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Learning-for-Use: A Framework for the Design of Technology-Supported Inquiry Activities

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Abstract: Meeting ambitious content and process (inquiry) standards is an important challenge for science education reform particularly because educators have traditionally seen content and process as competing priorities. However, integrating content and process together in the design of learning activities offers the opportunity to increase students' experience with authentic activities while also achieving deeper content understanding. In this article, I explore technology-supported inquiry learning as an opportunity for integrating content and process learning, using a design framework called the Learning-for-Use model. The Learning-for-Use model is a description of the learning process that can be used to support the design of content-intensive, inquiry-based science learning activities. As an example of a technology-supported inquiry unit designed with the Learning-for-Use model, I describe a curriculum called the Create-a-World Project, in which students engage in open-ended Earth science investigations using WorldWatcher, a geographic visualization and data analysis environment for learners. Drawing on the Learning-for-Use model and the example, I present general guidelines for the design of inquiry activities that support content learning, highlighting opportunities to take advantage of computing technologies. © 2001 John Wiley & Sons, Inc. J Res Sci Teach 38: 355–385, 2001

Science educators are facing rapidly increasing demands. At the same time that they are being asked to teach more content more effectively, they are being asked to devote more time to having students engage in scientific practices. The ambitious new *National Science Education Standards* (National Research Council [NRC], 1996) provide a compelling example of this pressure on teachers. With respect to content, the standards condemn the traditional emphasis on memorization and recitation in science education. Instead, they call for teachers to foster "deep" and "robust" conceptual understanding that students can draw on to create explanations, make predictions, and argue from evidence. With respect to process, they call at the same time for inquiry to play a much more prominent role in science learning to give students a firsthand experience of the dynamic processes of questioning, evidence-gathering, and analysis that characterize authentic scientific practice.

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Traditional science teachers often perceive these demands as unachievable because they view content learning activities and process learning activities as competing for the scarcest of classroom resources—time. In traditional science classrooms, content and inquiry skills are taught separately through separate learning activities. In these classrooms, content is taught didactically through lecture, reading, and problem sets, and scientific practices are taught through structured laboratory experiments. However, the ambitious objectives for both content and process in the national science standards are based on an inquiry learning model, in which students develop deep, interconnected content knowledge and inquiry skills through activities that incorporate authentic scientific inquiry. This inquiry-based pedagogy is embodied by the Learning Cycle, an approach to integrating content and process learning in science that was first proposed during the curriculum reforms of the late 1950s and early 1960s and has been adapted and refined since then (Abraham, 1998; Karplus & Thier, 1967; Lawson, 1995; Renner & Stafford, 1972). Despite documentation of the benefits of inquiry learning for fostering rich and robust content learning (e.g., Wise & Okey, 1983; Shymansky, 1984; Lott, 1983; Von Secker & Lissitz, 1999; Shymansky, Kyle, & Allport, 1983), teachers have remained resistant to it for a variety of reasons including the perceived time crunch mentioned above (Welch, Klopfer, Aikenhead, & Robinson, 1981; Costenson & Lawson, 1986).

Since 1992, my colleagues in the Center for Learning Technologies in Urban Schools and I have been investigating the use of technology to support inquiry learning with the hope that it can help to bring about this elusive reform. We are pursuing this research on technology-supported inquiry learning (TSIL) for three reasons. First, computational technologies have become increasingly important to the practice of science. Computers now play a central role in data collection, data analysis, modeling, and the communication of results in scientific research. Any effort to engage students in authentic scientific practices should reflect this trend. Second, computer tools offer important benefits for learning in their ability to store and present information in dynamic and interactive formats. Third, the introduction of computers into schools presents an unprecedented opportunity for reform. For reasons having more to do with politics than with educational research, computers are being installed in schools in large numbers. In many cases, those computers are being installed without a plan for how to integrate them into the curriculum. We believe that if we are able to present schools with compelling examples of the use of computers to achieve ambitious science education standards, the introduction of computers into schools will become an opportunity to engage those schools in science education reform.

In this article, I present the Learning-for-Use (LfU) model, a design framework that was developed to support the design of learning activities that achieve both content and process learning. I begin with an overview of the model, followed by an example of a technology-supported inquiry unit that is based on it. Drawing on that example, I then describe the design implications of the model in more detail, with a particular focus on the role that technology can play in the design of learning-for-use activities. I conclude with a discussion of open issues.

Learning for Use

A common criticism of traditional approaches to education is that they lead to shallow understanding because of their emphasis on memorization and recitation of facts. As Whitehead pointed out more than 70 years ago, the focus on memorization leads to “inert knowledge” that cannot be called upon when it is useful (Whitehead, 1929). The goal of the LfU model is to overcome the inert knowledge problem by describing how learning activities can foster useful conceptual understanding that will be available to the learner when it is relevant.

The LfU model is a theory of learning that is intended to provide a framework for design. It builds on fundamental theories of learning with the express aim of supporting designers in the development of learning activities. The model is based on four principles that are shared by many contemporary theories of learning:

1. Learning takes place through the construction and modification of knowledge structures.
2. Knowledge construction is a goal-directed process that is guided by a combination of conscious and unconscious understanding goals.
3. The circumstances in which knowledge is constructed and subsequently used determine its accessibility for future use.
4. Knowledge must be constructed in a form that supports use before it can be applied.

In the following discussion, I briefly elaborate upon these principles and their implications. The vocabulary that I use in this discussion is heavily influenced by models of understanding from symbolic artificial intelligence, particularly those of Schank (1982). However, the principles are compatible with a wide range of theories in the contemporary literature on learning, including those from both cognitivist and situated learning perspectives.

The first principle is the central tenet of constructivism. It states that learning is the process of constructing new knowledge structures and forging new connections between knowledge structures in an interconnected web (Quillian, 1966; Minsky, 1985; Schank, 1982). The implication of this principle for classroom learning is that understanding must be incrementally constructed from experience and communication. Knowledge cannot be transmitted directly from one individual to another, with the result that every individual's knowledge structures reflect his or her unique experiences. Neither can rich knowledge be constructed instantaneously. Understanding must be developed incrementally through the stepwise elaboration of knowledge structures.

The second principle captures the goal-directed nature of learning. To a certain extent, learning can be consciously monitored and directed through metacognitive processes (Brown, 1980; Flavell, 1973). However, the actual construction of knowledge structures takes place below the level of awareness and is guided by unconscious processes that attempt to make sense of experience (Leake & Ram, 1995; Anderson, 1983; Laird, Rosenbloom, & Newell, 1986; Schank & Abelson, 1977; Berlyne, 1966). The implication of this principle for the classroom is that learning must be (and can only be) initiated by the learner, whether it is through conscious goal-setting or as a natural, unconscious result of experience.

The third principle describes the influence of the learning context on the accessibility of knowledge. Whereas the third principle represents a central claim of situated theories of cognition (Brown, Collins, & Duguid, 1989; Greeno, 1989), it is also fundamental to cognitivist theories. This principle is based on the recognition that knowledge is retrieved based on contextual cues (Glaser, 1992; Schank, 1982; Chi, Peltovich, & Glaser, 1981; Simon, 1980), called *indices* in the vocabulary of case-based reasoning (Schank, 1982; Kolodner, 1993). When learning takes place, the connections that can be constructed for subsequent retrieval of the new (or newly elaborated) knowledge structures depend on the context in which the learning takes place. These connections may be elaborated later, whenever the knowledge structures become reactivated. This creation and elaboration of indices is a critical part of the learning process. The implication of this principle for classroom learning is that the learning context must support the learner in creating appropriate indices to knowledge structures. Otherwise the learner will be unable to retrieve those structures when they are relevant in the future.

The fourth principle captures the difference between declarative and procedural knowledge. To apply declarative knowledge, an individual must have procedural knowledge that enables him to apply that declarative knowledge, or he must be able to transform it into procedural knowledge (Anderson, 1983). When an individual is unable to operationalize his knowledge, he may, for example, be able to retrieve and recite facts that are relevant to a problem without being able to combine those facts to construct a solution to that problem. The implication of this third principle is that learning how to use conceptual knowledge must be part of the learning process, if the knowledge is to be useful.

Three Steps in Learning-for-Use

The LfU model incorporates these four principles and their implications into a description of learning that can inform the design of curriculum. The LfU model characterizes the development of useable understanding as a three-step process consisting of (a) motivation, (b) knowledge construction, and (c) knowledge refinement.

Motivation: Experiencing the Need for New Knowledge. The first step in learning for use is recognizing the need for new knowledge. This recognition, which need not be conscious, occurs when one comes up against a limitation or gap in one's knowledge (Schank, 1982; Berlyne, 1966). According to Schank (1982), reaching the limits of one's knowledge has two effects. It creates a desire (motivation) to address the limitation by acquiring new knowledge, and it creates a context in memory for integrating new knowledge. The knowledge structures that are activated at the point that a learner recognizes the limits of his or her understanding provide the connection points for new knowledge. By eliciting a desire to learn, the motivation step in the LfU model addresses Principle 2, the goal-directed nature of learning. By creating a context in memory for the integration of new knowledge, it also acknowledge the requirements of incremental knowledge construction.

Whereas this step in the LfU 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 LfU model.

Knowledge Construction: Building New Knowledge Structures. The second step in the learning process is the development of new knowledge. 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 LfU model recognizes incremental knowledge construction as the fundamental process of learning, as stated in Principle 1.

Knowledge Refinement: Organizing and Connecting Knowledge Structures. The third step is refinement, which responds to the need for accessibility and applicability in learning for use.

In the refinement step, knowledge is reorganized, connected to other knowledge, and reinforced 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 (Glaser, 1992; Schank, 1982; Chi et al., 1981; Simon, 1980; Kolodner, 1993). Knowledge refinement must achieve both of those goals. Refinement of knowledge can also take the form of reinforcement, which increases the strength of connections to other knowledge structures through the traversal of those structures and increases the likelihood that those connections between knowledge structures will be found in the future. This step addresses Principles 3 and 4, the situated nature of knowledge and the need for procedural knowledge.

Although 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.

The LfU Model as a Design Framework

The LfU model provides a basis for thinking about the design of activities that will contribute to the development of robust, useful understanding. From the perspective of design, the LfU model articulates the requirements that a set of learning activities must meet to achieve particular learning objectives. The hypothesis embodied by the LfU model is that a designer must create activities for each learning objective that effectively achieve all three steps in learning for use for that objective. To support this design process, the LfU model describes different processes that can fulfill the requirements of each step (Table 1).

