

**Engineering Pedagogical Reform:
A Case Study of Technology-Supported Inquiry**

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1. Background

It is not uncommon for researchers to suggest that the model for educational research should be engineering and the applied sciences, rather than the social and natural sciences (e.g., Collins, 1992; Zaritsky, Kelly, Flowers, Rogers, & O’Neill, 2003). However, it is less common for an individual with an engineer’s training to become an educational researcher. I am such a person, and in this paper, I will describe a research program in which I have been attempting to “engineer” learning experiences for middle and high school science students that incorporate inquiry. In this historical account, I will tell the stories of three different engineering problems that arose, a software design problem, a curriculum design problem, and a teacher professional development. For each, I will describe the problem, as it presented itself and evolved over time, the products that we designed to address the problem, the design framework we articulated to enable us and others to address similar problems, and the open research questions.

This line of research began in 1992 with the Learning through Collaborative Visualization (CoVis) initiated by Roy Pea, Louis Gomez, and Elliot Soloway, which had the goal of placing scientific visualization technologies that could support inquiry-based learning into the hands of high school students (Pea, 1993). In the 1980’s, as a result of a substantial investment by the federal government in high-performance computing, scientific visualization technologies had revolutionized the practices of many scientific disciplines, including the geosciences (McCormick, DeFanti, & Brown, 1987, Gordin & Pea, 1995). One of the premises of the CoVis Project was that the same properties that made visualization tools so valuable for scientists—that they harness the power of the human visual system in order to allow scientists to find patterns in complex data—would apply to students as well. The idea was that the same tools that allow scientists to expand the horizons of human understanding could allow students to expand the horizons of their personal understanding. So, in 1992 we initiated a program of research and development exploring the opportunities for scientific visualization in geosciences education that continues today.

The original goal of this work was to provide students with tools that would enable them to engage in open-ended geoscience investigations with data. The goal was for

students to initiate investigations with self-generated questions and pursue them through a largely self-directed and self-regulated inquiry process. While this goal of supporting open-ended inquiry remains largely unrealized, it is responsible for initiating an immensely productive research and development program.

One of the hallmarks of this research program is that the problem definition has expanded with every step of the research. The problem was originally conceived as a technology challenge. We recognized almost from the start that the tools used by scientists were not appropriate for high school students. Therefore, we initially defined the problem as one in designing scientific visualization tools that would be appropriate for high school students. However, as soon as we had made enough progress on that problem to begin classroom studies, we discovered that teachers were not able to take advantage of the software unless it was embedded in curriculum. In other words, getting the technology right was just the price of admission to work on the curriculum problem. Therefore, we reconceptualized the problem as being one of both software and curriculum design. However, once we had created curricula and attempted to expand to larger number of teachers, we discovered that many teachers were not prepared to use the technology-integrated and inquiry-based curriculum units we had created. Therefore, our ever-increasing research problem grew to include teacher learning and professional development, as well. It is my nightmare that I will eventually be forced to take on the problem of organizational context and school policy, but for now, I am restricting myself to the three interrelated issues of software design, curriculum design, and design to support teacher learning.

2. The Engineering Perspective on Educational Reform

To understand the perspective in this paper, it is important to understand the practice of engineering research. The goal of engineering research is to develop robust methods for designing solutions to a class of problems (in contrast to engineering itself, where the goal is the solution of specific problems). Some of the most important aspects of engineering research are:

- It rests on existing science. Engineering solutions start with what is already known reliably and reproducibly about the relevant phenomena.
- Engineering research starts where the science ends. Engineering research is necessary when the science is not sufficient to base design decisions upon.
- Engineering research is driven primarily by the design goals and secondarily by the goal of understanding the relevant phenomena. In other words design heuristics based on descriptive empirical results rather than a causal model is a satisfactory outcome for engineering research, where it would be considered unsatisfactory in scientific research.
- Engineering research proceeds through iterative, theory-guided experimentation. At each iteration, a design or partial design is developed and tested. The evaluation at each step extends or revises the theory and guides the next iteration in design.
- The outcome of engineering research is a set of guidelines for designing solutions to a class of problems, accompanied by a rationale for those guidelines grounded in science, theory, or empirical results.

This describes my own research, which I characterize as educational design research (Edelson, 2002) and is similar to what others have called design experiments (Brown, 1992; Collins, 1992) and design-based research (Design-Based Research Collective, 2003). By working on a range of specific design challenges in educational reform, my goal is to develop general guidelines for the design of a class of learning experiences. In particular, I am interested in the design of learning experiences in which students engage in scientific inquiry that incorporates authentic scientific practices in the service of improving students' understanding of both science content and science practice. I have chosen the context of Earth and environmental science because of the importance of these subjects to modern society and the insufficiency of current educational practices in these subjects to prepare citizens to make decisions they will face in their lifetimes that have implications for the environment. I include a focus on computational tools in my research because of their ability to represent scientific phenomena dynamically and because they are essential to contemporary scientific practices.

