You will be simulating global warming, draught, and composting" he said. "We will have 10 minutes for these explorations, and then we'll talk about what you found. Take notes!" "Lets grow each forest for 100 years. Take a census at 50 and 100 years." Several students wanted to know whether the soil fertility changes as trees die and decompose. The instructor explained that the model did not include this level of detail, and assumed a constant soil fertility, which was an OK first approximation. Students worked in three groups as suggested and found the optimal ranges. A class discussion followed.

Trial 2, Session 1 summary. We can note the following about this session:

- Students who were not in a botany class were given 20 minutes of introduction to concepts before the session. This degree of content introduction is probably necessary and sufficient.
- Note the balance between what is given ("taught") to the students and what is left for discovery. In this session all general botany principles are told to students. The inquiry is around discovering things related to specific species or site conditions.
- There were several instances where the instructor reframed questions and refocusing students attention toward for more productive learning.
- The instructor scaffold the session by progressing from open ended exploration to more systematic ones.
- The session had the characteristic pattern of cycling between convergent (whole class) and divergent (simulation-based) episodes.
- The instructor seemed to be using a strategy of accumulating the collective knowledge of the participants.
- The instructor organized the students into a collaborative exploration of the problem space.

Results of Analysis

We generalized our observations and analysis from all 14 sessions to produce instructional strategies and pedagogical principles for leading collaborative simulation-based inquiry activities in classrooms. Though these recommendations are based on the case study of the college botany professor described above, we believe that most of our findings are applicable across secondary school and undergraduate grade levels and science subjects, and merit further study and adoption. The majority of the strategies identified apply to scientific inquiry activities with or without computer simulations, but are particularly useful for simulation-based inquiry learning in collaborative contexts. We present this analysis in two parts: feedback and control strategies, and collaboration strategies.

Feedback and Control Strategies. These strategies involve the instructor responding to student questions, answers, and needs for help. In the 14 sessions we saw numerous instances of each of the following phenomena:

- **Leading questions and Socratic dialog**, i.e. asking questions rather than giving information. This is usually an attempt to show the student they already know or could figure out the answer; or to give just enough info to allow them to answer their question.
- We observed **pre-telling** ("you will soon discover that..."), **pre-asking** ("How can we answer this question using the simulation?"), **post-telling** ("what you just learned is..."), and **post-asking** ("What can we learn from what we just saw?") tactics. In general pre-telling and asking was used to prepare, prime, or scaffold an activity or discussion; and post-telling was used to summarize or re-frame an activity or discussion.
- **Opportunistic flow of activities**. We observed the instructor dynamically creating or choosing activities based on the following: student questions, student need to know, results of a previous activity, and unexpected problems with the software. As noted elsewhere, this level of flexibility may be heavily dependent on the teacher's level of subject matter knowledge. We commonly observe students posing their own questions and engaging in the types of "sustained inquiry" described in Soloway et al. (1997).
- **Committing to a hypothesis**. The instructor often asked students to pose a hypothesis or guess at an answer before starting an investigation. There were also instances of structuring a class activity based on testing a hypothesis randomly posed by an individual student. Beginning with a hypothesis in not only "good science," it can create more student investment and engagement.
- **Scaffolding and fading**. From our observations we found evidence of the following related factors used to determine activity sequencing: degree of background knowledge, time limitations, desired level of scaffolding, and level of open-endedness. We can describe the overall goal as one of maintaining learning within a "zone of proximal development" (Vygotsky 1970) for the class, by providing the correct amount of challenge without overwhelming or confusing students. This is primarily done through scaffolding, and later fading away the scaffolding (Brown et. al 1984). The scaffolding was sometimes pre-planned but was often done dynamically. For example, in Trail 4B the instructor initiated several inquiry cycles, each of which were essentially sub-goals of the original challenge, helping the students by breaking the original problem into more manageable steps.
- **Ownership questions**. The instructor tried to design activities to insure success and encourage ownership. One tactic for this was to start an activity with questions. The instructor began many sessions by asking questions such as "how do trees get their energy?," soliciting student responses and encouraging students to justify answers and take a stand on the issue. Sometimes this served as a lead-in to a mini-lecture on some concept, and at other times it served as a way to anchor student inquiry activities.

