Engineering Geosciences Learning Experiences Using the Learning-for-Use Design Framework

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Abstract

In this chapter, we consider the design of learning experiences in the geosciences. Recognizing that too often, educational experiences do not lead to understanding that the learner can draw on when it is relevant, we focus on learning that leads to usable understanding. We use the analogy of engineering research and development to describe the way we have applied findings from cognitive science research to the design of geosciences curricula. We present a design framework based on research in cognitive science that offers guidelines for the design of learning activities that motivate learning and provide learners with opportunities to apply what they are learning. We illustrate the design framework with an example of a middle school curriculum focusing on the relationship between physical geography and climate. We also present strategies for conducting formative evaluations of curriculum and describe how we use them to iteratively refine a design.

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Introduction

Learning is the interface between Earth and mind. Both scientists and others develop conceptions about Earth through learning processes. Scientists use research techniques to expand understanding at the forefront of human knowledge, while others apply their own learning skills to expand their personal understanding. In this chapter, we are concerned with the challenges of fostering geosciences learning in formal educational settings. We view education as an applied science akin to engineering. Education has its own knowledge base and practices, but it rests on the sciences of learning and of the domains that make up the curriculum. Addressing the educational challenges of the Earth sciences calls for an engineering approach that applies both the cognitive and Earth sciences.

Sound engineering proceeds through an iterative process of systematic design and evaluation. Both design and evaluation involve the application and extension of theory. As design researchers (Cobb *et al.*, 2003; Design-Based Research Collective, 2003; Edelson, 2002) in the Learning Sciences, we are particularly interested in the application and development of scientific theories of learning and education. Our objective in this chapter is to present a demonstration of how that engineering process can be carried out in the geosciences and to describe a particular framework that we are using to guide our own design and evaluation processes.

In the work we describe in this chapter, we are concerned with engineering learning experiences in the geosciences to address two substantial educational challenges that are not adequately addressed by traditional instructional approaches:

- motivating learners to learn (not just engage)
- ensuring that learners develop knowledge that they can access and apply when it is relevant.

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 retrieval and application of that knowledge, it remains inert. Inert knowledge (Whitehead, 1929) is understanding that exists in an individual's memory in some form but not in a form that leads it to retrieved or applied when it is useful. For example, a student might be able to recite a principle in an exam without being able apply that principle in a real world problem-solving context. We use the term *usable knowledge* to describe the opposite of inert knowledge Usable knowledge and skills are stored in an individual's memory in a form that supports retrieval and application when relevant.

To address the challenges of engagement and inert knowledge, we have developed the Learning-for-Use design framework (Edelson, 2001). The Learning-for-Use framework draws on contemporary research in cognitive science to provide guidance for the design of learning activities that foster usable understanding. In the first part of the chapter, we present Learning-for-Use as a framework for the design of geosciences learning activities. To illustrate the Learning-for-Use framework, we present an example of a curriculum unit that we designed using the framework. This unit, called *Planetary Forecaster,* is a 6-week middle school unit on climate modeling.

In the second part of the chapter, we focus on evaluation. In the process of engineering learning experiences, the role of evaluation is to understand how well the design is achieving the goals that have been established for it and why it may be falling short. The evaluation should generate results that can inform the revision of the design and allow the designers to determine when they have reached their goals. In the work we present here, we are specifically concerned with ascertaining how well a curriculum unit is achieving the goals of Learning-for-Use and how shortcomings that are identified can be addressed through iterative re-design. In the latter sections of this chapter we describe research methodologies that we have employed to assess how well units designed with the Learning-for-Use framework are achieving their goals, and we present examples from studies of Planetary Forecaster in public school classrooms.

Thus, our discussions of design and evaluation have dual goals—to demonstrate how a systematic process of curriculum engineering can proceed from theory and to describe a particular approach to the engineering of geosciences curriculum based on cognitive science research that we are pursuing.

1. Learning for Use

The Learning-for-Use design framework provides guidance to instructors and curriculum developers on how to design learning activities that foster engagement and useful understanding. It is based on research from cognitive science (e.g., Bransford *et al.*, 1999) that describes how people develop usable knowledge[1].

1.1 The Development of Usable Knoweldge

The foundation of the Learning-for-Use Design Framework is four robust findings from contemporary learning research . These are[2]:

- **Constructivism:** Learning takes place through the construction and modification of knowledge structures.
- **Goal-directed learning:** Knowledge construction is a goal-directed process that is guided by a combination of conscious and unconscious understanding goals.
- **Situated learning:** The circumstances in which knowledge is constructed and subsequently used determine its accessibility for future use.

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[1] To enhance readability, we often use the terms *knowledge* and *understanding* to refer to both conceptual knowledge and skills. The fact that we do not always use the term *skills* does not mean we place less emphasis on them.

[2] From (Edelson, 2001)

- **Inert Knowledge:** Knowledge must be constructed in a form that supports use before it can be applied.

In developing the Learning-for-Use Design Framework, we have drawn on these findings to build a model of learning that can distinguish between experiences that lead to the development of usable knowledge and experiences that either lead to no significant learning or lead to the development of inert knowledge. The result is a description of a process that characterizes experiences that lead to usable knowledge, This description represents the theory of learning on which the Learning-for-Use framework is built. This process model consists of three stages: (1) motivation to learn, *in which the learner experiences the need for new understanding based on its usefulness*; (2) knowledge construction, in which the learner builds new knowledge structures in memory based on experiences in the learning environment; and (3) knowledge organization, in which knowledge structures or connected, transformed, and reinforced to support future use.

