Cognitive Apprenticeship, Activity Structures, and Scientific Inquiry

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It is often said that good students are those who know how to play the game. This popular observation has recently been lent empirical validity by several researchers. Bruning, Schraw, & Ronning (1995) have found that for students to succeed they must attend to "procedural knowledge" before conceptual knowledge. Doyle (1979) and Mehan (1980) have concluded that students need to understand teacher expectations of how to participate in an activity and how the activity is structured, in addition to understanding content. Other researchers have focused on the exact nature of the "game." For example, Mehan (1979) has characterized a predominant activity structure as Initiation by Teacher—Reply by Student—Evaluation by Teacher, while Lemke (1990) describes the sequence more narrowly: Teacher Question—Student Answer—Teacher Evaluation. A recent investigation of U.S. mathematics and science classrooms by the Third International Mathematics and Science Study (TIMSS) has acknowledged that there currently are established, predominent structural patterns for classroom activities. In science education the predominent pattern involves the transmission of knowledge, and is of short duration (Valverde, 1988).

Many of the current reform efforts in education do not endorse current classroom activity structures. For example, the *National Science Education Standards* recommends an alternative activity structure wherein students ask and investigate their own questions rather than those of their teacher. However, before any alternative activity structure can be effective, students must become as proficient in the new structure as they are in the currently predominant structures. To expedite the acquisition of new structures, it would seem reasonable to repeatedly expose students to a small number of new structures in different classes. Doing so would counteract what Wasley (1994) observed: incoming students have to learn new structures for each new class.

In general, students would only need to become competent at a small number of activity structures that are repeated across subject areas and across grade levels. Through frequent exposure to this small set of activity structures, students would come to understand the nature of performance that teachers expect. Through practice, participation would become routinized, and students would not need to spend much cognitive energy trying to understand how to participate.

The participants in this symposium believe that education reform projects would benefit from the development of alternative activity structures that are useful in different subjects and across different grades. Students could then learn new activity structures in one class and carry this knowledge across classes (in middle school and high school) or across periods (in the elementary school). Researchers involved in reform could design alternative activity structures, unburdening teachers of the task. In a previous paper, Fuson and Smith (1998) discussed a variation of the common chalkboard activity structure. Their revised activity structure supports problem solving in elementary mathematics and provides mechanisms for students to connect the current lesson to previous lessons. This paper will expand on the model of Fuson and Smith (1998) by describing a problem-solving framework that would link individual activities to a larger problem-solving goal.

Scientific Inquiry

Students learn science best by engaging in scientific inquiry (National Research Council, 1996). The NRC defines scientific inquiry as "observing, posing questions, examining information to see what is already known, reviewing what is already known in light of experimental evidence, planning investigations, analyzing and nterpreting data, proposing answers, explanations and predictions, and communicating results" (NRC, 1996, p23). Together, these acitivites comprise "sustained investigation," that is, long-term investigations over the course of a quarter or semester.

Historically, educators have proposed a variety of activity structures to support science inquiry. Science textbooks commonly propose the Scientific Method, the process that mandates proper scientific experimentation: state a hypothesis, collect data by following a procedure, analyze the data to get results, and draw conclusions.

A recent survey of science textbooks by Lumpe and Scharmann (1991) revealed that the traditional Scientific Method as presented in most textbooks does not require scientific inquiry. This finding is consistent with those of the TIMSS that science teachers routinely use an activity structure (transmission of knowledge) that fails to support scientific inquiry. Moreover, the Scientific Method cannot achieve sustained investigation because the science experiments it prescribes are of relatively short duration.

A recent trend among educators is to seek out ways to support scientific inquiry and sustained investigation through the activity structures of multimedia products. Using the technological tools from these products, teachers have been able to conduct complex, long-term science investigations with their students. In some cases, the investigations have lasted an entire semester. Currently, there are just a handful of products to choose from. The University of Michigan has developed *Model-It*, a modeling environment that enables students to engage in extended scientific inquiry about the quality of a local stream (Jackson, Krajcik, & Soloway, 1998). The Learning through Collaborative Visualization Project (CoVis) has built visualization environments that enable students to conduct long-term investigations of weather and climate. (Pea, Edelson, & Gomez, 1994). In addition, the CoVis project has provided a *Collaboratory Notebook* that allows students to record their inquiry processes (Edelson & O'Neill, 1994).