Collaborative Strategies: Inquiry as Distributed Problem Solving. The strategies described above are not particularly novel and have been noted elsewhere in the literature. However, discovering a diversity of methods for collaborative problem solving does seem to be new. We observed teaching methods that repeatedly brought the entire class into collaboration around an inquiry question, after individual or small group activities. The simulation-based software provided a rich environment for such collaborative inquiry. This is due to several factors: 1) the ability to rapidly run experiments allows students to easily alternate between experimentation and class discussion; 2) it is relatively easy to set up initial conditions, thus making it easier to organize a search space amongst participants; and 3) the graphical representation of the simulation's parameters provides something for students to refer to concretely as they discuss their observations and ideas. We observed the following methods for structuring collaborative problems solving (these are not mutually exclusive strategies):

- **Alternating Convergent and divergent episodes.** Every session could be described as a cycling between divergent individual simulation-based work and whole-class convergent consensus-building discussion. In addition, the simulation-based work varied between exploratory open-choice activities and more systematic inquiry experiments. For example, in Trial 2 the instructor lead the students though several cycles of divergent exploratory work, systematic inquiry experiments, and convergent consensus-building activities.
- **Additive knowledge**. The entire class is given a very open ended task, such as "run the simulation and note what you observe." The class then reconvenes to share what they learned, compare, synthesize, and combine findings. This allows each student to benefit from the collective observations and insights of the whole.
- **Breadth search**. In a related method, each group is allowed to pose their own inquiry question and investigate. When they reconvene students are exposed to issues and information beyond what they would have had time to explore on their own.
- **Simulated annealing**. In computer science there exists a search strategy called "simulation annealing," in which a certain amount of randomness is introduces to an otherwise systematic search to avoid the problem of local minima. Simulated annealing serves a an apt metaphor for a collaborative inquiry strategies that we

observed in which students were allowed to explore a parameter space unsystematically. For example, in Trail 3 students were asked to "play with the simulation" to try to find site conditions that favored white pine. In this type of unconstrained exploration, it is hoped that at least someone in the class will loosely approach a solution. It is usually then followed by a more systematic approach as described below.

- **Jigsaw method state space search.** We saw several cases of the instructor dividing a search space and assigning components of it to groups. For example in Trail 2 the instructor organized a systematic exploration of a multi-variable space of temperature, soil quality, and rainfall conditions, asking each group to chose one of these to vary which keeping the other parameters fixed at a value that, through a simulated annealing method, was found to be close to a solution.
- **Collaborative hypothesis confirmation**. Finally, we observed several sessions (Trail 4 for example) in which the instructor assigned groups with conditions to test alternate hypotheses about a given phenomena. Students compared their results, building arguments to support or refute the hypotheses.

Conclusions and Implications

Enumerating observed teaching strategies is a first step in building a prescriptive theory suggesting the optimal applicability conditions for various strategies. Our results point to a wide variety of potentially effective strategies. It is possible to follow these initial results with more systematic controlled experiments that test the effectiveness of the various strategies under different conditions, isolating various factors. However, we believe that, due to the large number of interacting and hard-to-control variables, such studies would either be difficult to create or lack ecological validity. Because each student, class, and subject matter context will have differences in a large number of dimensions, it may not be practically possible to experimentally determine the optimal conditions for various strategies. Teachers bring a great deal of implicit knowledge and skill to the creation of classroom activities and structures, and we want to provide them with resources toward which to apply these skills. Simply characterizing a variety of strategies and the factors involved has been useful to us in our attempts to train teachers to incorporate collaborative simulation-based inquiry into their classrooms. Our goal was to enlarge their repertoire of strategies and make them more sensitive to important distinctions and decisions, rather than prescribe particular teaching methods for particular situations. In fact, the above analysis of strategies is too detailed and academic to be useful to practicing teachers. We introduced important concepts to them in simpler forms, through demonstrations, and through the ways that we explained what we were doing and answered their questions about classroom implementation.