Motivation,[3]. The first step in the development of usable knowledge is recognizing and feeling the need for new knowledge or skills. The motivate step generates the goal of developing new understanding. In this context, we are using *motivate* in a very specific sense. It describes the motive to develop specific knowledge or skills. This motivation to develop specific understanding is distinct from two other forms of motivation. First, it describes the motivation to learn, rather than the motivation to engage in a particular set of activities. Second, it describes the motivation to learn specific knowledge or skills, rather than a more general attitude or disposition toward learning in a particular context. To lead to usable knowledge, it is important that the motivation be grounded in the learner's recognition of the usefulness of the knowledge. If students are motivated to learn based on how the designers want them to be able to use that knowledge in the future, then their goals will lead them toward development of that knowledge in a usable form. If students are motivated to engage rather than learn or they are motivated to learn by goals other than how the designers want them to be able to use the knowledge, then they will not be motivated to develop the knowledge in a usable form. So, for example, if they are motivated by the goal of reciting knowledge in a testing situation, they will not necessarily be motivated to learn how to apply it. Edelson and Joseph (2004) refer to this motivation to acquire specific knowledge or skills for their usefulness *interest based in usefulness.*

Knowledge Construction: The second step in the development of usable knowledge is the construction of new knowledge structures in memory. Current models of learning describe the construction of new knowledge as the addition of new concepts to memory, subdivision of existing concepts, and the creation of 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.

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[3] While the first step in the Learning-for-Use model is called *motivation*, this phase is only concerned with a small portion of what is normally thought of as motivation in education. Addressing the broader motivational challenges of engaging students in schooling are critical to, but beyond the scope of, the Learning-for-Use model.

Knowledge organization. The third step in the development of usable knowledge is the organization of knowledge for use, which responds to the need for accessibility and applicability of knowledge. In the organization step, knowledge is re-organized, connected to other knowledge, and reinforced in order to support its future retrieval and use. (Anderson, 1983)To be retrieved when it is relevant, knowledge must be indexed by features of situations in which that knowledge applies that will cause that knowledge to be activated in those situations (Chi *et al.*, 1981; Glaser, 1992; Kolodner, 1993; Schank, 1982; Simon, 1980). One form of organization for use is the development of those indices and retrieval cues. Organization of knowledge for use 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. To support the application of knowledge once it is retrieved, knowledge must be stored in a form that supports its application. Therefore, a third form of organization for use is the transformation of, declarative knowledge into a procedural form that supports the application of that knowledge (Anderson, 1983).

While there is an inherent ordering among these three steps, this ordering does not preclude overlaps or cycles. For example, knowledge construction and organization may be simultaneous, and knowledge construction or organization can create motivation to address gaps in current understanding. 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.

The theory behind the Learning-for-Use framework is that all three of these steps are critical to the development of usable knowledge. The motivation step is necessary to provide students with *goals* that will guide and sustain the knowledge construction and organization required to develop usable knowledge. The knowledge organization step is essential to prevent students from constructing understanding that remains inert. While this model of learning represents a synthesis of existing research, it is designed to support the engineering of learning experiences that develop usable knowledge by focusing attention on the importance of *all three steps* in the learning process. We believe this is important because, despite the findings in cognitive science research that underlie this model, a great deal of current curriculum design, including that which draws on cognitive science research, continues to focus on knowledge construction, without commensurate attention to motivation and knowledge organization.

1.2 The Learning-for-Use Design Framework

Based on the this model of learning , we have developed the *Learning-for-Use Design Framework.* This framework provides guidelines for the design of activities that will lead to the development of robust, useful understanding. The model of learning described above 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 design framework provides guidelines and recommendations for achieving all three steps.

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 step. 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 particular, we have found that a balanced combination of different kinds of knowledge construction activities are most effective at achieving the goals of the knowledge construction step.

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 *elicit curiosity* 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 *direct physical experience or observation* 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	Student 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 *apply* 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

Because it is based on the same contemporary research as other design frameworks that have been developed in recent years, the learning-for-use design framework shares many qualities of them. For example, knowledge integration environments (Linn, 2000), goal-based scenarios (Schank *et al.*, 1993/1994), and anchored instruction (J. Bransford *et al.*, 1990) are all consistent with the learning-for-use approach. The goal of the learning-for-use design framework is to capture the elements of these effective designs at a level of generality that can encompasses the full range of effective approaches to developing usable knowledge. The contribution of the framework is that it describes the elements that are, at least partially, responsible for the effectiveness of these approaches and grounds them in research. For designers developing new approaches and activities, it is designed to draw attention to the importance of all three steps in the development of usable knowledge and to provide suggestions for how to achieve them. The learning-for-use framework has proven useful for both designing learning activities and analyzing existing activities.

In an analysis of specific research-based knowledge integration and anchored instruction environments, we found that the strengths of their designs and the differences among them were captured through an analysis of them in terms of the learning-for-use framework (Edelson & Bang, 2003). In science, the Learning Cycle that was developed in the 1960's as a way to engage students in learning through authentic inquiry (Abraham, 1998; Karplus & Thier, 1967; Lawson, 1995; Renner & Stafford, 1972) and its modern variants, such as the BSCS 5E design approach (Bybee, 2002) are consistent with learning-for-use, as is Krajcik et al.'s (1998), project-based approach.

In our own work, we have focused on a specific form of learning-for-use that we call *Scenario-based inquiry learning.* Scenario-based inquiry learning combines elements of goal-based scenarios and project-based science. In scenario-based inquiry learning, the same task is used to create demand for new understanding (motivate) and to enable learners to apply that understanding (organize for use). As in goal-based scenarios, the task comes from the scenario that provides students with a role and a goal. As in project-based science, a substantial portion of the knowledge construction in scenario-based inquiry learning occurs through firsthand scientific inquiry (guided or open-ended) on the part of students.

1.3 Learning for Use in the Geosciences

The Learning-for-Use design framework can be used both to develop new learning activities and analyze existing learning activities. In either case, the first step is to identify the learning goals for the activities. The process that follows goal identification typically involves cycles of identifying possible ways to motivate those learning objectives for the target audience of students, activities that would support knowledge construction for them, and activities that would give students the opportunity to re-organize their new understanding for use. As with any complex design process, selecting a coherent and effective combination of activities to achieve each stage of Learning-for-Use requires designers to balance numerous tradeoffs to achieve the best practical combination.