In the design of learning activities, the different processes in Table 1 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. In addition, in the knowledge refinement stage, there is increasing evidence that application and reflection are both critically important to the development of useful knowledge (e.g., White & Frederickson, 1998; Scardamalia, Bereiter & Steinbach, 1984; Palincsar & Brown, 1984; Schoenfeld, 1985).

The third column in Table 1 describes activities that educators can use to achieve the steps in the LfU model. This reflects the LfU model's goal of supporting the design of learning activities. To show how the different types of activities can be combined to achieve all three steps, I present an example of an inquiry-based science curriculum in this paper that incorporates all six of the processes described in Table 1. Following that example, I will return to the question of how activities can be designed to support each of these processes. In that section, I provide more complete descriptions of the individual processes in the LfU model.

Learning-for-Use and the Learning Cycle

The LfU model was designed as a general framework for the design of learning activities When it is applied in the context of inquiry-based science learning, the LfU model describes a

Table 1
The three steps in the Learning-for-Use model with descriptions of the processes that can comprise each step

Step	Process	Design Strategy
Motivate	Experience demand	Activities *create a demand* for knowledge when they require that learners apply that knowledge to complete them successfully.
	Experience curiosity	Activities can *elicit curiosity* by revealing a problematic gap or limitation in a learner's understanding.
Construct	Observe	Activities that provide learners with *direct experience* of novel phenomena can enable them to *observe* relationships that they encode in new knowledge structures.
	Receive communication	Activities in which learners receive direct or indirect *communication* from others allow them to build new knowledge structures based on that communication.
Refine	Apply	Activities that enable learners to *apply* their knowledge in meaningful ways help to reinforce and reorganize understanding so that it is useful.
	Reflect	Activities that provide opportunities for learners to retrospectively *reflect* upon their knowledge and experiences retrospectively, provide the opportunity to reorganize and reindex their knowlege.

variant of the Learning Cycle. The Learning Cycle was developed as part of the science education reform efforts of the 1960s (Abraham, 1998; Karplus & Thier, 1967; Lawson, 1995; Renner & Stafford, 1972). The Learning Cycle was developed as a way of translating the inquiry process used by scientists to advance human understanding into a process that can be followed by teachers and students to advance students' understanding (Karplus & Thier, 1967; Renner & Stafford, 1972). Informed by the cognitive theories of Piaget (Karplus & Thier, 1967; Renner & Stafford, 1972) the Learning Cycle was designed to help address the limitations of the traditional model of inquiry in science in developing robust understanding, which advocates of the Learning Cycle refer to as the *inform, verify, practice* cycle (Renner, 1982; Abraham, 1998). Different forms of the Learning Cycle were incorporated into several of the most influential reform curricula during this period including the Science Curriculum Improvement Study (SCIS), Elementary School Science Project (ESSP), and Biological Sciences Curriculum Study (BSCS).

Articulated initially by Robert Karplus, a physicist turned educator, the Learning Cycle characterizes scientific inquiry as consisting of three phases: exploration, invention, and discovery. In the exploration phase, a scientist gathers evidence; in the invention phase, the scientist induces relationships and names concepts; and in the discovery phase, the scientist uses those relationships and concepts to investigate other phenomena. As a process for science learning in the classroom, the Learning Cycle replaces the open-ended exploration, invention, and discovery of scientists with analogous processes that are selected and sequenced by curriculum designers or teachers and guided in the classroom by teachers. In the exploration phase of the Learning Cycle, students participate in activities designed to provide them with experience that will help them to understand specific scientific concepts. This phase typically consists of a hands-on laboratory or field experience in which learners collect observations or measurements. In the invention phase, students discuss their findings from the exploration phase and attempt to build explanations for them. The role of the teacher in this phase is to introduce or name concepts for students when he or she judges that the students are ready for them. In more recent descriptions of the Learning Cycle, the name *invention*, which was selected initially because it describes what scientists do in the second phase of inquiry, was replaced by *term introduction*, to more accurately reflect the way the Learning Cycle is conducted in classrooms (Lawson, 1995). In the discovery phase of the Learning Cycle, students make additional observations and attempt to apply the concepts they learned in the invention phase to verify or identify limitations in their understanding. This phase has more recently been described as the concept application phase (Lawson, 1995).

As a result of their shared foundations and goals, the Learning Cycle and the LfU model have many similarities. Both were informed by cognitive theories of learning, and both were developed to help curriculum designers integrate content and process learning. Key areas of overlap between the LfU model and the Learning Cycle are *Elicit curiosity* (LfU) and exploration Learning Cycle both involve motivating learning by introducing learners to discrepant phenomena; observe (LfU) and exploration Learning Cycle both describe processes of learning through direct experience; communicate (Lfu) and term introduction (Learning Cycle) both descnbe processes of identifying and naming regularities in phenomena; apply (LfU) and concept application (Learning Cycle) both describe processes for employing new knowledge.

There are four primary points of difference between the LfU model and the Learning Cycle as characterized by Karplus (Karplus & Thier, 1967) and Lawson (1995). First, the LfU model is a general model of learning that is not specific to either inquiry or learning, although that is where it is currently being applied. Second, in the LfU model, we have selected the names of the phases to place the primary emphasis on the learning process. Whereas the stages in the Learning Cycle have been named according to the activities that students and teachers engage in, the stages in the LfU model are named according to their role in the learning process. This distinction is subtle, but it is potentially critical for a framework whose primary goal is to communicate research-based design principles to designers. Third, the LfU model is designed to focus emphasis on the application of knowledge. In typical implementations of the Learning Cycle, the exploration and term introduction phases receive the primary emphasis. In its focus on fostering useful knowledge, the Lfu model emphasizes knowledge application. The existence of create demand as an explicit strategy for motivating learning in LfU but not in the Learning Cycle reflects that emphasis. The LfU model is intended to encourage designers to build units around a knowledge application task that can create demand for the learning objectives initially and then offer learners the opportunity to refine their understanding through the application of their newly acquired knowledge and skills. When designers create such tasks, they have accounted for both the motivation and application processes required by Learning-for-Use. Finally, like Collins. Brown, and Duguid's (1989) *cognitive apprenticeship* and Driver's (1989) *general teaching sequence* approaches, the LfU model incorporates reflection as an explicit knowledge refinement process.

None of the differences between LfU and the Learning Cycle represent fundamental incompatibilities. Rather, they reflect the LfU model's emphasis on knowledge application and its attempt to be as explicit as possible in the communication of design strategies about the requirements of robust learning.

The LfU Model in Action: The Create-a-World Project

The Create-A-World Project is a middle school curriculum unit that was designed with the explicit goal of teaching science content through inquiry activities. Its content focus is the relationship between physical geography and climate. Over the course of the project, students create their own fictitious worlds by inventing data that describe their worlds' geography and climate. The students are invited to invent any physical geography they want for their worlds, but they are asked to predict the climate realistically based on scientific principles. Students learn about the relationships that will enable them to model the climates for their worlds by conducting open-ended investigations of climate and physical geography on Earth.

Create-a-World Learning Objectives

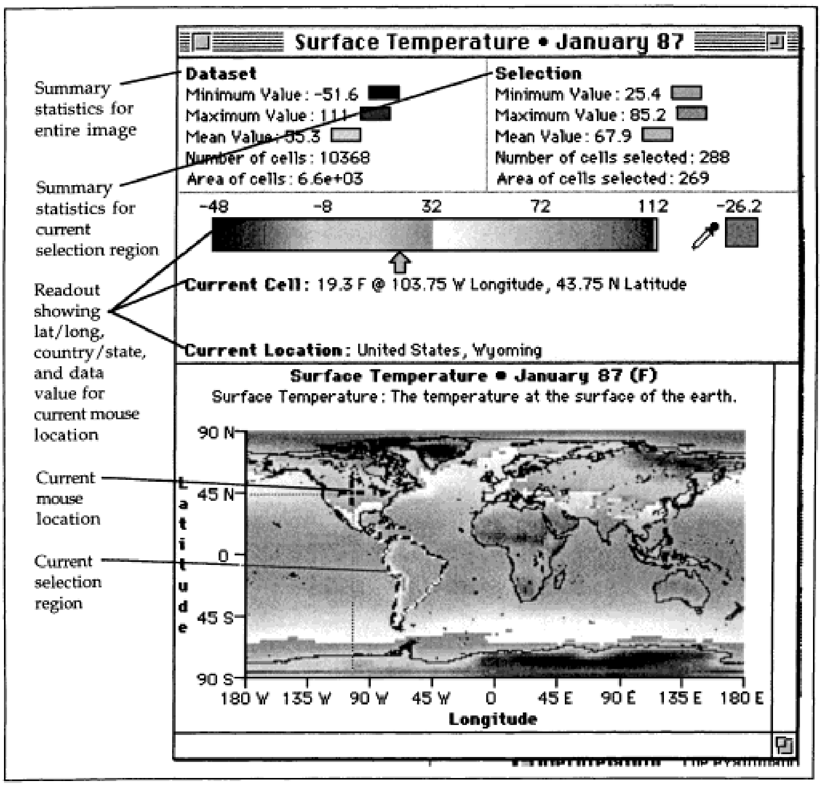
The Create-a-World Project targets content objectives in earth science. It focuses on the relationship between temperature and geography from a climatic perspective. For example, after completing the project, a student should be able to explain observed differences between January average temperature and July average temperature for a particular region, and to predict differences between the average air temperature over major geographic features such as the Andes or the Great Lakes and their neighboring regions. The specific physical processes that are covered include radiative energy transfer, (reflection, absorption, and emission of electromagnetic radiation), seasonal variation in incoming solar energy, reflectivity of the Earth's surface, pressure and temperature in gases, and specific heat. The goal of the project is for students to be able to use these concepts to explain or predict differences in temperature due to latitude and season, elevation, groundcover, and proximity to large bodies of water.

The Create-a-World Project targets inquiry skills, both general and domain-specific, and provide opportunities to develop and apply those skills. The general inquiry skills that it calls for include formulating hypotheses, collecting and evaluating evidence, and defending conclusions based on evidence. The domain-specific skills it calls for involve the visualization and analysis of quantitative data. The goal of the project is for students be able to formulate hypotheses based on observed patterns in data visualizations and to collect and evaluate evidence for those hypotheses using the data analysis tools described below.