3. The Software Design Story

As stated in the introduction, this program of research started with the goal of engaging secondary school students in open-ended inquiry in atmospheric sciences supported by visualization and data analysis technologies. The first challenge that we recognized was the challenge of using tools developed for scientists (Gordin & Pea, 1995; Edelson & Gordin, 1998). Therefore, the first design and evaluation iterations were focused on adapting the tools used by scientists to be appropriate for learners. In this case, we developed tools for visualization and analysis of gridded (raster) data of the sort used by climatologists and oceanographers. The final tangible product of this research is a software environment called WorldWatcher (Edelson, Gordin, Clark, Brown, & Griffin, 1997) that is still in use by schools. This design cycle, described in Edelson, Gordin, & Pea (1999), resulted in guidelines and strategies for the adaptation of scientific investigation tools for use by learners. These guidelines and strategies respond to the following challenges we identified through formative evaluation cycles in the design process (Edelson et al., 1999, p. 399-400):

1. Accessibility of investigation techniques. For students to engage in inquiry, they must know how to perform the tasks that their investigation requires, they must understand the goals of these practices, and they must be able to interpret their results. Scientific investigation techniques such as data collection and analysis can be complicated and typically require a level of precision and care that are not required of students in their everyday experiences. If students are not able to master these techniques, then they cannot conduct investigations that yield meaningful results. The need for tools to be accessible to learners across the full diversity of abilities and prior experiences is another challenge of Learner-Centered Design raised by Soloway et al. (1994).
2. Management of extended activities. To achieve the ultimate goal of open-ended inquiry, students must be able to organize and manage complex, extended activities. A scientific investigation requires planning and coordination of activity and the management of resources and work products. Students are not typically asked to manage extended complex processes as part of traditional

- educational activities. If they are unable to organize their work and manage an extended process, students cannot engage in open-ended inquiry or achieve the potential of inquiry-based learning.
3. The practical constraints of the learning context. The technologies and activities of inquiry-based learning must fit within the practical constraints of the learning environment, such as the restrictions imposed by available resources and fixed schedules. While this challenge may not have the same theoretical importance as the other two for advancing our understanding of the learning sciences, it has enormous practical implications for design. A failure to work within the available technology or fit within the existing schedule in a school will doom a design to failure. Therefore, meeting the constraints of the environment is a critical consideration in design that must be considered along side learning needs in the design of curriculum and technology.

In response to these challenges, we identified a number of software adaptation strategies, for which we were able to give guidelines.

To address the challenge of accessibility, we developed the design strategy of *embedding the tacit knowledge of experts in the novice's user interface*. For example, we discovered that scientists bring knowledge of geography to their interpretation of geographic visualizations that students lacked. By incorporating geographic references into the visualizations, we were able to provide students with access to information that was tacit knowledge for scientists Figure 1. Similarly, we developed interfaces for data libraries that allow students to access data through diagrams indicating the relationships among variables instead of the lists of scientific terms that scientists use as interfaces to data libraries.

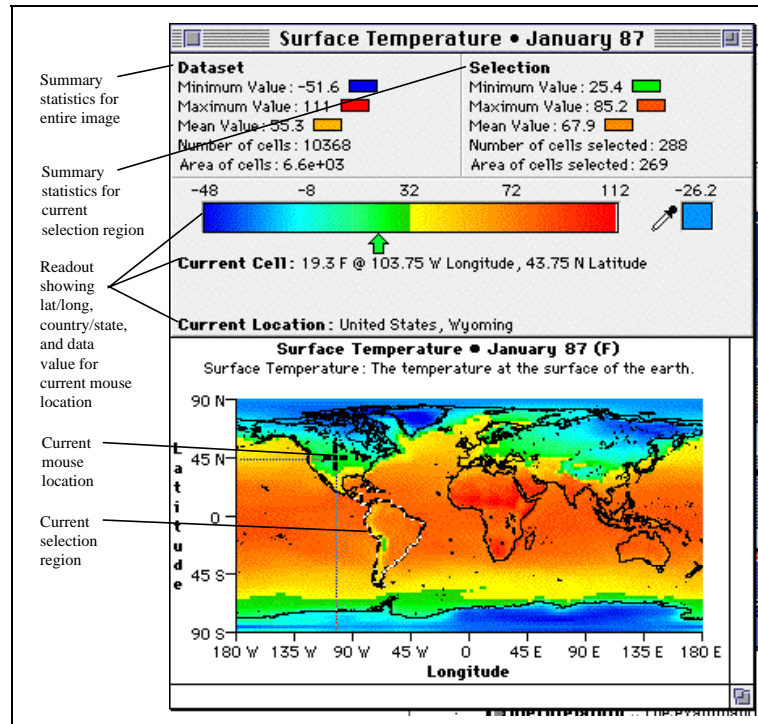


Figure 1. A Visualization window from the WorldWatcher software displaying surface temperature for January 1987.