So, the first step in applying Learning-for-use in the geosciences involves selecting learning objectives to address. In recent years, a number of reports have argued for the importance of geoscience education for an educated populace and have described specific geoscience knowledge and skills that students from elementary school through college should master (American Association for the Advancement of Science (AAAS), 1994; Barstow & Geary, 2001; Ireton *et al.*, 1996; Manduca *et al.*, 2002; National Research Council (NRC), 1996). Three themes that receive significant attention in these documents are: (1) the need for students to understand Earth Science from a systems perspective, (2) the centrality of field work and direct observation in the geosciences, and (3) the interpretation of historical data.

Having selected learning objectives, a designer must identify candidate activities for motivating those learning objectives, and constructing, and organizing knowledge for use. In considering motivation, a designer might consider specific techniques that might be useful in the geosciences for eliciting curiosity or tasks that create demand for geosciences knowledge and skills. A common way to elicit curiosity is to present a surprising phenomenon to students. In the geosciences that might be achieved by giving students the opportunity to directly observation surprising phenomena in the field or in data. In considering how to create demand through a task, it is often helpful to look at the way that geosciences knowledge and skills are used by expert practitioners, for example, in oil exploration, weather forecasting, or environmental policy making.

In knowledge construction, it is also important to look at the ways that geoscience concepts can be experienced, demonstrated, and explained. For example, some geosciences processes can be directly observed in the field, while others take place at scales of time or space that make them impossible to observe directly. In that case, evidence for the process may be perceptible in the field or in data, or processes can be demonstrated through dynamic processes. In general, it is inefficient and often unrealistic to expect students to "discover" scientific concepts. For that reason, providing students with direct experience and observation of scientific phenomena should generally be combined with offering them explanations and representations. The specialized representations that geoscientists use for describing and characterizing processes can be helpful to learners in developing their own understanding of those processes. In general, learners benefit from learning about concepts using multiple representations, models, or analogies, where the different approaches capture different essential features of the target content.

In organization for use, it is important to provide students with the opportunity to both *practice* using new skills and knowledge in simple contexts and to *apply* skills and knowledge in realistic contexts. Just as with motivation, tasks from authentic professional practices can be very effective contexts for applying new understanding. In helping students to reflect on what they have learned, it can be helpful to focus on the specific forms of explanation and argumentation that are used in the field. For example, if students were learning about an explanation for a phenomenon that is based on a historical record, it might be helpful to have them reflect on the structure of that kind of geosciences explanation and how the evidence supports the conclusion.

2. Planetary Forecaster[4]

Planetary Forecaster is a middle school curriculum unit for Earth systems science that we have developed using the Learning-for-Use design framework. It combines computer-supported investigations of geospatial data with hands-on laboratory activities in which students observe and measure the phenomena under study. The Planetary Forecaster curriculum unit is the product of an ongoing iterative development effort that involves teachers both directly as members of design teams and indirectly as implementers who are observed or provide feedback. The curriculum has been through three revision cycles based on three cycles of classroom implementation.

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[4] Planetary Forecaster is a re-design of the Create-A-World activity that was described in Edelson (2001)

2.1 Unit Scope and Sequence

The content goal for the unit is for students to understand how physical geography influences temperature at a climatic timescale. The premise of the curriculum unit is that students have been asked by a fictional space agency to identify the portions of a newly discovered planet that are habitable given information about the planet's topography, water cover, and the tilt of its axis. For simplicity, the planet has the same atmospheric make-up as Earth, is orbiting around a star with the same intensity as the sun, and has an orbit with the same radius as Earth's. This mission is designed to create a demand for understanding of the curriculum's target content.

There are four major relationships that students must understand to complete the task. They are:

Curvature—The effect of a planet's curved surface on the intensity of the solar radiation received at each point and the length of the day.

Tilt—The effect of the tilt of a planet's axis of rotation on intensity of solar radiation and length of day at different times of year.

Land/Water heat capacity—The effect of surface cover (land vs. water) on the temperatures at different locations due to differences in specific heat capacity and reflectivity.

Topography—The effect of surface elevation on the temperatures at different locations.

Understanding these relationships requires an understanding of fundamental scientific concepts that are commonly found in national, state, and local standards documents, such as the Earth-sun relationship, radiative energy transfer, conservation of energy, heat and temperature, specific heat capacity, and the ideal gas law.

The curriculum is divided into seven sections that take from 1-5 class periods each:

1. Setting the stage. In this section, students conduct an exercise in articulating prior conceptions in which they draw color maps showing their current conceptions of global temperatures. They then compare their maps with actual data from Earth and formulate initial hypotheses about the factors that influence temperature.
2. Getting the task. Students learn about their mission of identifying habitable regions on a newly discovered planet, *Planet X.* They do an exploration of habitable regions on Earth. (For the purposes of this unit, habitable is defined as having minimum temperatures above 25F and maximum temperatures below 80F.) Students are assigned to investigate the four factors listed above (shape, tilt, surface cover, and elevation), to investigate for their influence on temperature. They are told that they will receive data about the shape, tilt, surface cover, and topography of Planet X that will help them to develop a map predicting the distribution of temperature on Planet X.
3. Investigating shape. Students investigate the effect of angle of incidence of solar energy on surface temperature through hands-on labs and explorations of global incoming solar energy data for Earth. They create an initial temperature map for Planet X that shows variation of temperature with latitude.
4. Investigating tilt. Students investigate the effect of a tilted axis of rotation on temperature at different times of year, through explorations of incoming solar

energy data for Earth. They observe how the bands of incoming solar energy shift with seasons. They modify their temperature map for Planet X to account for seasonal differences.