The Create-a-World Project provides the opportunities for learners to acquire and refine these inquiry skills through well-defined, guided investigation activities. The interweaving of investigations and discussions allows students to employ and then reflect upon the general inquiry skills. The initial WorldWatcher activities are highly structured and introduce visualization and analysis techniques one at a time in a developmental sequence that starts with learning about the representation and progress through a series of techniques for manipulating data and representations. These structured activities lay the foundation for the open-ended investigations that follow them. As students progress through the project, they move from learning about inquiry techniques to employing them in the service of their project goals.

Technology Support

The Create-a-World Project uses two pieces of educational software designed at Northwestern as technology supports for inquiry learning. They are WorldWatcher, a scientific visualization and data analysis program designed for learners (Edelson, Gordin, & Pea, 1999; Edelson & Gordin, 1998), and the Progress Portfolio, an inquiry support environment that allows students to record, annotate, and organize the intermediate products of their projects (Loh et al., in press).



Summary statistics for entire image

Summary statistics for current selection region

Readout showing lat/long, country/state, and data value for current mouse location

Current mouse location

Current selection region

Surface Temperature • January 87

Dataset
Minimum Value: -51.6
Maximum Value: 111
Mean Value: 55.3
Number of cells: 10368
Area of cells: 6.6e+03

Selection
Minimum Value: 25.4
Maximum Value: 85.2
Mean Value: 67.9
Number of cells selected: 288
Area of cells selected: 269

Current Cell: 19.3 F @ 103.75 W Longitude, 43.75 N Latitude

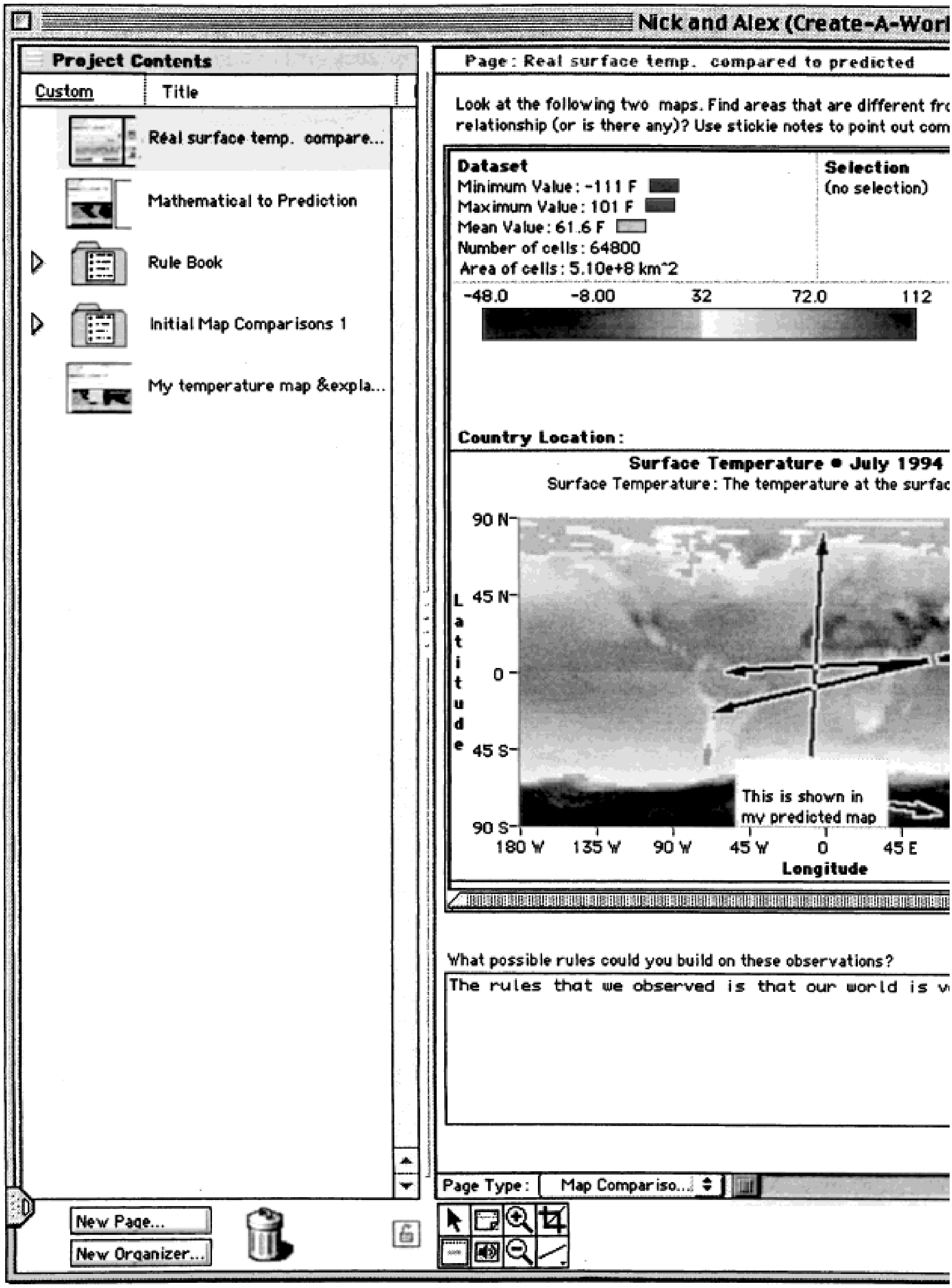
Current Location: United States, Wyoming

Surface Temperature • January 87 (F)
Surface Temperature: The temperature at the surface of the earth.

Figure 1. A WorldWatcher visualization window.

WorldWatcher. WorldWatcher was designed to bring the power of scientists' computational tools to learners (Gordin & Pea, 1995). It was created by adapting scientific research tools to provide the support required by students and teachers using the principles of learner-centered design (Soloway, Guzdial, & Hay, 1994). WorldWatcher displays gridded geographic data in the form of interactive color maps that users can customize by adjusting the colorscheme, magnification, and spatial resolution (Figure 1). In addition to data visualization, WorldWatcher supports data analysis through arithmetic operations and statistical analyses. It also allows users to enter or create new data using a conventional graphics program interface to draw the data.

The Progress Portfolio. The Progress Portfolio (Fig. 2) is an inquiry-support environment for learners that is designed to facilitate reflective inquiry by giving them a place to record and monitor their investigations (Loh et al., in press). The Portfolio provides students with a set of tools for capturing, annotating, organizing, and creating presentations from work in other computer applications. In the Create-a-World Project, students capture work from WorldWatcher and use the Progress Portfolio as a place to record their observations and their current hypotheses of explanations for those observations.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Project Contents
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Title
Real surface temp. compare...
Mathematical to Prediction
Rule Book
Initial Map Comparisons 1
My temperature map &expla...
New Page...
New Organizer...
Selection
(no selection)
-48.0
-8.00
32
72.0
112
Surface Temperature ● July 1994
90 N
45 N
0
45 S
90 S
Latitude
180 W
135 W
90 W
45 W
0
45 E
Longitude
This is shown in my predicted map
Page Type:
Map Compariso...

Page: Real surface temp. compared to predicted

Look at the following two maps. Find areas that are different fr
relationship (or is there any)? Use stickie notes to point out com

Dataset
Minimum Value: -111 F
Maximum Value: 101 F
Mean Value: 61.6 F
Number of cells: 64800
Area of cells: 5.10e+8 km^2

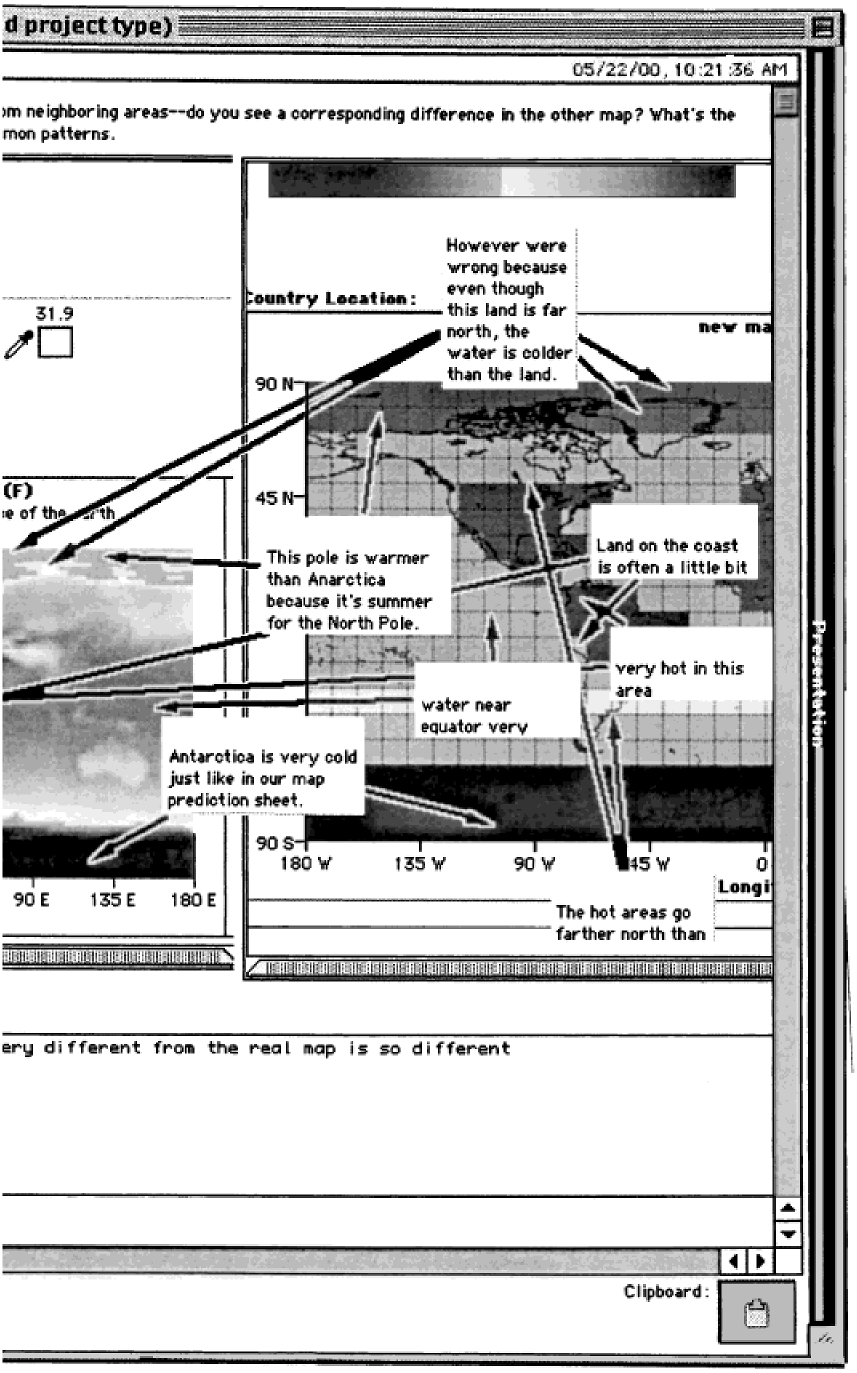
Country Location:

Surface Temperature: The temperature at the surfac

What possible rules could you build on these observations?