Another design strategy for the challenge of accessibility was the *strategic selection of functionality*. The goal of this strategy is to select functionality that provides learners with the functions of an expert's tool that will provide them with the most investigative power without overwhelming them with complexity in the form of too many functions or functions that are too difficult to implement. For example, we incorporated functionality for conducting simple arithmetic operations (addition, subtraction, multiplication, division, minimum, maximum, average) between two data sets (Figure 2) representing the same quantity (e.g., subtract January temperature from July). However, we decided to only support these simple two-place arithmetic operations and did not incorporate a facility for specifying operations through arbitrarily complex algebraic expressions, as was found in the experts' tools.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Figure 2. A Dialog for specifying a math operation between two datasets.

A third strategy for addressing the challenge of accessibility was *automating operations with minimal pedagogical value*. In an early phase of this research, we observed climate researchers engaged in data analysis with scientific visualization tools. They spent a large percentage of their time reformatting data and setting display parameters prior to actually analyzing data. The pedagogical value of students' engaging in these activities would be very low, and it would be very difficult to justify the time that these processes would take. Therefore, we made it unnecessary for students to participate in these tasks by either automating the tasks or pre-processing the data manually in advance of distributing it to students. Thus, when students select any data to visualize in WorldWatcher the display parameters have been set in advance to make it possible for them to start working with the data immediately. Students still have full control over all the display parameters (color scheme, spatial resolution, quantization, etc.), but it is not necessary for them to set them before they can begin their data interpretation and analysis.

Figure 3. A visualization magnified to show the individual data values in each cell.

A fourth strategy for the challenge of accessibility was *adding bridging functions*. A bridging function helps students understand the functionality of an expert tool in terms of concepts they are already familiar with. The result is adding functionality that would not be useful to an expert but has significant pedagogical value. One example in WorldWatcher is a feature that display numerical values for colored cells when a user zooms in on a visualization far enough to display them (Figure 3). This feature helps students to bridge between their familiarity with tables of numbers (e.g., spreadsheets) and the unfamiliar colors as numbers representation of color maps. Often students approach these visualizations with the metaphor of a printed map, where the colors are ink, rather than a dynamic representation of numerical values. Once a student understands a color map visualization as an array of numbers, an arithmetic operation between two visualizations makes sense, whereas a subtraction doesn't make sense to someone with a model of the visualizations as colors without numbers behind them. Other examples of bridging functions are a feature that enables learners to modify or create data sets by drawing on visualizations using a paint program metaphor (Figure 4) and another that enables them to print visualizations as cut-and-fold images that they can assemble into three-dimensional globes (Figure 4).

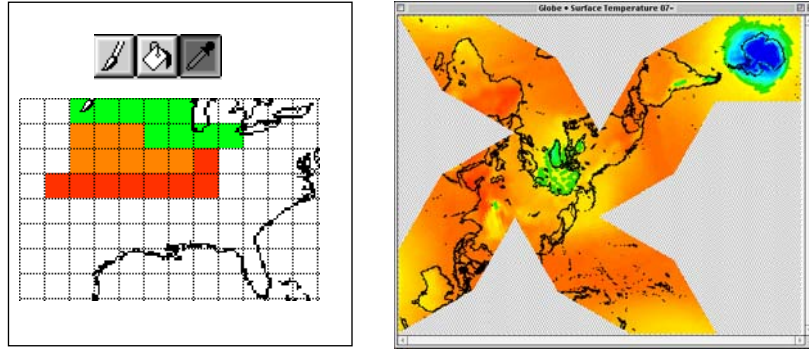


Figure 4. Images from WorldWatcher showing (a) the paint interface for drawing “data” and (b) cut-and-fold globe generated from a temperature visualization.

A strategy for addressing the challenges of open-ended tasks was to develop inquiry-support software tools that allow teachers or curriculum designers to structure students’ activities and provide students with tools for planning, recording, and monitoring their progress in an investigation.