5. Investigating surface cover. Students investigate the effect of land versus water on temperatures through hands-on labs looking at specific heat of water and soil and explorations of global surface temperature data for Earth. They modify their temperature map for Planet X to account for differences in temperature over land and water.
6. Investigating elevation. Students investigate the effect of elevation on temperature through explorations of global surface temperature data for Earth. They modify their temperature map for Planet X to account for differences in temperature at different elevations.
7. Final Recommendations. Students identify habitable areas by looking at maximum and minimum temperature values in their temperature maps for Planet X. They present their findings and their recommendations for colonization.

The curriculum materials place a special emphasis on forming and revising hypotheses and includes journaling activities that ask students to record their hypotheses together with evidence and explanations. At each stage of the curriculum, students are asked to describe the factors that they believe affect temperature, how they affect temperature (i.e., the direction of the effect), and why (i.e, the underlying causes). They are also asked to provide any evidence they might have for these hypotheses and any open questions. They first record their hypotheses about the factors that affect temperature during the initial "setting the stage activity". During the portions of the unit where they investigate individual factors, they record their initial hypothesis about how each factor affects temperature before they do their investigations, and then they record their revised understanding following the investigation. It is this revised description of the relationship between a particular factor and temperature that they use when they construct their temperature maps for Planet X.

2.2 Planetary Forecaster as an Example of Learning-for-Use

Planetary Forecaster is an example of *scenario-based inquiry learning* In the case of Planetary Forecaster, students adopt the role of a scientist and the goal of identifying areas that are suitable for colonization in the fictional scenario of a newly discovered planet. As a scenario-based inquiry learning unit, Planetary Forecaster incorporates seven strategies from the Learning-for-Use design framework to achieve all three steps in learning for use.

Motivate. The curriculum *creates a demand for understanding* through the mission of determining habitable areas on Planet X. This mission requires that they model temperatures for Planet X based on the data provided about the planet, which in turn demands that students understand the relationships between physical geography and temperature that comprise the content learning objectives for the unit. It also *elicits curiosity* through the stage-setting activities which ask students to articulate their prior conceptions about the content and confronts them with the limitations of their understanding. After trying to create temperature maps for Earth based on their prior understanding, students become curious about what the actual temperature patterns are and why they are that way.

Construct. Students learn about the relationships between physical geography and temperature through a combination of hands-on labs, computer-based investigations of Earth science data, readings, lectures, and discussions. The hands-on labs provide them with *direct experiences* with the phenomena and relationships they are learning about. The computer-based investigations provide them with *indirect experiences* of these same relationships at a scale that they cannot experience directly. The readings, lectures, and discussions provide them with *explanations* of the phenomena and relationships from which they can construct understanding and give them opportunities for *sense-making*.

Organize for use. The process of constructing temperature maps for Planet X gives students the opportunity to *apply* their understanding of the relationships between physical geography and temperature as they are developing it. Classroom discussions and the journaling activities where students record their hypotheses encourage students to *reflect* upon their developing understanding.

3. Evaluating Learning-for-Use Curricula

The engineering of effective learning environments requires an iterative cycle of design and evaluation. In this section, we move from the question of how to design learning environments for the geosciences to how to design evaluations that can inform their improvement, a process known as *formative evaluation*. The concern for motivation, knowledge construction, and knowledge organization in Learning-for-Use raises specific questions for formative evaluation. The first set of questions one must ask are whether the designs for each of the stages in the learning for use model is functioning as intended. For example, are the motivation activities actually eliciting curiosity or creating a demand for new understanding? The second set of questions one must ask are whether the individual elements of the design are working together to enable students to develop usable knowledge—knowledge that they can retrieve and apply in authentic contexts..

In this section, we describe the design of studies that we have constructed to conduct formative evaluations of Planetary Forecaster, together with some illustrative examples of findings from these studies. These studies are designed to show how models of learning and design frameworks, such as the ones presented in the previous section, can guide evaluation.

3.1 Studying Motivation: Role and Goal Adoption

A critical issue for a scenario-based inquiry learning unit like Planetary Forecaster is, do the students "buy in" to the scenario sufficiently to create a motivation to learn the target learning objectives? To investigate this question, we have developed a methodology for investigating the extent to which students adopt the role and goal associated with a scenario. This methodology was developed as part of a larger research program investigating differences in role and goal adoption across students, differences in individual students' buy in over time and across different types of activities, and the impact of these differences on engagement and learning (Pitts & Edelson, 2004).

This research design is based on several assumptions. First, expectancy-value theory developed by Eccles and colleagues (1998) predicts that students are likely to adopt a role and goal when they see the role and goal as being consistent with some aspect of their identity (who they want to be, what they like to do) and believe they are capable of playing the role and achieving the goal . However, their role and goal adoption is likely to be influenced by their understanding of the role and goal, which will generally evolve over the duration of a curriculum unit. Finally, a student's engagement in the context of any specific activity will be influenced, not just by the nature of their role/goal adoption, but by their perception of the relationship between that day's activity and the role and goal.

Thus, to study role and goal adoption, it is necessary to understand some relatively stable traits about students, such as their attitudes and beliefs about the role and goal in the unit, including both desirability and perceived abilities. For example, does a student view the role of scientist as a desirable role, or does she feel she is capable of conducting extended scientific investigations? It is also necessary to understand how these beliefs and attitudes evolve over the course of a unit, and how they are influenced by their perceptions of the relationship of specific activities to the overall role and goal. For example, does a student's level of goal adoption increase over time, or does she feel that certain activities are not authentic to the practices of scientists? Finally, it is necessary to understand the nature and level of students' engagement over the period of a unit and their learning outcomes. For example, does a student find the scientific investigations compelling or boring, and has she mastered specific learning objectives by the end of the unit?

To collect this information, we have designed a diverse array of data collection methods that have been selected to create as complete a picture of role/goal adoption and engagement as possible. This data collection includes:

- Pre-surveys on students' attitudes and beliefs about school, the role and goal associated with the curriculum, and about their abilities.
- Classroom observations
- Daily mini-surveys about students' engagement, perceived level of role and goal buy in, and perceived fit of each day's activity to the role and goal.
- Periodic extended interviews to understand students' perceptions of the role, goal, and specific activities in depth.
- Pre- and post-tests.