Finally, we address the question of whether teaching strategies identified in college classes are applicable to secondary school situations. Our experience is only suggestive, but is concrete. As expected, on average the secondary school teachers did not employ these strategies with the same level of skill as the "expert." Also, the level of analysis and systematicity of the collaborative problem solving activities was lower in the secondary school classes than in the college class. However, the secondary school teachers were able to learn from and adapt the strategies that we presented, and they felt that their classes were successful. This gives us some confidence in the possible generality of the teaching methods we culled from the expert. However, since the secondary school teachers incorporated these strategies in very diverse ways, our evaluations of the secondary school teaching sessions did not include a detailed evaluation of their teaching strategies. Thus our contribution is in describing and analyzing the teaching strategies used by the expert, but not in demonstrating convincingly that these strategies are effective or transferable to other teachers. We did, however, demonstrate the validity of the approach of introducing teachers to a variety of diverse strategies and helping them adopt these to their own needs and styles.

References

Alloway, G., N. Bros, K. Hamel, T. Hammerman, E, Klann, J. Krajcik, D. Lyons, T. Madden, J Margerum-Leys, J. Reed, N. Scala, E. Solloway, I. Vekiri, R. Wallace (1996). "Creating AN Inquiry Learning Environment on the World Wide Web." *Proceeding of International Conference on Learning Sciences*. 1996, pp 1-8.

American Association for the Advancement of Science (1993). *Benchmarks for Science Literacy: Project 2061*. Oxford Press: New York.

Blumenfeld, P., Fishman, B. J., Krajcik, J., Marx, R. W., Solloway, E., (2000). "Creating Usable Innovations in Systemic Reform: Scaling Up Technology-Embedded Project-Based Science in Urban Schools," *Educational Psychologist*, Vol 33 No 3 pp 149-164, 2000.

Botkin, D.B. (1993). *Forest Dynamics*. Oxford Univ. Press: Oxford.

Cobb P. (2000). "Conducting Teaching Experiments in Collaboration With Teachers." In *Handbook of Research Design in Mathematics and Science Education*, Edited by A. E. Kelly & R.A. Lesh. Erlbaum: Mahwah, NJ. pp 307-332.

Collins, A., Brown, J. S., & Newman, S. E. (1989). Cognitive Apprenticeship: Teaching the Craft of Reading, Writing, and Mathematics. In L.B. Resnick (Ed.) *Knowing, Learning, and Instruction*. Erlbaum: Hillsdale, NJ.

Edelson, D.C., D.N. Gordin, and P.D. Pea (1999). "Addressing the Challenges of Inquiry Based Learning Through Technology and Curriculum Design." The *Journal of Learning Sciences*. 8(3&4): 391-450. 1999..

Feldman, A. & Minstrell, J. (2000). Action research as a research methodology for the study of the teaching and learning of science. In *Handbook of Research Design in Mathematics and Science Education*, Edited by A. E. Kelly & R.A. Lesh. Erlbaum: Mahwa, NJ. pp 429-455.

Garet, M. S., Porter, A. C., Desimone, L, Birmna, B. F., Yoon, K. (2001). "What Makes Professional Development Effective? Results From a National Sample of Teachers." American Educational Research Journal. Winter 2001, Vol 38, No 4, pp. 915-945.

Gery, G. (1991). *Electronic Performance Support Systems*. Weingarten Publications: Boston.

Gomez, L.M., D.N. Gordin and P. Carlson (2000). "A Case Study of Open Ended Scientific Inquiry in a Technology Supported Classroom." http://www.covis.nwu.edu/info/papers/html/tech-class.html. October 5, 2000.

Haury, D. L. (1993). "Teaching Science Through Inquiry" *ERIC Clearinghouse for Science, Mathematics, and Environmental Education*, Digest 3, March 1993.

Howe, A. C., Stubbs, H. S. (1996). "Empowering Science Teachers: A Model for Professional Development" *Journal of Science Teacher Education*, Vol. 8, No 3, pp 167-182.

Krajcik, J., Blumenfeld, P. C., Marx, R. W., Bass, K. M., Fredricks, J. (1998). "Inquiry in Project-Based Science Classrooms: Initial Attempts by Middle School Students" The *Journal of the Learning Sciences*, Vol 7, No 3-4, pp 313-350, 1998.

Maanen, J. Van, (1988). *Fieldwork, Culture, and Ethnography: Tales of the Field on Writing Ethnography*. The University of Chicago Press, Chicago, 1988. pp., 1- 12.