Our strategies for responding to the practical constraints of school technology infrastructures consisted of reducing or eliminating our reliance on high-end computers or reliable network connections, developing interfaces that protect students from needing to interact directly with computer file systems, and simplifying installation and administration processes.

Based on classroom use of the most recent version of WorldWatcher, we believe that we have been relatively successful in identifying challenges to the use of investigation tools to support inquiry and in developing strategies to address them. Based on that success, we have been engaged in a similar effort to adapt geographic information systems (GIS) technologies for learners for the last several years, drawing on these same strategies in the context of a technology that offers a much larger and more sophisticated set of investigation tools than the technologies that served as the model for WorldWatcher.

However, our classroom experiences also revealed that there were significant challenges to the implementation of technology-supported inquiry learning that could only be partially addressed by software design, if at all. In Edelson et al. (1999), we reported the following challenges in that category (p. 399-400):

1. **Motivation.** For students to engage in inquiry in a way that can contribute to meaningful learning they must be sufficiently motivated. The challenging and extended nature of inquiry requires a higher level of motivation on the part of learners than is demanded by most traditional educational activities. To foster learning, that motivation must be the result of interest in the investigation, its results, and their implications. When students are not sufficiently motivated or they are not motivated by legitimate interest, they either fail to participate in inquiry activities, or they participate in them in a disengaged manner that does not support learning. Motivation is recognized by Soloway et al. (1994) as one of three primary challenges for Learner-Centered Design.
2. **Background knowledge.** The formulation of research questions, the development of a research plan, and the collection, analysis, and interpretation of data, all require

science content knowledge. In designing inquiry-based learning, the challenge is providing opportunities for learners to both develop and apply that scientific understanding. If students lack this knowledge and the opportunity to develop it, then they will be unable to complete meaningful investigations.

In this first phase of research, we were able to address motivation by creating data libraries as part of our software that supported investigations on topics that middle and high school students found meaningful. We were able to address background knowledge by creating a facility that enabled teachers and curriculum developers to link documents with content information to data sets and to activity guides. However, we found that we needed to turn our focus to the design of learning experiences (curriculum) in order to address these challenges.

4. The Curriculum Design Story

Since 1998, the primary focus of my research on engaging students in inquiry has been curriculum and activities design. The delayed onset of this research relative to the software research reflects, in part, a naïve view that students would be prepared to engage in open-ended inquiry without requiring a structured curriculum that was followed by an equally naïve view that teachers would be able to develop whatever curriculum was required for their own classrooms. My own work on curriculum development began in earnest in 1998 with the initiation of two new efforts. The first was an NSF Instructional Materials Development grant to create a one-year environmental science curriculum for the high school around inquiry supported by WorldWatcher. The second was the NSF Center for Collaborative Research on Learning and Technology called the Center for Learning Technologies in Urban Schools (LeTUS), which took on as a central focus of its work the creation of inquiry-based, technology-integrated science curriculum units for use in middle schools in Chicago and Detroit.

Approaching this work from the perspective of engineering research, I set about trying to understand what the science of learning had to contribute to the design of inquiry-based curricula, and I drew on contemporary research in the cognitive sciences to develop a set of guidelines and strategies for curriculum design that I call the Learning-for-Use (LfU) design framework (Edelson, 2001). The Learning-for-Use Framework is concerned with the design of learning activities that develop what I call *useful knowledge*. Its goal is to address two significant challenges to teaching that are often overlooked in the design of learning activities: fostering engagement and ensuring that learners develop knowledge that they can access and apply when it is relevant in the future. Regardless of the nature of the learning activities that students participate in, if they are not sufficiently and appropriately engaged, they will not attend to those activities in ways that will foster learning. Likewise, if students do not construct knowledge in a manner that supports subsequent re-use of that knowledge, it remains inert (Whitehead, 1929). The Learning-for-Use design framework is based on a model of how people acquire useful knowledge. The four principles are¹:

- Learning takes place through the construction and modification of knowledge structures.

¹ From (Edelson, 2001)

- Knowledge construction is a goal-directed process that is guided by a combination of conscious and unconscious understanding goals.
- The circumstances in which knowledge is constructed and subsequently used determine its accessibility for future use.
- Knowledge must be constructed in a form that supports use before it can be applied.

The model incorporates these four principles and their implications into a description of learning. It characterizes the development of useful understanding as a three-step process consisting of (1) motivation, (2) knowledge construction, and (3) knowledge refinement.

*Motivate: Establish perceived need for new understanding*². The first step in learning for use is recognizing the need for new knowledge. The *motivate* step in the learning-for-use model creates a need for specific content understanding. In this context, *motivate* is being used in a very specific sense. It describes the motive to learn specific content or skills, not a general attitude or disposition to learn in the particular context. Understanding the usefulness of what they are learning provides a motivation for students to engage in learning activities and to construct understanding in a useful form.