The rules that we observed is that our world is v

Figure 2. A Progress Portfolio screen showing a table of contents on the left and annotated student work on the right.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Presentation
Clipboard:

m neighboring areas--do you see a corresponding difference in the other map? What's the mon patterns.

However were wrong because even though this land is far north, the water is colder than the land.

This pole is warmer than Anarctica because it's summer for the North Pole.

Land on the coast is often a little bit

very hot in this area

water near equator very

Antarctica is very cold just like in our map prediction sheet.

The hot areas go farther north than

ery different from the real map is so different

The Five Activities in the Create-a-World Project

As described below, the Create-a-World Project takes 20–25 hr of class time. It was originally piloted in two 1-week workshops conducted at Northwestern University in the summers of 1997 and 1998 with the author serving as instructor. In the 1998–1999 and 1999–2000 school years the project was also implemented in seventh- and eighth-grade classes in six schools in the Chicago area. The examples in this section are drawn from across these settings. The five activities in the Create-a-World Project are as follows.

Activity 1. Introduction: Thinking about Global Temperature. Activity 1 is designed to start students thinking about temperature variation and to introduce them to the data representation used in WorldWatcher. In this activity, students are each given six crayons and a blank map of the world. They are asked to draw their best guess of the average temperature all around the world in the month of July. Figure 3 shows an example of a student's hand-drawn map. The students are told that this activity is just intended to get them thinking about differences in temperature around the world and assured that their work will not be judged.

Once they have drawn their maps, students share their maps with each other and participate in a group discussion of how they drew them, what knowledge they drew on in constructing them, and what questions the activity raised for them. The large majority of students' drawings consist almost entirely of horizontal bands of color (Figure 3). A minority also include some influence of major geographic features, such as oceans and deserts. When they discuss the process of drawing their maps, students often report that they did not think they could do the task at all at first. Then they decide that they know enough to draw some broad trends, but they typically finish with questions and doubts even about what they thought they knew. When students discuss the strategies they used in drawing their maps, they often describe an approach in which they start with a familiar location and draw increasing temperatures toward the equator and decreasing temperatures toward the poles. Another common strategy is to use a case-driven approach in which students find locations for which they have some basis for judgment and interpolate between them. During these debriefing discussions, students often become impatient to see the real thing.

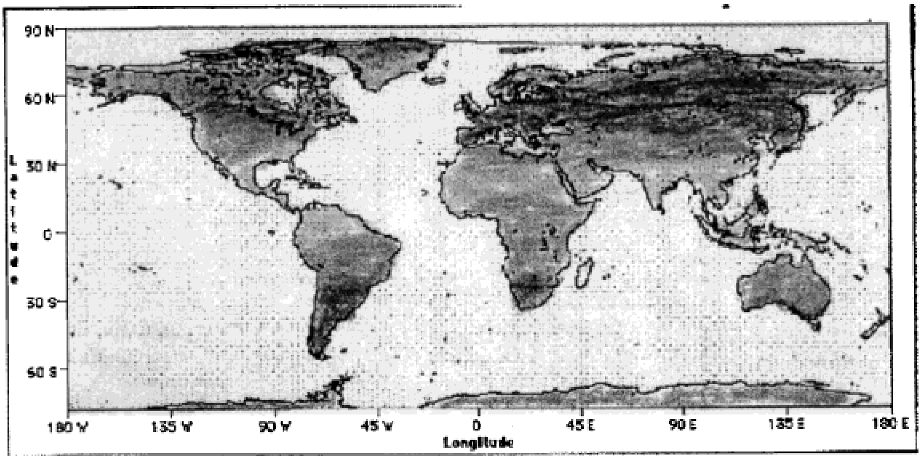


Figure 3. A student's hand-drawn map of estimated July temperatures.

With respect to the LfU model, the goal of Activity 1 is to elicit curiosity about temperature patterns by having the students confront the limitations of their current understanding.

Activity 2. Compare Their Conjectures with Real Data Using WorldWatcher. In Activity 2, students move from paper to the computer. They are first taught how to use WorldWatcher to draw data visualizations. To input data, learners use the color scheme displayed above the visualization as a palette and draw on visualizations using the same type of paintbrush and paint can tools found in common graphics programs. Working in pairs, the students create new maps on the computer, using their individual maps and what they learned in the discussion in Activity 1. Once they have created their visualizations, they learn how to access scientific data sets showing average global temperatures for July, and they engage in a series of activities in which they use WorldWatcher's visualization and analysis tools to compare their own maps with the measured temperature for July (Fig. 4).

The twin goals of this 45-min activity are to introduce students to the basics of geographic visualization and data analysis using WorldWatcher and to use their own drawings to focus their initial investigations of global temperature. The students' drawings serve as a point of comparison that helps them to notice patterns in the data that they may not have noticed otherwise. Although some students approach this activity as an evaluation of how well they did in drawing their own maps, it still helps to focus them on patterns of temperature variation that lay the groundwork for subsequent activities.

During the activity, students place copies of their maps in the Progress Portfolio and are asked to record the places where their maps came close to the actual temperatures, where they were particularly far off, and anything that strikes them as surprising about the actual temperatures. After the drawing and comparison activity, they participate in a group discussion about their observations. The students in our trials were often reasonably accurate for North America and far off near the poles, particularly the South Pole, and they frequently make the oceans more extreme than they really are. Although their knowledge of the actual locations of geographic features can vary enormously, students in the course of this discussion often identify one or two of the sources of global temperature variation, such as the presence of deserts, mountains, and large bodies of water.

From the content perspective, the goal of this activity is to enable students to begin to observe patterns of temperature variation and to elicit curiosity about their causes. From the inquiry skills perspective, this activity contains an entire Learning-for-Use cycle. The activity creates a demand for data visualization and analysis skills that enable students to compare the patterns in different data sets. This demand is fulfilled by the teacher's explanation of how to use WorldWatcher's tools. Finally, it gives students opportunities to apply these skills in their comparisons of their maps and measured temperature data.

Activity 3. Laying Out a Planet. In Activity 3, students begin the process of inventing their own worlds. They are told to think of their worlds as being alternative topographies for Earth. This means that their worlds are the same distance from the sun as Earth is, with the same orbit, size, axis tilt, and day length. Students use the paint interface to create the topography for their worlds in the form of continent outlines and an elevation data set. Figure 5 shows some examples of students' creations that are notable for the care and artistic talent that their creators displayed. As the visualization with shark-shaped continents shows, students occasionally choose to create worlds whose layouts are pictorial.

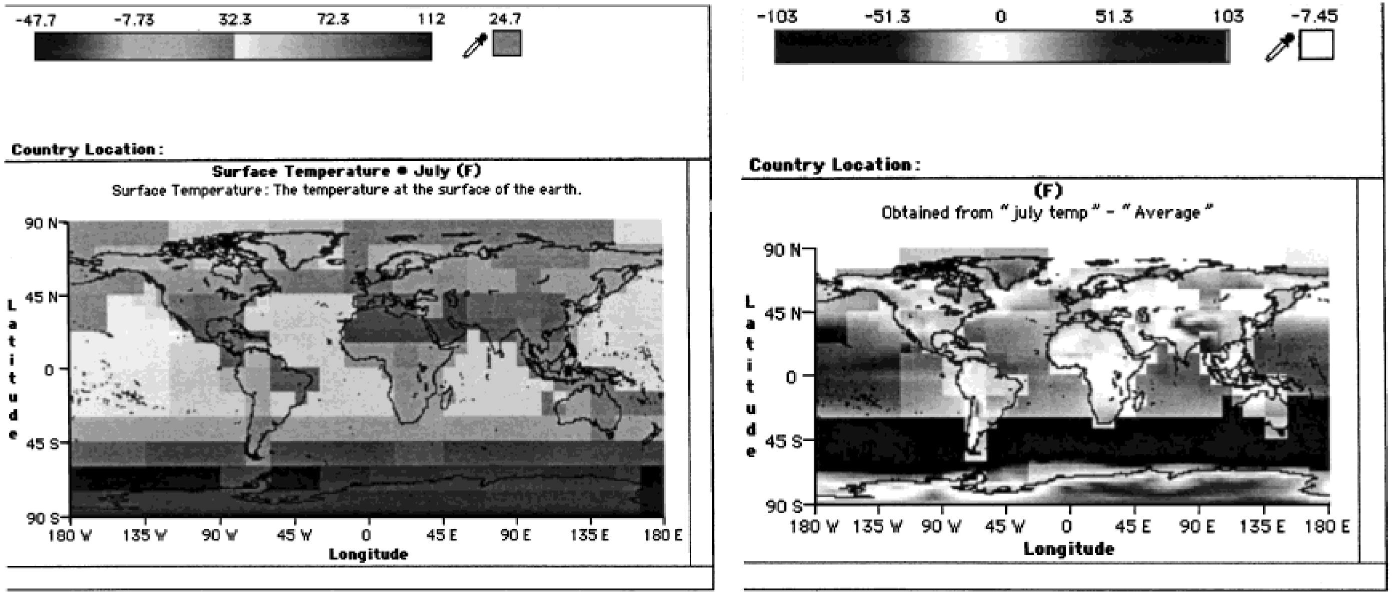
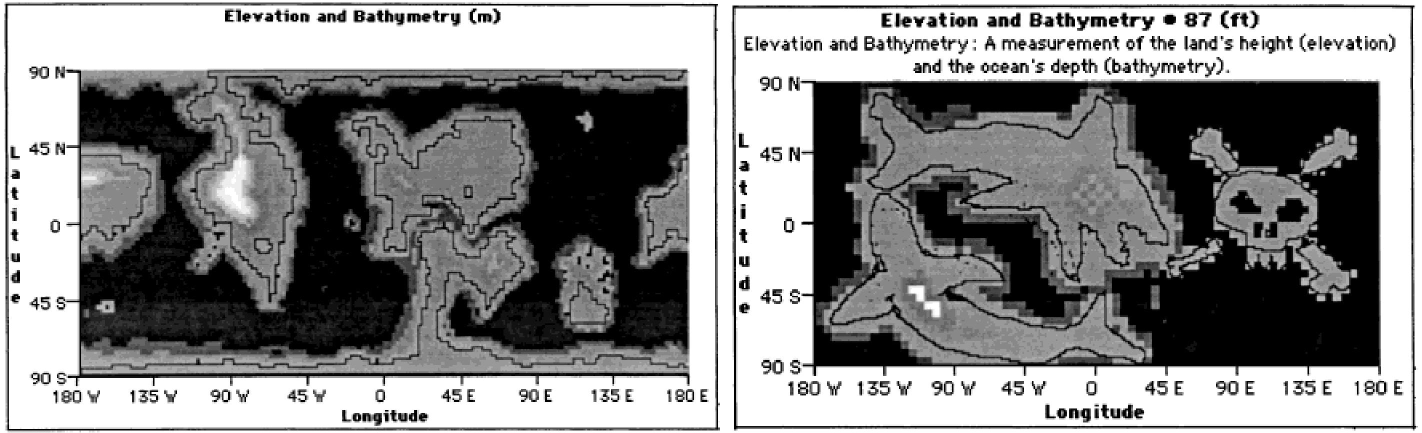