McNeal, A. P., D'Avonzo, C. (1996). "Student-Active Science: Models of Innovation in College Science Teaching. Saunders Publishing, Philadelphia, 1996.

Murray, T. Winship. L. , Galton A., Stillings, N., (2002). "Classroom implementation of an educational simulation supporting inquiry learning in forest ecology." Presented at Transforming Practice with Technology conference, Amherst, MA March 1 2002.

Murray, T., Winship, L., Stillings, N., Shartar, E. and Galton, A. (2003A). NSF Project Final Report: An Inquiry-Based Simulation Learning Environment for the Ecology of Forest Growth. Hampshire College School of Cognitive Science Technical Report.

Murray, T., Winship, L. , Stillings, N. (2003B). Measuring Inquiry Cycles in Simulation-Based Leaning Environments. To appear in Proceedings of Cognitive Science, July, 2003, Boston, MA.

Murray, T., Stillings, N., Winship, L., Galton, A. & Miller, W. (2003C; in submission). Results from a one-year professional development intervention for integrating inquiry software into secondary school classes.

National Research Counsel. *National Science Education Standards*. Washington DC: National Academy Press. 1996.

Perkins, D. (1986). *Knowledge as Design*. Lawrence Erlbaum Asso., Hillsdale, NJ.

Prince, G. & Kelly, N. (1996). Hampshire College as a Model for Progressive Science Education. Chapter 3 in McNeal, A. & D'Avanzo, C. (Eds) *Student-Active Science: Models of Innovation in College Science Teaching.* Saunders Publishing, Philadelphia.

Roth, W. & Roychoudhury, A. (1993). The Development of Science Process Skills in Authentic Contexts. *J. of Research in Science Teaching*, Vol. 30, No 2. pp. 127-152.

Simon, M. A. (2000). "Research on the Development of Mathematics Teachers: The Teacher Development Experiment". In *Handbook of Research Design in Mathematics and Science Education*, Edited by A. E. Kelly & R.A. Lesh. Erlbaum: Mahwah, NJ. pp 335-364.

Smith, C., Maclin, D., Houghton, C., & Hennessey, M. G. (2000). Sixth-grade students' epistemologies of science: The impact of school science experience on epistemological development. *Cognition and Instruction*, 18 (3), 349-422.

Soloway, E., Pryor, A. Z., Krajcik, J. S., Jackson, S.., Stratford, S. J., Wisnudel, M., Klein, J. T. (1997). "ScienceWare's Model-It: Technology to Support Authentic Science Inquiry." *T.H.E. Journal.* October 1997. pp 54-56.

Stillings, N. A., Ramirez, M. A., & Wenk, L. (1999). Assessing critical thinking in a student-active science curriculum. Paper presented at the meeting of the National Association of Research on Science Teaching, Boston, MA.

Stillings, N. A., Ramirez, M. A., & Wenk, L. (2000). Teaching and learning the nature of science in inquiry-oriented college science courses. Paper presented at the annual meeting of the American Educational Research Association, New Orleans, LA.

Stratford, S. (1997). A Review of Computer-Based Model Research in Pre-college Science Classrooms. In *J. of Computers in Mathematics and Science Teaching* (1997) 16(1), 3-23.

Tabak, I., Smith, B. Sandoval, W., & Reiser, B. (1996). Combining General and Domain-Specific Strategic Support for Biological Inquiry. In Frasson & Gauthier (Eds). *Proceedings of the Third International conference on Intelligent Tutoring Systems*. Springer: New York.

White, B. & Frederiksen, J. (1986). Qualitative Models and Intelligent Learning Environments. AI and Education, Lawler and Yazdani (Eds.), Ablex Publ. Corp.

White, B. & Frederiksen, J. (1995). Developing Metacognitive Knowledge and Processes: The Key to Making Scientific Inquiry and Modeling Accessible to All Students. Technical Report No CM-95-04. Berkeley, CA: School of Education, University of California at Berkeley.

Wilenski, U. & Resnick, M (1999). Thinking in Levels: A Dynamic Systems Perspective to Making Sense of the World. *J. of Science Education and Technology*, 8(1).