McGee (1996) analyzed the extended science projects in which CoVis students engaged. He determined that the activity structures used by CoVis teachers were organized around four phases: selecting the purpose, initial planning, executing the plan, and sharing the results. These phases are consistent with phases used in successful Progressive-Era projects (Collings, 1923). This activity structure framework provided a research tool for describing the categories of events that took place across a variety of projects. Using the framework, it was possible to determine that formal feedback from the teacher was an important predictor of student engagment in scientific inquiry (McGee, 1996). Polman (1997) extended McGee's project by tracking one of the CoVis teachers over a two-year time span to see how the phases of activity structures evolved.

Astronomy Village®: Investigating the Universe

The NASA Classroom of the Future program (COTF) is a NASA-funded research and development center that specializes in the development and testing of educational multimedia for math, science, and technology education. In March 1996, COTF published a CD-ROM called *Astronomy Village: Investigating the Universe* for use as a curriculum supplement in high school science classrooms. It has been distributed to over 11,000 teachers, educators, and resource centers, and it won *Technology and Learning* magazine's Science Software of the Year Award for 1996 (Technology and Learning, 1996). *Astronomy Village* uses the metaphor of living and working at a mountain-top observatory (the Village) as the primary interface from which students investigate contemporary problems in astronomy (see Pompea and Blurton, 1995). Academic activities are designed to promote learning of both astronomical concepts and processes related to scientific inquiry.

Students form research teams and choose one of ten investigations to complete. In the Stellar Nursery investigation, for example, students investigate the Orion nebula to find out how images of the region can be used to investigate star formation. For each investigation, students progress through five phases: background research, data collection, data analysis, data interpretation and presentation of results. For any given phase, there are from three to seven content-related activities to be completed before proceeding to the next phase. The primary means of tracking progress through an investigation is the *Research Path Diagram*-- a chart that shows each phase of the investigation and icons to represent activities within each phase (see *Figure 1*). When a student clicks on one of the icons in the Research Path Diagram, a virtual mentor appears and describes activities relevant to the investigation. At all times students have access to an electronic LogBook for recording their scientific notes and observations.

A Design Experiment with *Astronomy Village*

In a recent evaluation of *Astronomy Village*, the COTF team analyzed whether the activity structures suggested in the Research Path Diagram would help students synthesize results across different phases of research. Using a design experiment paradigm, they collaborated with three teachers who used the COTF facilities to implement *Astronomy Village*. They began with the activity framework suggested by the software and made adjustments to the activity framework based on the results of three implementations (see McGee, Howard, & Hong, 1998 for a complete description of the design experiment).

Design Experiment Method

In the first study, their purpose was to implement the curriculum as closely as possible to the curriculum as intended by the software designers. Students completed activities related to background research, data collection, data analysis, data interpretation, and presentation of results.