-47.7
-7.73
32.3
72.3
112
24.7
Country Location:
Surface Temperature • July (F)
Surface Temperature: The temperature at the surface of the earth.
90 N
45 N
0
45 S
90 S
Latitude
180 W
135 W
90 W
45 W
0
45 E
90 E
135 E
180 E
Longitude
-103
-51.3
0
51.3
103
-7.45
Country Location:
(F)
Obtained from "july temp" - "Average"
90 N
45 N
0
45 S
90 S
Latitude
180 W
135 W
90 W
45 W
0
45 E
90 E
135 E
180 E
Longitude

Figure 4. A student-drawn map of July temperature entered into WorldWatcher (left) and a visualization depicting differences between this map and actual Earth surface temperature (right).



Elevation and Bathymetry (m)

Elevation and Bathymetry • 87 (ft)

Elevation and Bathymetry: A measurement of the land's height (elevation) and the ocean's depth (bathymetry).

90 N
45 N
0
45 S
90 S
Latitude
180 W
135 W
90 W
45 W
0
45 E
90 E
135 E
180 E
Longitude

Figure 5. Elevation data for their new worlds created by two groups of students.

The primary goal of Activity 3 is to create demand. It begins the process of creating a new world that can only be completed by understanding climate well enough to predict temperatures on the new world.

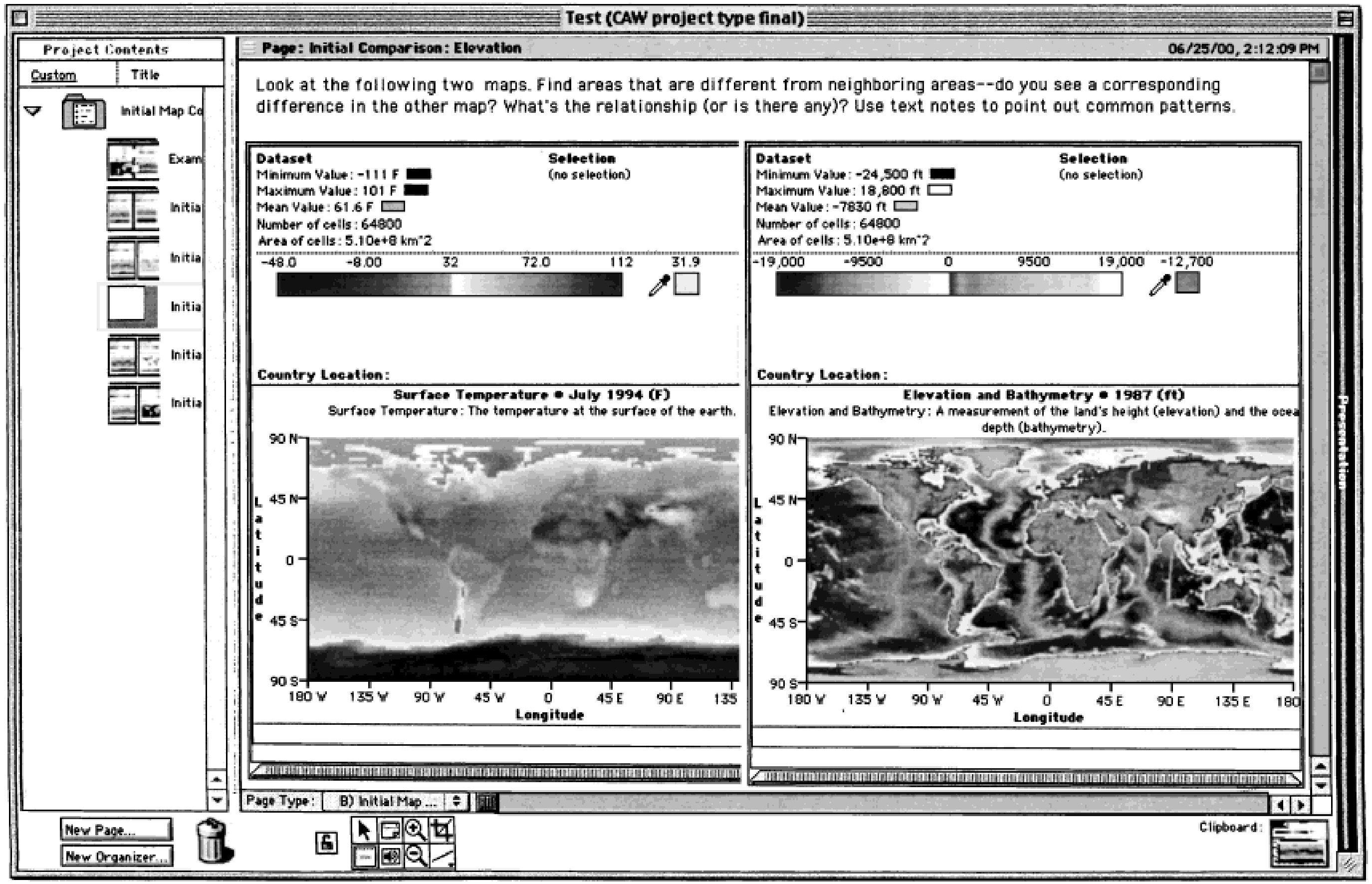
Activity 4. Investigating Earth. In Activity 4, students conduct open-ended investigations of Earth with the goal of identifying relationships between geography and temperature that they can use to create temperature maps for their own worlds. Students use the tools in WorldWatcher to look for apparent relationships among variables. In addition to average temperature data sets for each month of the year, students work with data sets showing Earth's elevation (Figure 6), dominant groundcover, incoming solar energy, and population. Students place copies of the maps they work with in the Progress Portfolio and annotate them with the relationships that they see.

After their investigations, the students participate in a group discussion of the relationships they identified. This discussion provides an opportunity to discuss, not just observed relationships, but the collection of evidence. For example, students often begin by arguing that deserts are warmer than surrounding areas based on one or two examples. However, when asked to look at all the deserts, they observe that some are cooler than their surrounding areas. The result of Activity 4 is a list of hypotheses of relationships between temperature and physical geography. Figure 7 contains a collection of these relationships that were recorded in the Progress Portfolio by students in an eighth-grade class. The teacher in this class asked students to record the relationships as rules for determining temperature and to support their rules with observations that led them to propose the rule and their initial explanations for those observations.

From the perspective of the LfU model, Activity 4's primary content goal is to enable students to observe relationships between temperature and other variables. The subsequent discussion also provides an opportunity for additional knowledge construction through communication and knowledge refinement through reflection. In the course of Activity 4, students experience the demand for additional WorldWatcher data analysis skills, which are demonstrated by the teacher, and applied in students' investigations. The discussion provides an opportunity to reflect upon these skills and their role in generating and evaluating hypotheses.

Activity 5. Explanation and Laboratory Exploration. In Activity 5, students participate in a sequence of discussions and traditional hands-on laboratory investigations to investigate the factors that they identified in Activity 4. For each factor, the teacher engages the students in a discussion of the causes of the observed relationships. These discussions provide the opportunity for the teacher to offer explanations and address misconceptions. The labs explore the processes behind the differential heating of the earth in miniature. For example, to investigate the latitudinal differences in temperature, students investigate the effect of angle of the incidence of sunlight on the Earth's curved surface by shining a lamp on paper at different angles. In similar labs, they look at reflectivity of different colored paper, compare the specific heat of water and soil, and observe the relationship between pressure and temperature in gases. These labs are designed to provide them with concrete experiences of the relationships that they had previously observed in the data. In explaining the causes of these relationships, the teacher can then draw on the students' observations of these relationships in both abstract and concrete forms.

In Activity 5, the labs provide the students with the opportunity to extend their content understanding through observation. The discussions provide them with the opportunity to build and refine content knowledge through communication and reflection. The labs also create demand for specific inquiry skills including measurement and data analysis, which the teacher communicates if necessary, and students apply.


Test (CAW project type final)
Project Contents
Custom
Title
Initial Map Co
Exam
Initia
Initia
Initia
Initia
Initia
New Page...
New Organizer...
Page Type:
B) Initial Map ...
Clipboard:
Presentation

Page: Initial Comparison: Elevation

06/25/00, 2:12:09 PM

Look at the following two maps. Find areas that are different from neighboring areas--do you see a corresponding difference in the other map? What's the relationship (or is there any)? Use text notes to point out common patterns.

Dataset
Minimum Value: -111 F
Maximum Value: 101 F
Mean Value: 61.6 F
Number of cells: 64800
Area of cells: 5.10e+8 km^2

Selection
(no selection)

Country Location:

Surface Temperature • July 1994 (F)
Surface Temperature: The temperature at the surface of the earth.