Knowledge Construction: Building new knowledge structures. The second step in learning for use is the development of new understanding. This step results in the construction of new knowledge structures in memory that can be linked to existing knowledge. An individual constructs new knowledge as the result of experiences that enable him or her to add new concepts to memory, subdivide existing concepts, or make new connections between concepts. The “raw material” from which a learner constructs new knowledge can be firsthand experience, communication from others, or a combination of the two. This step in the Learning-for-Use model recognizes incremental knowledge construction as the fundamental process of learning.

Knowledge Organization: Organizing and connecting knowledge structures to support use. The third step in learning –for use is refinement, which responds to the need for accessibility and applicability of knowledge. In the refinement step, knowledge is reorganized, connected to other knowledge, and reinforced in order to support its future retrieval and use. To be useful, declarative knowledge must be reorganized into a procedural form that supports the application of that knowledge (Anderson, 1983). Useful knowledge must also have connections to other knowledge structures that describe situations in which that knowledge applies (Simon, 1980; Chi, Peltovich, & Glaser, 1981; Roger .C. Schank, 1982; Glaser, 1992; Kolodner, 1993). Refinement of knowledge can also take the form of reinforcement, which increases the strength of connections to other knowledge structures through the traversal of memory structures and increases the likelihood that those connections between knowledge structures will be found in the future.

² While the first step in the Learning-for-Use model is called *motivate*, this phase is only concerned with a small portion of what is normally thought of as *motivation* in education. In this context, I am using *motivate* to refer to a specific type of motivation—the motivation to acquire specific skills or knowledge within a setting in which the student is already reasonably engaged. Addressing the broader motivational challenges of engaging students in schooling are critical to, but beyond the scope of, the Learning-for-Use model.

While there is an inherent ordering among these three steps, the ordering does not preclude overlaps or cycles. For example, knowledge construction and revision may be interleaved, and knowledge construction or revision can create new motivation. Because of the incremental nature of knowledge construction, it can require several cycles through various combinations of the steps to develop an understanding of complex content. Even with this cyclical nature, the order of steps is important. To create the appropriate context for learning, motivation must precede construction, and to insure accessibility and applicability, refinement must follow construction.

Based on this model of learning, I developed the *Learning-for-Use Design Framework*. This framework provides guidelines for the design of activities that will contribute to the development of robust, useful understanding. The design framework articulates the requirements that a set of learning activities must meet to achieve particular learning objectives. The Learning-for-Use model poses the hypothesis that for each learning objective a designer must create activities that effectively achieve all three steps in the learning for use model.

The Learning-for-Use design framework describes different design strategies that meet the requirements of each step (Table 1). The different design strategies for each step can be treated as alternative or complementary ways to complete the steps. In the case of rich content, however, several learning activities at each step involving both of the processes for that step may be necessary.

Table 1. Overview of the Learning-for-Use Design Framework.

Step	Name	Description	Desired Effect
Motivate	Create task demand	Students are presented with a task that requires new understanding.	Creates a perceived need for new knowledge or skills.
	Elicit curiosity	Students are placed in a situation that <i>elicit curiosity</i> by revealing an unexpected gap in their understanding.	Student becomes aware of limits of knowledge and need for new knowledge to address those limits.
Construct	Direct experience	Students are provided with <i>direct physical experience or observation</i> of phenomena.	Students construct knowledge structures encoding the attributes and relationships that describe the phenomena.
	Indirect experience	Students hear about, view, or read about phenomena.	
	Modeling	Students observe another person performing a task.	Students construct knowledge structures that encode the elements of a practice.
	Instruction	Students are told or read about how to perform a task.	
	Explanation	Students are provided with explanations of phenomena or processes.	Students construct knowledge structures that encode causal information behind the relationships among phenomena or elements of a process.
	Sense Making	Students engage in explanation or synthesis activities.	
Organize for Use	Practice	Students use components of new understanding outside of motivating context.	Students construct procedural representations from declarative representations, reinforce understanding, expose limitations and need for further knowledge construction
	Apply	Students <i>apply</i> understanding in context.	Students develop indices for retrieval, construct procedural representations from declarative, reinforce understanding, expose limitations and need for further knowledge construction
	Reflect	Students articulate what they have learned and what the boundaries of that understanding are.	Knowledge is re-indexed for retrieval, expose limitations and need for further knowledge construction

Although it was designed to describe learning in general, when applied to inquiry-based science learning, the Learning-for-Use design framework represents a variant of the Learning Cycle (Karplus & Thier, 1967; Renner & Stafford, 1972; Lawson, 1995; Abraham, 1998). While they are similar in many ways, the two frameworks were developed with different goals. The Learning Cycle was developed as way to bring the process of learning from inquiry that scientists engage in to students. The Learning-for-Use design framework has been developed to highlight the need for motivation based on usefulness and the need to develop knowledge that is organized to support access and application (the *motivate* and *refine* phases in the framework), because they are too often overlooked.