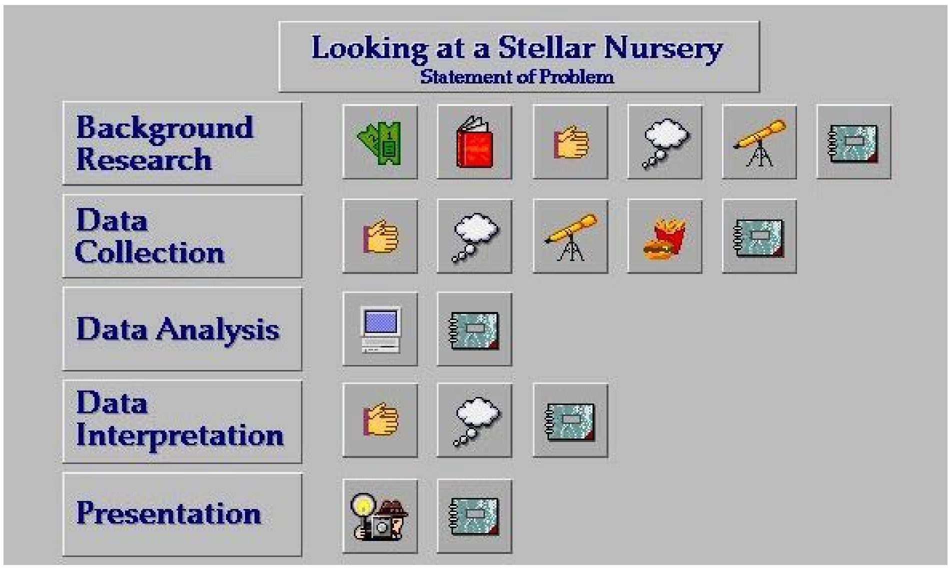

Figure 1. Stellar Nursery research path diagram

By following the Research Path Diagram, students should have been able to complete the steps necessary to learn the appropriate concepts and conduct the level of problem solving needed for their investigation.

In the second study, the researchers tried to overcome some of the difficulties prevalent in the first study. First, students had spent too much time on early phases resulting in insufficient time to complete later phases of the project. In second study, the teacher imposed deadlines for phase completion so that students could pace themselves and complete more activities. Second, although students in the first study had completed an introductory tutorial that included details of software use they would need in later phases, the students had difficulty remembering these details when the time came. For the second study, teachers demonstrated how to use the software features on an as-needed basis, at the beginning of each phase of research.

In the first two studies, the researchers noticed that students were capable of completing the activities and summarizing them, but they were not synthesizing across phases of research. In study three, the research phases were revised and truncated into five alternative phases: the motivating question phase, background research, background review, data analysis, and reflection. In the motivating question phase, the teacher posed the main investigation question and the students individually typed responses in their electronic notebooks. Next, the teacher showed the students the data that they would be analyzing and asked them to record observations. These two activities were meant to activate students' prior knowledge and connect it to the activities of the investigation. In the background research phase, the teacher selected the three most relevant articles from the pathways, and students each read one of the three articles and developed an activity summary. In the background review phase, students used their activity summaries to answer questions as a team that would prompt students to integrate across the readings that were done individually. Since each student was an expert on only one of the articles, students would be forced to discuss the readings with each other in order to answer the question. In the data analysis phase, students completed analysis worksheets as a team. And finally, in the reflection phase, students responded to integrative, teacher-posed questions in their notebooks.

Design Experiment Results

Although the original Research Path Diagram provided some support for students to engage in scientific inquiry, it was deficient in some ways. Researchers found that for students to engage in scientific inquiry that spans many weeks, they need structure to synthesize the results of individual activities; otherwise, students will view the activities as a collection of isolated experiences (McGee, Howard, Hong, 1998). The researchers supplemented the Research Path Diagram by assigning deadlines and creating question prompts that encouraged students to synthesize multiple activities. These supplements resulted in students being able to complete more activities and make better connections between activities.

Table 1 provides a comparison of four phases of scientific inquiry across the traditional Textbook Scientific Method, the CoVis science projects, and *Astronomy Village*. The general phases of research come from successful models of progressive-era projects (Collings, 1923). Each phase of research has a unique educational role in the process of problem solving. The goal of the *Selecting a Purpose* phase is to generate interest in the problem and activate relevant prior knowledge about the problem. Student engagement is a key determinant in successful problem-solving. The goal of the *Initial Planning* phase is to foster the application of problem-solving strategies, support the generation of predictions about the problem investigation, and promote the use of metacognition during problem solving. The goal of the *Executing the Plan* phase is to develop specific scientific investigation skills such as skill with experimental apparati, and to foster comparisons between the prediction and the results of the investigation. The goal of the *Presentation* phase is to provide an opportunity for students to learn from their experiences by synthesizing and reorganizing their experience in order to communicate it to others.

Experiments that follow the Textbook Scientific Method are often referred to as “cookbook” experiments . Cookbook experiments do not have a phase to motivate student interest in the experiment. The only planning typically required is the statement of the experimental hypothesis, which is often *given* to the students (Lumpe & Scharmann, 1991). The strength of the Textbook Scientific Method is in the Executing the Plan phase, where students gain proficiency in scientific techniques such as graphing results.