-48.0
-8.00
32
72.0
112
31.9
90 N
45 N
0
45 S
90 S
Latitude
180 W
135 W
90 W
45 W
0
45 E
90 E
135
Longitude

Dataset
Minimum Value: -24,500 ft
Maximum Value: 18,800 ft
Mean Value: -7830 ft
Number of cells: 64800
Area of cells: 5.10e+8 km^2

Selection
(no selection)

Country Location:

Elevation and Bathymetry • 1987 (ft)
Elevation and Bathymetry: A measurement of the land's height (elevation) and the ocea depth (bathymetry).

-19,000
-9500
0
9500
19,000
-12,700
90 N
45 N
0
45 S
90 S
Latitude
180 W
135 W
90 W
45 W
0
45 E
90 E
135 E
180
Longitude

Figure 6. A Progress Portfolio page set up for students to record relationships they observe between average monthly temperature (left) and elevation (right).

	Rule	Observations	Explanation
Group 1	its always cold near hills	hills are high and they are near sky	having cold on hills
	it is always cold near northpole.	becuse its always snow there	5/5 its snowing there
Group 2	Both poles are colder cause it is away from the equater	Well here in Chicago in July is hot but in both poles they are cold.	Well its far away from the equater thats why it is colder.
	I think that the water is a little colder than the land next to it. What we found out. in our summer water is cooler than land[north] in our winter water is warmer than land[south]	We know this because when we go the lake in July it is usually colder than on the land.	We do not know.
	It is warmer near the equator than near the poles.	I have been to Mexico in December and it is hot there. It is snowing here and very cold.	I know by expierience.
Group 3	Where there are high mountains the temperature is colder than the surrounding land. Where the north pole is warmer then where the south pole is , which is colder.	Comparing my map to the real map.	The mountains are high so the temperature is colder. I think that the air is thin and that means that there is less stuff to absorb the heat. So it is colder than the land around it.
	Anything near 0 degrees would be hot.	I figured that since the equator is near the son it will be hot.	We thought that since the galopagos island is near the equator and it has never in a long time seen a cold day, that everything near the equator would be hot .
Group 4	Temperature decreases as altitude incresesess.	An Africa there is blue on the real map in the middle of yellow.	The farther away from sea level you are the cooler the surface temperature is.
	It is warmer near the equator than near the poles.	*Warm Places:* Bahamas, Hawaii, Jamacia, Mexico. *Cold Places:* Alaska, Antartica, Upper Canada, Greenland	'Cuz the sun hits the equator head on every thing else is in indirect sunlight.
	It usually cooler in the water everywhere (expect for in your plumbing). Cooler than the land that is closet to it.	Water temperatures	

Figure 7. Preliminary rules generated by eighth-grade students for determining temperature based on physical geography.

Activity 6. Modeling Climate for the Invented Worlds. In the final activity of the project students create temperature maps for their invented worlds that incorporate all of the factors that they have studied (Fig. 8). To account for the influence of groundcover on temperature, they must also create data showing their world's groundcover (Fig. 8). In the earlier implementations of the project, students created their maps in one step; however, students found it difficult to remember and account for all of the factors that affect temperature simultaneously, so in the most recent implementations students built up their maps one factor at a time, immediately after their laboratory investigation of that factor. Thus, for example, after the lab focusing on the relationship of the angle of incidence of light and its intensity, students create a honrizontally banded map showing just the influence of sunlight. In subsequent steps, they increase or decrease temperatures locally to account for land–water differences, elevation, and the reflectivity of ground cover. Creating the temperature data typically requires that students return to the data WorldWatcher to quantify these relationships.

As part of the map creation process, students document the rules that they are using and how they used them in the Progress Portfolio. Once they have created temperature maps for their worlds, students present them to each other and discuss how they determined the temperatures in different areas. In one implementation of the activity, students also exchanged worlds with each other and generated temperature maps for each other's worlds. This provided them with the opportunity to compare results and discuss the reasoning behind their temperature estimates.

This final activity is designed as the primary application task for the content learning objectives. Students must use their understanding of the relationships between physical geography and temperature to create the temperature maps for their worlds. It is also a final opportunity for the application of data analysis skills to quantify those relationships.

Summary of Learning-for-Use in the Create-a-World Project

The Create-a-World Project is a particularly good example of the implementation of the LfU model for content learning because it uses all six of the design strategies in the LfU model. Table 2 summarizes those strategies.

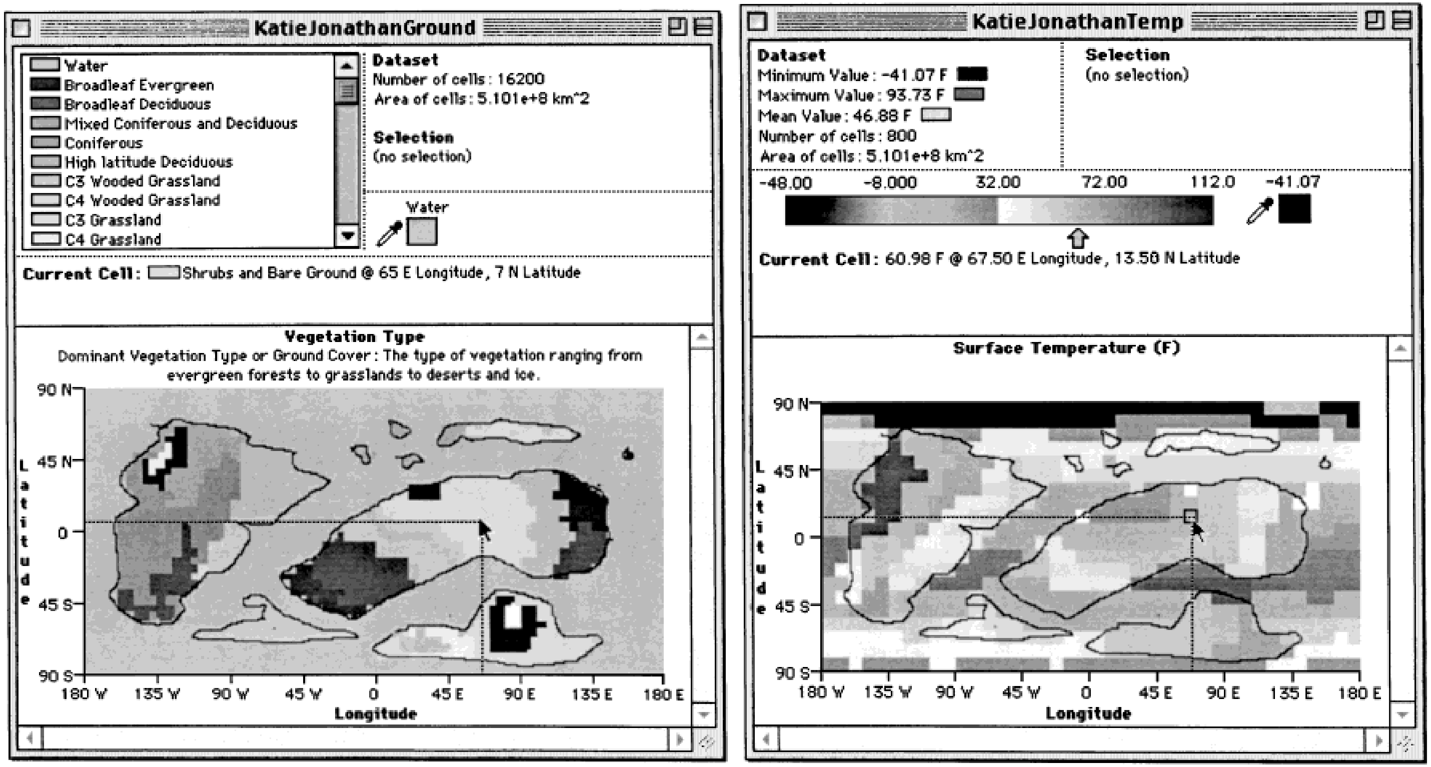
Design Strategies: Fostering Learning-For-Use

Building on the Create-a-World Project as an example, we now turn to the question of how the LfU model can be used to design inquiry activities in general and technology-supported inquiry activities in particular. The LfU model provides a framework for considering this question by dividing learning into the three required processes of motivation, construction, and refinement, and by providing strategies for meeting the requirements of each step. In this section, I describe the implementation of these strategies in more detail.

Fostering Motivation

The LfU model is concerned with a focused form of motivation, the motivation to acquire specific knowledge or skills within a context. To maintain student engagement, this focused motivation must operate within a larger interest-driven as in the project-based (Blumenfeld et al., 1991), goal-based (Schank, Fano, Bell, & Jona, 1993/1994), or anchored-instruction (Cognition & Technology Group at Vanderbilt, 1997) approaches. Of course, the strategies for creating demand and eliciting curiosity described here benefit from the larger motivational context as well as contributing to it.

The emphasis on content-focused motivation in the LfU model contrasts sharply with the approach to motivating learning found in most traditional instructional practice. Traditional educational practice emphasizes achievement-based motivation and assumes that such motivation carries over to all content. The LfU approach recognizes that for robust learning to occur, the learner must be motivated to learn the specific content or skills at hand based on a recognition of the usefulness of that content beyond the learning environment. In the LfU approach, the strategies of creating demand and eliciting curiosity build that motivation.



KatieJonathanGround

- ▭ Water
- ■ Broadleaf Evergreen
- ■ Broadleaf Deciduous
- ▨ Mixed Coniferous and Deciduous
- ▨ Coniferous
- ▨ High latitude Deciduous
- ▭ C3 Wooded Grassland
- ▭ C4 Wooded Grassland
- ▭ C3 Grassland
- ▭ C4 Grassland

Dataset
Number of cells: 16200
Area of cells: 5.101e+8 km^2

Selection
(no selection)

Water

Current Cell: ▭ Shrubs and Bare Ground @ 65 E Longitude, 7 N Latitude

Vegetation Type
Dominant Vegetation Type or Ground Cover: The type of vegetation ranging from evergreen forests to grasslands to deserts and ice.