Each of these sources of data provides a different perspective on student motivation and engagement. The pre-surveys provide us with a baseline understanding of a students' stable attitudes with respect to science, school, their self-confidence, and interests. It also provides us with shallow data about their initial reaction to the scenario in the unit. Classroom observations provide us with a record of classroom activities, including whether and how the teacher connects individual activities to the scenario context. It also enables us to gather observational data about student engagement. The daily mini-surveys (1-minute multiple-choice questionnaires) provide a picture how students' engagement and perception of the relationship of the activity to the goal and role vary from day to day and. This data can be used to see how the nature of the activity interacts with the students' level of overall buy in to the scenario to influence both: (1) the engagement in a given day and (2) their subsequent buy in to the scenario. For example, if a student does not perceive a fit between the activity and either the role or the goal, he or she is not likely to be motivated by the scenario to engage in that activity. In that case, the demand created by the scenario will not effectively motivate the knowledge construction or organization activities that day. On the other hand, if the activity of a particular day changes the student's understanding of the role or goal in a way that makes it more appealing, then the student's overall buy in to the scenario will increase. In looking for these effects, we also must attend to the influence of self-confidence and other variables that may be influencing their engagement on a given day and their overall buy in. The extended interviews provide a richer picture of students' interests, buy-in, and perceptions of specific activities. In these interviews, students are asked in-depth questions about their interests, attitudes about the scenario, and responses to specific activities. In these interviews, we ask students to list days when they felt particularly engaged and when they felt particularly motivated by the scenario, and when they felt least engaged and least motivated by the scenario. This helps us to understand how students' understand the scenario and the activities and how those understandings interact with their stable attitudes and interests. The pre-test and post-tests measure student content learning and is being collected to see if there are correlations between patterns of motivation and engagement and learning outcomes.

We have collected this data in the context of several scenario-based inquiry units over a two year period, including one enactment of Planetary Forecaster.

3.2 A Study of Motivation, and Role/Goal Adoption in Planetary Forecaster

In this section, we report on a pilot study of role and goal adoption conducted in an eighth grade all-girl science classroom in a Chicago public school. In this study, we collected and analyzed student interviews. Since the time of this study, we have completed studies using the full range of data collection methods described above, but in the context of other scenario-based inquiry units. Additional studies of Planetary Forecaster are planned.

In this study, eight students were selected for interviews based on their pre-surveys. The sample was selected to include some students who reported that they liked science and some who reported that they didn't; some who prefer challenging task and are curiosity-driven, and some who prefer easier tasks and are more extrinsically motivated; some students who believe they have a high ability in science and some who didn't. We report findings about interest and role adoption, which correspond to the strategies of eliciting curiosity and creating task demand in the Learning-for-Use framework.

Interest. Seven of eight students interviewed reported that they were interested in the content of Planetary Forecaster. In particular, they expressed interest in its connection to their own weather: "I think it's interesting 'cause you're wondering about the weather, you wonder why it's so cold in October, but in other places it's hot…". "I like learning about the weather 'cause I'm usually talking about the weather, and I'm interested in it."

Role adoption. Five of six students liked the idea of taking on the role of scientist. "Oh, I love it. I really do. Because you want to get it from another person's perspective. So I'm in a science perspective right now…you wonder how scientists feel, learning about new ideas, and discovering and having new strategies." However, a majority (5 out of 7) students saw themselves as more of a student than a scientist when they did the curriculum. For the most part, reasons for "seeing themselves as a scientist" (or not) had to do with the extent to which the task characteristics matched their idea of a scientist, specifically:

- The extent to which they were learning (like a student) vs. the extent to which they knew what they were doing (like a scientist). For example, "I'm kinda in the middle … I'm still learning, (so) I feel like a student, the teacher is still explaining things to me, but I do feel like a scientist 'cause I know a lot to kinda make a prediction."
- The extent to which the activities they were doing were those a scientist would engage in. For example, "More as a scientist, because, um, the activity that we did when we pointed the light, that was something that not a lot of students would actually do"
- The extent to which they were thinking on their own. "… when we were coloring what we thought the temperature was, I kind felt like a scientist." (when asked why) "Because I was on my own, and I was putting what I thought."

One student talked about becoming more of a scientist as she really started "getting into" what they were talking about. She said, "At first I think of myself as a student, but then when I start getting into what they're talking about it changes, that's when we start researching and stuff …"

One of the surprising results of this study was that one student did not realize that the scenario was fictitious. In fact, she told the researcher that she was beginning to suspect that it was not real and was going to be angry with her teacher if it turned out to be made up. We have found similar students in subsequent studies of other units, and it has raised questions about how to present scenarios to students in scenario-based inquiry learning in such a way that it engages students in the role and pursuit of the goal because of their plausibility without misleading them about their realism. In ongoing curriculum design work, we are exploring ways to present scenarios to students as fictitious but helping them to understand how adopting the role and goal can help to contextualize their learning

The overall impression we gained from this study about Planetary Forecaster's effectiveness at eliciting curiosity and creating task demand is that it was sufficiently effective at both. It successfully channeled students' interests in weather variation into curiosity about climate, and it provided students with an opportunity to play a desirable role. However, there were clear limits to the extent to which students adopted the role in the curriculum. In ongoing research, we are looking at the effect on student role/goal adoption of the prominence of the role and goal in the curriculum materials and the teacher's statements . We also are studying the relationship between role/goal adoption and learning outcomes.

3.3 Studying Learning: Students' Conceptions

In conducting a formative evaluation of a Learning-for-Use curriculum, it is also important to understand to what extent students have developed usable understanding—understanding that they can retrieve and apply in context. While a traditional written test can be helpful in assessing students' understanding, we have found it more helpful to conduct extended interviews of students that enable us to expose not just the correctness but the nature and structure of their understanding.