The LfU model does not make any commitment to particular approaches to motivation, construction, or apply, but in my own work, I have been pursuing a specific approach that I call *Scenario-Based Inquiry Learning* (SBIL). Scenario-based inquiry learning draws from project-based science (Krajcik, Czerniak, & Berger, 1999), anchored instruction (Cognition & Technology Group at Vanderbilt, 1997), and goal-based scenarios (Roger C. Schank, Fano, Bell, & Jona, 1993/1994), which share a focus on authentic tasks as a way of motivating and contextualizing learning. In scenario-based inquiry learning, the motivate phase of LfU is accomplished by introducing students to a scenario in which they must achieve a goal that necessitates the achievement of the learning goals associated with the unit. This goal might be answering a driving question as in project-based science, solving a problem as in anchored instruction, or achieving a goal in a role-play as in goal-based scenarios. In addition to providing the motivation, this scenario also provides the opportunity to organize their new understanding for use by applying it. As with, project-based science inquiry plays an important role in scenario-based inquiry learning. A substantial part of the knowledge construction is supported by activities in which learners engage in inquiry.

In one example drawn from the *Looking at the Environment* high school environmental science curriculum, the scenario focuses on water resources management in California's Central Valley. In this scenario, students are asked to make a policy decision about how to manage water resources in the Fresno area, where one of the most productive agricultural regions in the U.S. and a fast-growing urban population are using surface and underground fresh water supplies at a faster pace than they are being restored. Students are given several policy options that include drilling more wells, changing irrigation practices, removing land from agricultural cultivation, restricting housing development, and restricting domestic water usage. This scenario is designed to motivate students' learning about agricultural practices, irrigation, surface and underground freshwater reserves, dams and wells, ecological impacts of water engineering, and domestic water use, among others. In this 12-week unit, students conduct a range of investigations and other learning activities to develop an understanding of the science necessary to make the policy decision in the scenario. For example, in one sequence they grow Wisconsin Fast Plants in soils of different water retention capabilities, then use a spreadsheet model of a farm water budget to try to create efficient irrigation plans for different crops in different soils, and finally try to develop a plan for improving efficiency of a real farm based on data from precision agriculture that they visualize and analyze in WorldWatcher. At the conclusion of the unit, they investigate the policy options using a variety of GIS data, then select and defend a specific option using a framework for environmental decision-making that they learned in a previous unit.

In other scenario-based inquiry learning units we have developed, students develop climate models for a fictitious planet, participate in a mock international conference on global climate change, create a design for a new school building to minimize impact on the site's natural ecosystem, and select an energy source for an electrical power plant for a specific community.

These units have demonstrated a measure of success across settings that have included urban, suburban, and rural schools, and across diverse student populations. While none of the evaluations conducted on these units would qualify for the What

Works Clearinghouse, we have collected pre/post-test data on tests involving a combination of multiple choice, short answer, and extended response questions that assess a mix of factual knowledge, conceptual understanding, and scientific inquiry practices. For example, in an evaluation of the LeTUS unit on Global Warming conducted in the 2001-2 school year, Herman and colleagues measured a pre to post effect size of .66 ($n=623$ 7th and 8th graders; $P<.001$) (Herman, MacKenzie, Sherin, & Reiser, 2002). In an external evaluation of one unit of the Looking at the Environment high school curriculum, researchers from SRI International measured an effect size of .68 ($n=280$; $p<.000$) (Crawford & Toyama, 2002). We hope to be able to do evaluations in a randomized field trial in the future to understand the differences in effectiveness of these curricula in comparison to more traditional approaches. In addition to evaluations of learning outcomes, we have also begun to conduct research on the motivational effectiveness of these curriculum units. The theory behind them posits that students will adopt the role and/or goal associated with the scenario, and that that will motivate them to participate in the learning activities and contextualize their learning in a way that improves learning outcomes. In the first stage of this research, we are investigating the primary assumption that students do “buy in” to the scenario by looking at individual differences among students through data collection that includes interviews, daily questionnaires, and observation (Pitts & Edelson, 2004). In our first round of small scale studies, we have found that most students do buy in, but that the degree of buy in differs significantly and the nature of that buy does as well. For example, some students described themselves as “pretending” to be a scientist in one scenario, while others reported that they were “interested” in working on the scenario because the problem seemed interesting or important. Others, reported that the scenario did not engage them, and that their motivation was based on a concern for doing well in school.