90 N
45 N
0
45 S
90 S
Latitude
180 W
135 W
90 W
45 W
0
45 E
90 E
135 E
180 E
Longitude

KatieJonathanTemp

Dataset
Minimum Value: -41.07 F ■
Maximum Value: 93.73 F ■
Mean Value: 46.88 F ▭
Number of cells: 800
Area of cells: 5.101e+8 km^2

Selection
(no selection)

-48.00
-8.000
32.00
72.00
112.0
-41.07

Current Cell: 60.98 F @ 67.50 E Longitude, 13.50 N Latitude

Surface Temperature (F)

90 N
45 N
0
45 S
90 S
Latitude
180 W
135 W
90 W
45 W
0
45 E
90 E
135 E
180 E
Longitude

Figure 8. A groundcover (left) and temperature (right) visualization for an invented world.

Table 2
Learning-for-Use strategies for content objectives in the Create-a-World project

	Learning-for-Use Strategy	Create-a-World Design Element	Explanation
Motivate	Create demand	Overall structure	To design their fictitious worlds successfully, students must develop an understanding of the relationship between physical geography and climate that they can apply to their own worlds.
	Elicit curiosity	Introductory map-drawing activity	The map-drawing activity elicits curiosity about temperature and the reasons it differs by asking students to articulate their initial conceptions.
Construct	Observe	Open-ended investigations of data and hands-on labs	In their WorldWatcher investigations, students use analytic tools and data to identify patterns across data sets that indicate systematic covariation among variables. In the hands-on labs, students observe and measure those covariations as directly perceivable phenomena
	Communication	Teacher explanations	Building on students' experiences with World Watcher, the teacher provides students with explanations of the factors they observed.
Refine	Reflect	Discussions	After the initial knowledge articulation, the Earth investigation, and the final climate modeling tasks, students engage in discussions in which they examine their actions and their observation explain and justify them to others.
	Apply	Climate-modeling task	To create a temperature profile for their new words, the learners must apply the principles that they learned through the investigation of earth and ensuing discussion. This application task requires that learners be able to operationalize their understanding of climate, because they must be able to generate specific temperature values.

Creating Demand. A designer creates demand for knowledge by setting up a context in which the learner must have that knowledge to successfully achieve his or her goals within that context. In the Create-a-World project, the task of modeling climate for a fictitious world creates the demand for knowledge about fundamental climate processes. To create an intrinsic or authentic motivation to learn, the demand must be generated by a natural use of the knowledge. Thus, although a teacher can create a demand for knowledge by creating an exam that requires students to recite a certain body of knowledge, that would not constitute a natural use of the knowledge for the purposes of creating an intrinsic motivation to learn. Therefore, the first step in designing activities that create a natural demand for learning objectives is to identify tasks for which the knowledge is useful.

In the design of inquiry-based science, inquiry activities can serve to create a demand, fill a demand, or both. In the Create-a-World project, the demand for knowledge about climate processes is created by the climate-modeling task, which is a form of inquiry activity. The demand is also partially fulfilled by inquiry activities in the form of the investigation of data for

Earth. The project also creates a demand for inquiry skills because students must master visualization and analysis techniques to successfully complete their investigations.

Technology can play a significant role in creating a demand by supporting the task that creates the demand. In the case of the Create-a-World project, the task that creates the demand is the task of inventing a fictitious world. WorldWatcher provides the mechanism by which learners invent their own world through its interface for painting data. The ability to input data by hand is not a feature of the scientists' visualization environments that WorldWatcher is modeled on, but was added specifically to support this kind of constructive task for learners.

Eliciting Curiosity. A learning activity elicits curiosity by surprising a learner with limits or gaps in his knowledge. Researchers have described situations that elicit curiosity as discrepant (Berlyne, 1960), as violations of expectations (Schank, 1982), and as problematic (Hiebert et al., 1996). Curiosity results from a failure to understand an experience that an individual feels he could or should have understood. Curiosity is experienced as a compelling desire to understand the surprising situation, a form of "situational interest" (Hidi, 1990). In this way, curiosity creates a direct motivation to learn.

Two notable ways to elicit curiosity are to present students with a discrepant event or to ask them to articulate their prior conceptions. The widely used science demonstration is way of presenting students with a discrepant event. For example, a teacher might show water being drawn upward to create interest in a lesson on the capillary effect. The introductory map-drawing activity in the Create-a-World project is an example of asking students to articulate their prior conceptions. The articulation of prior conceptions has been recognized as a valuable technique for identifying potential misconceptions and for activating existing knowledge structures to which new knowledge can be connected (Hunt & Minstrell, 1994). Articulating prior conceptions can also elicit curiosity by exposing gaps and limits in current knowledge. Asking students to draw global temperature variations presents students with the lirnits of their understanding, helping to build interest in the specific content issues addressed by the Create-a-World Project.

Both techniques for eliciting curiosity offer an important benefit for the subsequent stages of learning. They activate relevant knowledge structures in learners' memories so that as they begin to construct new knowledge, they can connect it appropriately to existing knowledge. Often, both techniques for eliciting curiosity can be combined, as, for example, when a teacher asks students to make predictions before a demonstration or experiment. In the Create-a-World activity, articulating prior conceptions is followed by a discrepant event, when students have the opportunity to compare their hypothesized Earth temperatures with actual measured temperatures.

Technologies can play an important role in both techniques for eliciting curiosity. Interactive media can often improve upon the real world for presenting discrepant events. For example, a phenomenon that is inaccessible to direct observation can be presented in a recorded or simulated form. Thus, phenomena that are too small or too large, too fast or too slow, too hot or too cold for direct observation can all be reproduced using recording or simulation technologies. Technology can also provide the mechanism for articulating conceptions in the way that the data-drawing capabilities in WorldWatcher allow students to draw their conjectures about global temperatures.

Fostering Knowledge Construction

The recognition of learning as a process of knowledge construction rather than passive knowledge absorption is probably the most important impact of cognitive science research on education. This view of learning focuses attention on activities for students, other than passive listening or reading, that will support the construction of knowledge. Constructivism does not invalidate reading, viewing, and listening as elements of the learning process, but it means that the traditional focus on the form and content of the information being presented to students is insufficient. The designer or teacher must also pay attention to the preparedness of the learner to receive the information and the processing and use of the information that the student will be asked to do in the learning context.

The LfU model describes two processes that enable learners construct understanding: (a) observation through firsthand experience, and (b) reception through communication with others. In thinking about the design of activities to support knowledge construction, it is important to bear in mind that knowledge construction is not orderly or discrete. The construction of understanding is a continuous, iterative, often cyclical process that consists of gradual advances, sudden breakthroughs, and backward slides. As a result, developing an understanding of a complex scientific concept, such as energy transfer and its influence on atmospheric temperatures, requires many different knowledge construction activities that present different perspectives on and experiences with the target concept.

Observation. Observation in the LfU model describes the natural process of learning through direct experience. (In certain contexts, the term *observation* can imply passivity; that is, that the learner is a passive, uninvolved observer of others' experiences. In the context of the LfU model, *observation* is intended to describe the active process of learning from direct experience and interaction with the world.) Observation can play two roles in the construction of knowledge. It can lead to the understanding of new concepts, in what is often called *discovery* (Bruner, 1961), or it can provide new new forms of support for existing understanding. In science education, inquiry activities provide an excellent opportunity for knowledge construction through discovery. Scientific inquiry is a structured process of discovery with an accepted set of practices for accumulating, analyzing, and drawing conclusions from evidence. When students engage in scientific inquiry, they have the opportunity to apply the tools and techniques of science to assist in their own sense-making. In the Create-a-World project, the students use visualization and data analysis techniques to look for correlations. Their investigations of data enable them, for example, to identify an inverse relationship between temperature and elevation.

Inquiry activities also provide the opportunity to ground abstract understanding in concrete experience. For example in the Create-a-World project, students conduct hands-on labs that provide them with firsthand experience of the physical phenomena that they are learning about. In the labs on angle of incidence and reflectivity that students conduct to learn about the effects of the curvature and surface reflectivity of Earth, students gain firsthand experience with the properties of light whose effects they previously observed abstractly through visualizations of global data. The goal of these observation activities is to provide students with direct, concrete experience that they can use to support the abstract knowledge that they construct from their investigations of data in WorldWatcher.

Computer tools can provide a variety of supports for discovery. Scientific practice increasingly relies on computers to assist with data collection and analysis, modeling, and prediction. WorldWatcher, like other recent science investigation environments for learners, is designed to bring the power of scientific such tools to learners by providing the additional support that learners require. These tools enable students to participate in guided discovery by allowing them to conduct investigations with data. Another way that computer tools can support discovery is by providing simulations of physical phenomena that students can directly interact with. For example, ThinkerTools (White, 1993) provides a simulation environment for learning about Newton's Laws of physics. Students interacting with ThinkerTools have the opportunity to learn basic principles of physics through direct interaction with the simulation.

Communication. As beneficial as knowledge construction through direct experience might be, there are important reasons for learning through communication from others. For example, learners may lack an appropriate framework for interpreting certain experiences, or it may be impractical for learners to have the range of experiences necessary to learn specific content. The solution to these challenges is to design activities that communicate information to learners in a context that allows them to build the appropriate knowledge structures. It is important to distinguish communication in the context of the LfU model with the favorite straw man of constructivists, the transmission approach in which teachers attempt to transmit knowledge to passive learners through lectures and readings. The problem with these traditional approaches is not that they attempt to communicate knowledge instead of giving students opportunity to construct it through direct experience, but that the transmission approach does not acknowledge the importance of the motivation and refinement stages of learning and relies too strongly on communication to support knowledge construction. The LfU model recognizes the potential value of communicating knowledge, as long as the appropriate motivation to learn has been established before the communication, that communication activities are balanced with observation activities, and the communication is followed by appropriate knowledge refinement activities. In the design of inquiry activities, presentation of information can help provide learners with the knowledge that they need in order to initiate or conduct investigations, and it can provide them with additional knowledge to make sense of their investigations.

In the Create-a-World Project, the teacher presents explanations of the relationships between temperature and physical geography to the students once they have identified and provided evidence for those relationships through inquiry. Thus, for example, once students have identified and provided satisfactory evidence for the fact that large bodies of water moderate air temperature, the instructor provides an explanation of specific heat that accounts for the differential heating of land and water. This example is important because it demonstrates how the LfU approach builds context for the direct communication of information. The sequence of steps that lead up to this explanation of specific heat begins with the creation of demand by the Create-a-World task and with the curiosity about patterns of temperature variation elicited by the introductory map-drawing activity. This motivation carries into students' investigations of Earth, in which they observe consistent difference in air temperatures over large bodies of land and water. This observation establishes a connection point for the new knowledge. The way in which this sequence of activities creates a context for the explanation contrasts sharply with the traditional *inform, verify, practice* (Renner, 1982; Abraham, 1998) approach to science instruction that would have started with the explanation and followed it with an observation activity.