In order to assess the impact of Learning-for-Use curriculum units on student understanding and track the development of that understanding over time, we have developed a data collection methodology that involves several elements:

- Written pre- and post-tests consisting of multiple choice and short answer to be able to assess student understanding efficiently for a large number of students.
- Clinical interviews before, during, and following the enactment of a unit to assess student understanding in-depth for smaller numbers of students.
- Classroom observations to understand the way that the unit was implemented by the teacher and to track in-class experiences of specific students.
- Collection of student work to understand how students performed work that was assigned and to assess the understanding that was called for by those assignments.

The goal of combining all these elements is to put together as complete a picture as possible of what students have learned and how this learning is explained by the students' experiences as part of the unit. Ideally, they can be done in a way that sheds light on the value of specific knowledge construction and knowledge organization activities, to see both their independent and combined impacts.

3.4 A Study of Students' Conceptions in Planetary Forecaster

In this section, we describe a study of in Planetary Forecaster that implemented many of the elements described above. As with the previous study, this was a pilot study that was designed mostly as a way to test the evaluation methods.

3.4.1 Context

This study was conducted in a 5th grade classroom of 27 students in a Chicago Public School with a diverse, urban population. Classroom observations indicated that the teacher, Martha (a pseudonym), successfully created an inquiry-based learning environment in which students investigated phenomena rather than simply receiving information about it. She repeatedly told her students, "I'm not going to tell you all the answers, you'll have to come up with them yourselves," Martha had high expectations of her students, and the discourse was at times above a typical fifth-grade level; for example, these fifth-graders referred to times when they had to be "metacognitive," or, "think about [their] thinking." Class sessions generally involved significant discussion among Martha and the students. Finally, Martha structured her science class so that her students paralleled scientists. When students were confused about anomalous data in a lab, she would ask them what real scientists do in this situation, to which they would respond "recollect the data," and, time permitting, would do just that. Overall, the classroom environment was excellent for the implementation of a inquiry-based curriculum such as Planetary Forecaster.

3.4.2 Methods

Data were collected via pre- and post-interviews of selected students, written pre- and post-assessments, student work, and classroom interactions with students. Five participants were interviewed individually before beginning the curriculum and again near the end. The purpose of the interviews was to elicit more in-depth explanations from the students, by probing their understanding of involved concepts in a way that could not be done on a paper-and-pencil test. The teacher selected students based on the interviewer'srequest to include students of varying academic abilities who were capable of articulating their thoughts fairly well.

The interviews were designed with the intention of examining not only what students think happens in temperature-related phenomena, but also *why* or *how* they think that event happens. The content of the pre-interview included all four factors covered in the curriculum. A main question for each of the four content areas was generated, and, based on prior research and expected student responses, follow-up questions contingent on the response were included in the script. Students were asked to draw pictures to aid their verbal explanations, especially for the questions involving the earth-sun relationship and the seasons. The mid-point interview discussed here focused primarily on the earth-sun relationship and effect of the curvature of the Earth on intensity of sunlight. It also touched on the seasons, a topic that the class had partially covered.

The pre-test was administered at the start of the curriculum and the post-test was administered several weeks after the teacher completed her enactment of the curriculum. The written assessment was designed with the objective of getting a greater breadth of data than could be obtained from the interviews alone. The test consisted of multiple choice, short answer, and true/false questions. The answer options for the multiple choice questions often contained "lure" choices; that is, misconceptions that have been previously demonstrated by other students, such as "In the winter, the Earth is farther away from the sun, and in the summer, the Earth is closer to the sun." Similarly, four of the six true/false questions were lure statements. Exams were scored on the basis of whether a student answered the question correctly, answered the question incorrectly by giving or selecting a lure answer, or answered the question incorrectly without giving or selecting a lure.

The class was observed two to three times a week throughout the duration of the curriculum. During lecture and whole-class sessions (approximately half of the classes were run in this format), the researchers sat in the back of the classroom and record field notes. During group work sessions, they occasionally worked with various small groups in the same manner as the teacher – facilitating discussion, attaining a grasp on student understanding, answering questions, etc. Additionally, student work completed either in class or as homework assignments was collected for analysis. Many of the assignments were completed in small groups of three to five students in class.

The study focused on the portion of the curriculum, in which students investigate the effect of Earth's spherical shape and the tilt of its axis of rotation on the intensity of the incoming solar energy at different latitudes at different times of year. Students engage in several hands-on and computer-based activities to support their construction of knowledge about this content. All the activities are designed around a conceptual model of incoming solar energy as parallel "rays" of light. We selected this model of insolation in the design of the curriculum because it is sophisticated enough to explain variation in heating at different latitudes but simple enough to be accessible to middle school students. In the portion of the unit on the effects of curvature, students engage in two knowledge construction activities. In the first one, they conduct a hands-on lab where they use a penlight to represent the Sun and measure the area of the light beam from the penlight as it strikes paper at different angles. Each angle of the paper represents a different angle of incidence of sunlight from the equator to the poles. This lab is designed to demonstrate that with increasing angles (as you move toward the poles), the same amount of light spreads out over a larger area, resulting in a lower amount of energy per unit of area. The second activity allows them to see data visualizations of measured incoming solar energy showing the same decrease in energy intensity at a global scale that they viewed in their hands-on lab. In the section on tilt, students conduct a hands-on investigation with globes and penlights, in which they process the globe around the light source observing which portion of the globe receives the most and least direct sunlight at the equinoxes and solstices. This activity, too, is accompanied by a computer activity, in which students compare visualizations of Earth's incoming solar energy at each season.

3.4.3 Selected Findings

In the following paragraphs, we present a case study of the evolution of an individual student's conceptions over a portion of the Planetary Forecaster unit. We include it here to show the value of a detailed picture of a students' understanding for formative evaluation. Because our goal in this chapter is to illustrate rather than report complete findings, we are only presenting one of three case studies that we developed as part of this study. Salierno, Edelson, and Sherin (2005) present all three cases and a detailed analysis of the misconceptions literature that is relevant to Planetary Forecaster. In this case study, we present a detailed description of the state of Alice's (a pseudonym) understanding of the differential heating of the Earth at different latitudes due to the angle of incidence of solar radiation. We describe her understanding as demonstrated before the unit, followed by a description of our observations of Alice during the unit, and then her understanding as demonstrated in the interview following the segment of the unit dealing with curvature of the Earth's surface and angle of incidence of solar radiation.