In contrast, teachers on the CoVis Project support all phases of the research process. Student interest in a problem is promoted since the students select the problem to investigate. During the Initial Planning phase, students generate a plan that incorporates possible solution strategies and makes predictions about the outcome. Students implement the plan that has been proposed. The

Research Phase	**Educational Role of Phase**	**Textbook Scientific Method**	**CoVis Approach**	***Astronomy Village***
Selecting a Purpose	• develop interest • activate relevant prior knowledge		• Select Group • Select Broad Topic	• Pick Pathway
Initial Planning	• select solution strategies • make predictions • promote metacognition	• State Hypothesis	• Background Information • Research Proposal	• Research Path Diagram • Background Research
Executing the Plan	• develop scientific skills • compare predictions and results	• Conduct Experiment • Analyze data • Draw Conclusions	• Data Collection • Data Analysis	• Data Collection • Data Analysis • Data Interpretation
Sharing Results	• synthesize results with prior knowledge		• Research Report • Class Presentation	• Virtual Press Conference • Class Presentation

Table 1: Summary of Phases of Scientific Inquiry

plan should have more meaning and activate relevant prior knowledge for the students over the cookbook experiments because the students planned it themselves. Students have ample opportunity to synthesize the results of the investigation through both a final report and a classroom presentation. The strength of approaches like CoVis lies in the open-ended nature of the projects. There is high student interest and great opportunities for students to develop flexible solution strategies (Scott, 1994). The weakness of the approach is that students' invented methods for analyzing data are often not consistent with specific techniques used by the scientific community. For example, research indicates students often make errors in drawing conclusions from a table of numbers by merely visually inspecting the data (McGee, 1996).

The *Astronomy Village* program attempts to combine the strengths of the Textbook Scientific Method with the strengths of the CoVis Project. Students are provided with the necessary resources to conduct investigations in astronomy. Since it is difficult for them to independently develop techniques for analyzing astronomical data, *Astronomy Village* provides scripts that students can follow to analyze the images associated with the research investigations. The Selecting-a- Purpose phase involves students in selecting one of the ten research investigations, and in Initial Planning students are provided with the Research Path Diagram. In both phases, students are left with few choices and thus their interest and their understanding of the relevance of the investigation re potentially limited.

The changes made during the design experiment of *Astronomy Village* were meant to increase opportunities for students to see the relevance of the investigation, thus boosting student interest and providing them with structure to manage the investigation process and develop new solution strategies. In the end, it was still very difficult for students to understand the specific analysis techniques that were presented in *Astronomy Village*. The next section will discuss current speculations about how to augment the Research Path Diagram so that students will be able to conduct investigations in astronomy that are more open-ended, much like the CoVis students were capable of doing in more familiar domains.

Cognitive Apprenticeship

In this section we speculate about a framework of activities for helping students engage in complex problem solving in the form of virtual research investigations. The speculative activity framework is based on the results of the *Astronomy Village* design experiment and is consistent with theoretical instructional frameworks proposed by Dewey (Tanner, 1997) and Collins, Brown, & Newman (1989). The activity framework was created by adding a set of activities that students would conduct prior to engaging in activities like *Astronomy Village* and adding a set of more open-ended activities that would follow *Astronomy Village*. The first set of activities in the framework is called Nonspecific Goal Exploration (Sweller, 1988) and is designed for students to learn strategies and techniques for problem solving in a new domain. The second set of activities is called Teacher Research Question. where the teacher poses a problem to the students, who then attempt to apply the strategies they developed in the previous set of activities to solve the problem. It is hypothesized that this set of activities will help students see the kinds of problems for which the strategies are useful. The Teacher Research Question set most resembles the current Research Path Diagram in *Astronomy Village*. The third set of activities is called the Student Research Question, where the students formulate their own problems to solve. These three sets of activities comprise what we call the Research Unit Activity Framework.