While we are able to report success for these curriculum units in classrooms, the story would not be complete without a discussion of teacher preparedness. The teachers that were included in the studies summarized above all received substantial professional development that was offered as a result of our earlier implementation efforts.

5. The Teacher Learning Story

The teacher learning story is the newest and least fully developed of the three. The best way to motivate is through the early implementation efforts for the curricula developed by LeTUS in Chicago. These curricula had been developed by teams of researchers from Northwestern and teachers from Chicago Public Schools around the district and state science standards that had recently been released. Before enacting each 6-8 week curriculum unit, each teacher participated in a 3-hour session at a summer workshop and a one-day in-service workshop on that curriculum. They also had access to a professional development specialist who could answer calls by phone, visit schools for planning meetings, and co-teach lessons that teachers were not comfortable with. Despite that level of professional development and support, our experience in the first year of implementation was that the vast majority of teachers either never started teaching the unit they had signed up to teach or never completed it. This was a pretty dramatic lesson that this representative group of teachers either were not adequately prepared or did not feel adequately prepared to teach these technology-supported inquiry units.

This led us to initiate a program of research on both the content and structure of teacher professional development on technology-supported inquiry-based science teaching that is still underway. In the case of this research, we do not yet have well-developed design frameworks, but we have strategies that we are investigating.

The primary challenges that we have identified are consistent with the literature on teacher knowledge and teacher learning. Often teachers lack knowledge of specific content, particularly in the case of a curriculum unit that has a context or emphasizes depth of knowledge in a particular area that goes beyond the typical textbook. For example, the unit on water resources management described earlier goes beyond the content of a standard environmental science curriculum on agricultural practices or water engineering. Often teachers' pedagogical content knowledge, e.g., how to specify learning objectives, how to respond to students' ideas, and how to assess student understanding, is weak. For many teachers, the pedagogical approach is new. They have difficulty implementing both the scenario-based and inquiry-based elements because they don't fully understand the rationale, they lack the knowledge and skills necessary to implement them, and they don't have prior experiences to draw on. Finally, the specific scientific practices and uses of technologies are often unfamiliar and intimidating to teachers.

One observation that surprised us is that many of the LeTUS teachers who failed to implement or to complete the units had participated in substantial amounts of professional development on inquiry approaches to science teaching. In fact, they could often describe the goals and techniques of inquiry-based science teaching as well as or better than we could. This disconnect between the talk and the walk was a puzzle. Our conjecture is that the decontextualized way in which that professional development was implemented (inquiry in the abstract) prevented teachers from being able to apply it in the specific context of LeTUS units. Therefore, an important strategy we have been pursuing is that *professional development ought to be conducted in the context of specific curriculum*. We call this curriculum-linked professional development. Therefore, in LeTUS we began offering extended professional development experiences (10-week graduate credit courses) focusing on a specific LeTUS curriculum unit. While this approach carries the risk of devolving into training for a particular unit, we attempt to design our professional development experiences so that teachers develop understanding in a particular context but are encouraged to recognize how that understanding would transfer to other curriculum contexts. An important rationale from this approach comes from the fact that offering professional development in the context of a curriculum that a teacher intends to implement provides a motivation for the teacher to learn. In this way, the curriculum-linked approach to professional development fulfills the requirements of the "create demand" and "apply" strategies in the Learning-for-Use framework.

A second strategy that works in concert with the curriculum-linked approach is to *extend the professional development activities over the time that the teachers are implementing the curriculum*. In the case of the graduate courses offered to LeTUS teachers, the teachers were required to implement the curriculum in their classes over the same period that they were enrolled in the class. This gives the facilitators of the professional development to link the activities in the PD to classroom activities and experiences. While this approach has proven successful for a community that is in close proximity, as in LeTUS, it poses problems for a community that is geographically

dispersed. For that reason, we are exploring the use of online tools to support this approach to professional development.

Our experience with this approach to professional development is that a much larger percentage of teachers who are taking the courses complete the units associated with the courses than those who don't. More important, they are more likely to teach the unit again and to try other LeTUS units as well. On the other hand, we only have very limited information about the quality of their classroom implementations, other than the test scores of their students. In future research, we hope to identify scalable techniques for characterizing teacher implementation and to use these techniques to study the impact of different forms of professional development.