Before the unit. Alice presents an intriguing case because she revealed initial conceptions that were not documented in prior research. When asked why Florida is warmer than Alaska, she indicates that different parts of Earth are heated by different parts of the sun, and that Florida receives its sunlight from a warm part of the sun. She draws a picture showing Florida receiving longer sun rays than Alaska, and explains in answer to the question, "Does the way sunlight hits the earth have to do with temperature at different places?" that the strength of a ray of sunlight is determined both by its length and the part of the sun from which it originates. In answer to both questions, she indicates that longer rays carry more heat, although it is not clear whether she means that rays that travel farther through space carry more heat, or she is simply using length to indicate strength in her written representation. Alice also draws rays of sunlight that curve, including some that curve around Earth to reach portions of the globe that are facing away from the sun.

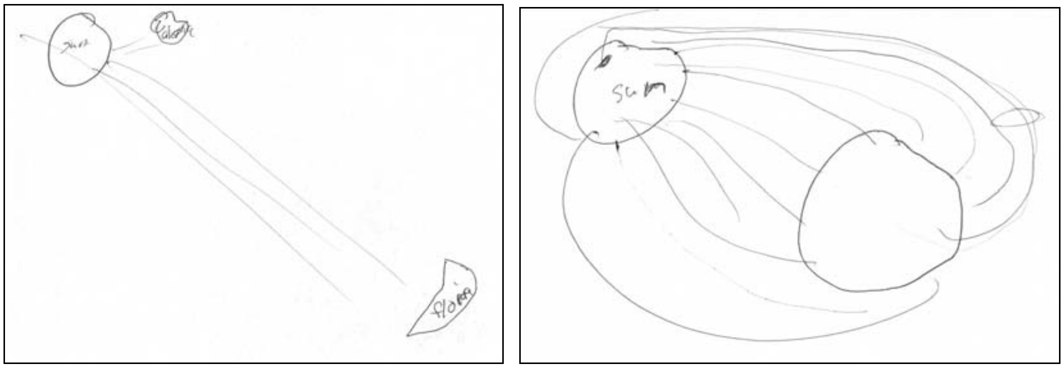

Figure 1. Drawings from Alice's pre-interview. On the left is her drawing showing the longer sun rays reaching Florida and shorter sun rays reaching Alaska. Right is her more general drawing of how the rays of the sun reach the Earth. The dark spot on the sun was drawn to indicate a particularly warm portion of the sun.

Alice’s description of the causes of temperature change with the seasons is very disjointed. She knows that it is winter in the southern hemisphere when it is summer in the northern hemisphere. However, she is unable to explain why, and she presents several partial arguments about the spinning of Earth on its axis, the movement of Earth around the sun, and “maybe because of the atmosphere.” In answer to a question asking why it was cold on the day of the interview (a winter day) even though it was sunny, she says that the sunlight is somehow different. Her pre-test was consistent with the interview. She missed three of the eight questions about the Earth-sun relationship, giving answers that were consistent with the explanations she gave in her interview.

During the unit. Despite being talkative in her interviews, Alice spoke very little during class discussions and groupwork. However, researchers did observe her on two occasions make comments or draw diagrams that were consistent with her pre-interview statements about the sun’s rays. Both her statements within her group and her answers to the reflection questions in the penlight lab revealed that she observed that the area covered by the penlight increased as the angle became more acute, however she did not recognize that the brightness of the light decreased. Making this observation is probably critical to understanding that the increase in area results in a decrease of intensity. The likelihood of a student understanding the relationship between angle and intensity in the absence of this concrete observation is diminished because the student must instead apply the abstract principle of conservation of energy. Alice, in fact, does not demonstrate in her lab write-up that she understands the relationship between angle and intensity.

Following the unit. In the post-interview, Alice correctly explains that the equator is the warmest part of the earth because it is almost at a 90 degree angle to incoming sunlight and therefore receives the most direct light. She does not mention differences in length of rays or refer to rays that originate in different parts of the sun. In answer to the questions about Florida and Alaska, she says:

Researcher: Last time we talked about…Florida and Alaska…why again would it be warmer in Florida than Alaska?

Alice: I think it was because Florida would get part – part sunlight - part direct, but it's not really direct, it's like at a slanted angle, but it would be at ninety degree

Researcher: Ok, so it would be more slanted than ninety…What kind of sunlight does Alaska get?

Alice: I don't think Alaska gets that much light.

Researcher: Ok, so they just get less? Do you know why they might get less than Florida?

Alice: Less direct sunlight

However, when asked directly about the relationship between angle of incident light and intensity, Alice has the relationship reversed. She states consistently that heat and light intensity increase with area, claiming that the same amount of light spread out over a larger area has more heat and greater intensity than it would spread out over a smaller area. In addition, while she has mostly eliminated curved rays from her drawings, when asked about the difference between temperatures at the equator and the poles, she explains that at the poles it is cooler because the light has to curve to get there, and she draws curving lines of light arriving at the poles. In the post-test Alice actually scores worse than on the pre-test, missing four rather than three questions. The lack of improvement[5] appears to be due to the fact that she still does not understand the relationship between angle and intensity.

3.4.4 Discussion of Results

Alice is typical of the students that we studied in that she has fragmented and mostly incorrect conceptions initially. Like the other two students that we interviewed, significant misconceptions that appeared in her pre-interview were no longer apparent in the post-interviews (although additional assessments would be necessary to verify that they did not reappear at a greater interval following the curriculum). In their post-interviews, all three students understood the central relationship of this portion of the curriculum, that temperatures decrease with increasing latitudes. However, none of them was able to bring together all the pieces that the section was trying to teach in order to connect angle of incidence to intensity of sunlight (via conservation of energy) and to use this relationship to explain differences in temperature. Based on the detailed information about these three students and the post-test results of the other students in the class, we concluded that the curriculum is making a difference in these students' abilities to retrieve and apply relevant knowledge, but the unit is not fully achieving the goals of its designers.