The cognitive apprenticeship model (Collins, Brown, and Newman, 1989) and a recent reinterpretation of Dewey's stages of discipline (Tanner, 1997) provide the theoretical foundation for the design of the Research Unit Activity Framework. The three sets of activities in the Research Unit Activity Framework are parallel to Dewey's three stages of discipline. In Dewey's first stage, the *personal and social interest* stage, students explore the materials of a new domain to develop

	Research Phases Scaffolded
Nonspecific Goal Exploration	• Initial Planning • Selecting the Purpose
Teacher Research Question	• Selecting the Purpose
Students Research Question	None

Table 2: Scaffolding of Research Phases within each Set of Activities in the Research Unit Activity Framework

confidence with the materials and interest in the problems in the domain. In the second stage, the *means-end stage*, students attempt to solve problems as posed by the teacher. In the third stage, the *generative* stage, students conceptualize the problem in addition to solving it.

Cognitive Apprenticeship provides a model for helping students move from one set of activities to the subsequent set. Cognitive Apprenticeship suggests using teacher strategies and sequencing activities that will help students learn complex problem solving. One teaching strategy suggested by Cognitive Apprenticeship is to design the initial tasks in such a way that students are able to accomplish the task on the first try. This can be accomplished by having the teacher complete portions of the task and allowing the students to focus on certain other components of the task. Eventually, the teacher withdraws help as students are able to take on more of the task themselves. This process is called scaffolding and fading. The Research Path Diagram in *Astronomy Village* provides scaffolding for students to complete the paths, but it currently does not provide fading of the structure so that students can take on more responsibility for conducting the investigation. As proposed in the Cognitive Apprenticeship model, the Research Unit Activity Framework provides scaffolding so that students can get a global view of the scientific process. The scaffolding is faded from one set of activities to the next, in the opposite order of how scientists engage in inquiry. The fading goes from Executing the Plan to Initial design to Selecting the Purpose.

It is possible for teachers to provide scaffolds at each of the four general phases of a research investigation as defined above: selecting a purpose, initial planning, executing the plan, and sharing results (see Table 2). In the first set of activities in the Research Unit Activity Framework, Nonspecific Goal Exploration, the teacher provides scaffolds for the Selecting-a-Purpose and the Initial-Planning phases. Students focus on developing and understanding specific scientific skills related to the research. For example, students might be given a set of images of stars and the distances to those stars. The teacher would then prompt students to explore alternative methods to use the images to determine the distances to the those stars. Nonspecific Goal Exploration has been found to be an effective means of helping students learn problem solving in a new domain, since focusing initially on a specific goal can be detrimental to the development of problem-solving strategies (Sweller, 1988).

In the second set of activities, Teacher Research Question, the teacher fades the scaffold for the Initial-Planning phase, but maintains the scaffold for the Selecting-a-Purpose phase. The questions in this phase would be very similar to the kinds of questions asked in *Astronomy Village*, but now the students would not be dependent upon specific scripts provided by the Research Path Diagram. The students would be capable of designing solution strategies using the techniques that were developed in the Nonspecific-Goal-Exploration phase. For example, students might be asked to investigate differences between the Milky Way galaxy and other galaxies. In order to investigate this question, students must first use techniques developed in the Nonspecific Goal Exploration activities for measuring distances to determine whether the stars are in the Milky Way or another galaxy.

In the third set of activities, the Student Research Question, the teacher removes all scaffolds and the students design their own question, investigation, and measurement techniques. After developing proficiency in specific astronomical techniques and developing solution strategies in astronomy, students would now be in position to ask questions that are of interest to them and that they are capable investigating. The sequencing of activities is consistent with the Cognitive Apprenticeship recommendation to sequence activities from global to local skills.

Conclusion

In order to promote reform, it is necessary to develop alternatives to the predominant Initiation by Teacher—Reply by Student—Evaluation by Teacher activity structures that currently exist in schools. In the area of science, it is necessary for students to engage in extended inquiry in order to best learn scientific concepts. The Research Unit Activity Framework can help students learn to engage in extended inquiry. The framework is general enough that it could be used in a variety of subject areas. Thus, it could potentially serve as one of the handful of activity structures to be repeated across subject areas and across grade levels. The benefits would be even greater when students were already familiar with the expectations for performance within the activity structure. In the next paper in the symposium, Polman (1998) will discuss the results of applying the CoVis activity framework to the domain of history.

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