6. Reflections

Reflecting back upon the research programs summarized here, I am struck by one clear conclusion and two important open questions. The conclusion is that this is demanding research requiring large teams representing diverse expertise. It falls into the paradigm of “big science”. It cannot be performed by a solitary individual alone in his or her garret. It requires individuals representing expertise in science, technology, cognitive science, classroom teaching methods, and teacher professional development. On our research and development teams, we have had faculty, graduate students, and postdocs in learning sciences, geoscience, and computer science, programmers, teachers, and professional development specialists. It has involved long-term partnerships among universities, school districts, and schools. Finally, it has required individuals to get out of their usual places of work and into each others for extended periods of time. Researchers have spent extensive periods of time both observing and participating in classroom, and teachers have spent extensive periods of time in the university setting, participating in design meetings and developing materials as part of design teams.

The first question is a research methods question. It is, *How can lessons about design be shared?* I typically characterize the products of my research as being design frameworks. But, what is a design framework? In what form can and should design theories be shared? For example, a design framework can consist simply of a set of questions that should be answered, issues that should be considered, or tradeoffs that should be weighed in a design process. Or, a design framework can consist of strategies, guidelines, and recommendations, that do not simply enumerate issues, but provide guidance on how to respond to those issues. At what level of detail can and should issues and recommendations be expressed? The nature of content and pedagogy mean that educational design can not be reduced to a mechanized process. The differences in disciplines and content areas within disciplines mean that each area is a special case. The misguided efforts to teach *the* scientific method show the pitfalls of attempting to treat science or any other content area as a uniform whole. Therefore, the challenge of creating design frameworks is identifying the “sweet spot” that captures essential commonalities across content areas and disciplines, while leaving room for designers to improvise and adapt to the specifics of content area, audience, and context. Finally, what is the relative value of abstractions, like issues and strategies, compared to examples. People are naturally case-based reasoners (Roger .C. Schank, 1982; Kolodner, 1993). In complex domains like design, where there can be no complete theory, it is often more natural to design by finding and adapting relevant examples than by designing by rules

and principles. I have been struck that people are more likely to tell me how much they appreciate the examples in my papers than the abstract principles. It might be that the educational design community can best be served by creating large libraries of cases to consider than handbooks full of issues to attend to and guidelines to follow. I believe that understanding how designers can best be served by research is a question that educational design researchers must begin to address directly if we are to have impact on practice.

The second question is about inquiry itself. The question is, *How do we enable students to make the transition from guided inquiry to open-ended self-directed inquiry?* To me, our lack of insight on this question represents the major shortcoming of this research program to date. In the research described here, we made the conscious decision, based on our initial experiences, to develop curricula that would engage students in guided, or structured, inquiry. In these curricula, the driving questions or problems are presented to students. They engage in structured investigations of portions of the problem and are challenged to synthesize their own research results together with information that is provided to them to construct a solution to the overall problem. Their experience has important elements of inquiry, but it is not self-guided, and it is open-ended within a provided structure and context. We justified this approach based on the observation that the middle school and high school populations that we have worked with were not adequately prepared to engage in open-ended inquiry, nor were their teachers prepared to supervise them in truly open-ended inquiry. As an exception that proves the rule, one CoVis teacher did create a curriculum to engage his students in open-ended inquiry, with fascinating results described by Joe Polman in a book based on his Ph.D. dissertation (Polman, 2000). This book describes the extraordinary effort required by an exceptional teacher and is inspiring in the possibilities that it demonstrates while discouraging in the challenges that it exposes. I believe that we have made a sound decision in pursuing a developmental approach that builds inquiry skills in a scaffolded fashion with the goal of fading those scaffolds at some time in the future. The question, however, is when and how to fade those scaffolds. In my own research area, I characterize one of the skills necessary to conduct open-ended inquiry as *analytical fluency*. Analytical fluency is the ability to select and apply a particular set of analytical tools to answer a specific question. Most students only appear to gain the ability to apply analytical tools and interpret their results from the curricula they have developed. They do not appear to acquire the ability select the appropriate analytical operations for a particular question or context. I see understanding how to help students make the transition to analytical fluency as being the next major challenge to developing true inquiry skills in students. However, making this transition will require both creative educational designs and time. It is not clear that the current curricular emphasis on broad content will offer students and teachers the opportunity to spend the required amount of time on inquiry to develop those skills.

7. Conclusion

The design of learning experiences that will enable students to develop the skills and knowledge required to engage in inquiry is in many ways an engineering problem. We currently have sufficient science and theory to begin to engineer solutions to the “inquiry” problem. However, it is not a simple problem that can be solved through narrow approaches. It requires systemic approaches that attend to the challenges of both student and teacher learning and of the physical and organizational context.

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