We have several hypotheses for why the students are not achieving a better level of understanding of the target concepts. The first is that fifth grade students are not developmentally ready for the abstract reasoning that this unit requires. There is evidence for this in the fact that they are able to understand directly observed relationships, such as the relationship between angle and area, but not able to extend this

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[5] The additional incorrect answer was a question on seasons that the class had not covered yet. The answer she gave was consistent with what they had learned about curvature, but did not reflect the additional effect of tilt.

via an abstract principle such as conservation of energy, to understand the relationship between angle and intensity. In fact, the curriculum is targeted at 6-8th grades. Another hypothesis for why students did not achieve the desired depth of understanding is that there is important prerequisite understanding that the curriculum does not address directly. To understand the implications of angle of incidence and tilt for temperature, students must understand the “ray” model of light and must understand the Earth-sun relationship, including the shape of Earth’s orbit, period of Earth’s revolution around sun, and period of Earth’s rotation around axis, well enough to overcome common misconceptions. The curriculum assumes that students understand these concepts or that they will pick them up as a result of their experiences with the curriculum. In fact, there is some evidence that students do “pick them up.” For example, Alice mostly abandoned her theory of curving rays of sunlight, despite the fact that there is no activity that directly addresses the nature of these rays, just numerous representations of sunlight using straight arrows to represent sunlight. Presumably, the curriculum could be more effective if it were to target these important pre-requisite concepts and if it were to include activities that directly address problematic misconceptions, such as those documented here.

Our final hypothesis raises questions about Planetary Forecaster as an implementation of the Learning-for-Use design framework. In fact, the task that students are asked to do does not demand that they understand the reasons that latitude and seasons effect temperature. It simply demands that they know what the relationships are. In the end, the task that students are being asked to do is to apply their understanding *that* temperature varies with latitude and *how.* It does not clearly require that they be able to explain *why*. In fact, all three students demonstrated in their classwork, in their post-interviews, and their post-tests that they do know that temperature decreases as you move away from the equator. It is possible that a re-design of the curriculum that placed a greater demand on explaining why the four factors affect temperature would be more effective. On the other hand, it is also possible that students are not sensitive enough to the actual demands of the task that their learning of the *that* and the *how* but not the *why* is the result of the knowledge demands of the task.

3.5 Reflections on Evaluating Learning-for-Use

In this section, we have described methods for evaluating two different critical aspects of Learning-for-Use:

- The extent to which a particular unit instilled the goal of achieving its learning objectives (motivation)
- The extent to which it fostered the development of its target understanding (knowledge construction)

We also presented cases of how these methods have been applied in formative evaluations of the Planetary Forecaster curriculum. The lesson of both of these studies is that the unit is at least partially successful in achieving its goals. In the motivation study, students found the goal interesting and the role of scientist appealing. However, they reported that for the most part, they did not feel that they were playing the role very much of the time because they did not find the activities to be consistent with their understanding of a scientist’s activities. This finding has important implications both for the design of activities and for the need to help students understand how specific activities fit into the role. In the student conceptions study, students' conceptions showed evidence of change toward the target understanding, but they did not demonstrate the complete understanding that the designers of the curriculum were targeting. This result requires further study, but it has led us to consider several implications for the design of the unit, including the possibility that the task does not create demand for the depth of understanding that we were seeking.

The studies we described in this chapter were designed to look at effectiveness of an individual unit, rather than assessing the effectiveness of the general approach. In order to evaluate the general approach, it would be necessary to conduct investigations across multiple units. It would also be necessary to conduct comparative studies that looked at the impact of removing elements of the Learning-for-Use framework. In future work, we hope to be able to do this research. For example, to look at the effect of the motivation strategy of creating task demand, we would like to conduct a study that will compare Planetary Forecaster with a unit that contains all of the same knowledge construction, reflection, and application activities, but without the contextualizing scenario. Similarly, to investigate the role of application, we would like to conduct a study of a unit that contains the same motivation and knowledge construction activities withut the opportunity to reflect on or apply what the students have learned in context.

4. Learning-for-Use in the Geosciences

Recent reports have called for reform in geoscience education, including an emphasis on a systems approach and the techniques of geoscience inquiry and explanation (American Association for the Advancement of Science (AAAS), 1994; Barstow & Geary, 2001; Ireton et al., 1996; National Research Council (NRC), 1996). If these reform efforts based on contemporary trends in the geosciences are to have a positive impact, they must be implemented in accordance with contemporary understanding on how people learn. The Learning-for-Use design framework has been developed to encode that understanding in a set of design guidelines. The development and research efforts described in this chapter are intended to serve as a model of how these guidelines can be implemented and evaluated in a geosciences context. However, significant additional research remains to be done on learning in the geosciences (Manduca et al., 2002) and on Learning-for-Use.

In closing, we feel it is important to emphasize the critical need for disciplinary expertise in developing effective curriculum units. Planetary Forecaster is one of several scenario-based inquiry learning units in the geosciences that have been developed by the Geographic Data in Education (GEODE) Initiative at Northwestern University. In every case, geoscientists have played critical roles in identifying appropriate scenarios, clarifying the learning goals, developing knowledge construction and application tasks, developing scientific explanations, verifying the scientific accuracy of curriculum materials, and developing assessment. We have been successful in creating partnerships between curriculum developers, teachers, technologists, and geoscientists by developing common ground around goals and strategies. The Learning-for-Use framework and its implementation in the form of scenario-based inquiry learning have provided an important part of that common ground by giving individuals with diverse expertise a shared vocabulary for discussing curriculum design.

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