The ability to present information in a wide variety of formats is a well-recognized benefit of computing technology for learning. Because computers can mix text, graphics, audio, and interactive computational objects they can present information using multiple representations and customize the presentation medium to both individual students and the nature of the material being presented. This makes the computer a promising mechanism for communicating the information that learners need to support knowledge construction. However, the as-yet limited ability of a computer to understand the knowledge needs of a learner means that the computer as a judge of what information to present and when remains more promise than reality.

Fostering Knowledge Refinement

The refinement stage in the LfU model is the phase in which existing knowledge structures are transformed and reorganized to support future retrieval and use. To a certain extent, the distinction between knowledge construction and refinement in the LfU model is artificial. In both stages, knowledge structures are built and extended. However, separating them calls attention to the fact that knowledge may not be constructed on a first encounter in a way that supports future retrieval and application. The separation of initial construction and subsequent refinement in the LfU model emphasizes the fact that knowledge must be organized and elaborated in ways that will make it available for retrieval when it is needed, and it must be stored in a form that supports use, not just recitation. The processes of reflection and application in the refinement stage help to create indices for retrieval of knowledge and organize knowledge for use.

Reflection and application both make important contributions to the inherently cyclical nature of learning. Because the acts of reflection and application activate existing knowledge structures in new contexts, they often reveal limitations in an individual's knowledge, triggering curiosity. In addition, activities that serve to refine some existing knowledge may simultaneously create a demand for additional knowledge.

Reflection. In reflective activities, learners look back at their experiences to explore the connections between their experiences and the understanding that they took from those experiences (Collins et al., 1989). In an effective reflection activity, students should revisit the evidence for their conclusions in order to assess their validity, identify the limitations of their understanding, and clarify its applicability. Because reflection requires perspective, activities that engage learners in communication about their activities and understanding can be particularly effective at fostering real reflection. For example, an instructor-led, reflective discussion might ask students to review and justify their findings from a set of investigations. Similarly, when students must prepare presentations of their findings after an investigation, they must reflect upon their experiences and create appropriate organizational schemes to communicate about their activities and knowledge. The Create-a-World project incorporates a number of reflective group discussions at significant points in the project. For exarnple, following their initial investigations of Barth's climate, students are asked to share their observations about relationships between temperature and physical geography, compare them with each other, and speculate on their causes.

Technology can play two important roles in supporting reflection on inquiry activities. It can support record-keeping during inquiry in a way that provides concrete products for reflection, and it can support reflective communication (Loh et al., in press). One of the obstacles to reflective inquiry for learners can be that the inquiry process itself is ephemeral. Unless some record of the process is preserved, when it comes time for students to reflect, they are often unable to recall or recreate the inquiry process. Computer technologies can address this problem by allowing students to record the intermediate products of their investigations, as well as their plans, hypotheses, and observations. The Progress Portfolio provides these capabilities for the Create-a-World project through its tools for capturing, annotating, and organizing visualizations.

The second form of support that technology can provide for reflection is in providing the medium for reflective communication. A number of computer-supported collaborative learning environments have been developed to facilitate reflective dialogues among learners (Hoadley, Hsi, & Berman, 1995; Edelson, Pea, & Gomez, 1996; Scardamalia, Bereiter, McLean, Swallow,

& Woodruff, 1989). These can supplement or replace face-to-face discussions by providing some of the benefits of computer-mediated communication, such as allowing multiple, parallel discussion threads, eliminating forced turn taking, and allowing extra time to construct responses. Computer technologies can also provide support for more formal communication, by providing access to multimedia for both written and oral presentations. This is particularly valuable when students are using computer-based investigation tools such as WorldWatcher. Multimedia document and presentation topis allow learners to incorporate the graphical or dynamic representations that these investigation tools generate into their presentations. In several of the classroom pilots of the Create-a-World Project, teachers used the presentation capabilities of the Progress Portfolio to allow students to present their work.

Application. In the application phase of learning, students activate and use their newly constructed knowledge structures. The application process creates and reinforces links to those knowledge structures and restructures them, if necessary, to support use. In science, where the goal is building causal accounts of natural phenomena, the most common uses of knowledge are to construct explanations and make predictions. However, there are other applications of scientific knowledge that can be used effectively in inquiry-based curricula, such as design (engineering) or decision making (policy). Because the goal of the application phase is to refine knowledge so that it is available for use in the future, the application activities should reflect legitimate, meaningful use of the knowledge. Thus, although defining a term does require a learner to apply his or her knowledge, it does not necessarily lead to new indices or organizational structures that might help that learner to apply that knowledge in a problem-solving context. In contrast, in the Create-a-World Project learners apply their knowledge about the relationships between physical geography and temperature to predict climate conditions in much the same way that climate modelers do. In inquiry-based learning in general, the act of inquiry can play two roles with respect to application. Inquiry can provide the means for constructing knowledge, as in the investigations of Earth data in Create-a-World, or it can serve as a knowledge application activity, as in the final temperature prediction activity.

Technology has an important role to play in supporting knowledge application activities. For many forms of scientific knowledge, knowledge application is a technology-dependent process. Because knowledge application requires meaningful, goal-directed tasks, the technologies that can support knowledge application are the technologies that will allow learners to conduct meaningful tasks. In the case of the modeling task in the Create-a-World project, WorldWatcher supports this knowledge application task through its expressive operations that allow learners to create data.

Computer Support for Learning-for-Use

In the preceding discussion, I highlighted the role that technology can play in supporting inquiry and learning-for-use. It is important to note that the role of technology in this form of inquiry-based learning goes beyond simple investigation tools. In the Create-a-World Project, for example, technology provides investigation tools in the form of WorldWatcher's visualization and analysis capabilities, but technology also provides support for artifact construction, expression, and record keeping. WorldWatcher provides artifact construction and expression capabilities through its data creation tools, and the Progress Portfolio provides record keeping tools that support reflection. These additional tools provide critical context and support for learning from inquiry. As this example shows, it is important to think more broadly about how technology can support learning from inquiry than just focusing on investigation tools. Table 3 summarizes the ways that computer tools can support learning-for-use, with examples drawn from the Create-a-World curriculum.

Open Issues

The LfU model is a framework to support the design of learning activities that integrate content and process learning. Several ongoing research projects at Northwestern are using the model both to construct designs for learning activities and to identify weaknesses in existing designs. One of the goals of these efforts is to explore some of the assumptions behind the LfU model that are as yet untested. In this concluding section, I highlight three of these assumptions.

The first assumption is that inquiry activities designed in accordance with the LfU model will enable students to master science content and process objectives more effectively and efficiently than traditional activities that separate content learning from process learning. One could certainly argue that traditional lectures and readings could convey the science content to students in less time than the Create-a-World Project. The real issue is which approach provides the best combination of effectiveness and efficiency in a time-limited system. There is ample evidence that traditional approaches do not provide the deep conceptual understanding that the new standards call for, and some reason to believe that the Learning-for-Use approach will be more successful at developing deep, accessible understanding. Although horserace comparative evaluation of instructional approaches is difficult in education, it is important to engage in summary evaluation that can start to quantify the effectiveness of LfU activities at achieving content and process objectives in terms of the time and resources used.

The second assumption is that the LfU model is a useful framework for educators to support the design and implementation of effective learning activities. This assumption would prove unfounded if designers were unable to apply the framework, either because of a flaw in the framework itself or because of the difficulty of learning and applying it. The constructivist theories of learning apply to teachers and designers as well, which means that adopting a framework like Learning-for-Use is not a simple process. If they are to learn to use it successfully, they must go through a learning process themselves that incorporates the steps of Learning-for-Use. This assumption is difficult to evaluate for two reasons. First, it assumes there is some metric for determining whether an individual educator or curriculum constitutes an example of Learning-for-Use. The model, as currently expressed, would not support any such metric. Second, evaluating the assumption requires some way to quantify how effective a framework is in supporting design and implementation. This implies some way of comparing one design approach to another and measuring the ease and effectiveness of these frameworks in supporting design. Nevertheless, the difficulty of evaluating the assumption of claim definitively does not eliminate the possibility of researching it. As a first step, we intend to engage in formative evaluation of educators' efforts to learn and apply the framework, to better understand the obstacles to its use.

The third assumption behind this research is that the development of technology-supported inquiry curricula will contribute to reform. As I stated in the introduction, the underlying goal of this research is to provide compelling examples of the use of technology-supported learning activities to achieve ambitious content and process objectives. Success at creating those examples is only one step on the road to reform. The introduction of technology into schools is creating an opportunity for reform because schools are looking for ways to take advantage of

Table 3
The role of technology in supporting Learning-for-Use, with examples from the Create-A-World Project

	Learning-for-Use Design Strategy	Role for Technology	Create-a-World Example
Motivate	Create demand	Tools that allow students to *design or construct artifacts* can support meaningful application tasks that demand understanding.	Drawing capability in WorldWatcher allows students to construct a world.
	Elicit curiosity	Tools that allow students to *express* their beliefs or understanding enable them to articulate their conceptions and confront the limitations of their understanding	Drawing capability in WorldWatcher allows students to express prior conceptions.
		Tools that *simulate* natural processes can serve as demonstrations of discrepant events.	None
Construct knowledge	Observe	*Investigation tools* offer students the opportunity to identify relationships through exploration of data.	The data visualization and analysis capabilities of WorldWatcher enable students to conduct investigations with data.
		Simulation tools can enable students to observe natural processes that may be impossible to observe in classroom settings.	None
	Communicate	*Reference tools* can provide students with access to information in a wide variety of media.	None
Refine knowledge	Reflect	Tools that enable students to maintain a *record of their activities* support reflection. with objects for reflection.	The record-keeping, annotation, and monitoring capabilities in the Progress Portfolio provide students
		Collaboration and presentation tools that enable students to engage in discussions with others can facilitate reflection.	None
	Apply	Tools that allow students to *design or construct artifacts* can support meaningful knowledge application tasks.	The drawing capabilities in WorldWatcher allow students to apply their understanding in creating a world

these new technologies. However, meaningful reform requires a great deal more than just examples. A substantial amount of work remains to be done to understand how to initiate and maintain the changes in teachers' and students' practices that the LfU model and other constructivist learning approaches entail.

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