Situationally Embodied Curriculum: Relating Formalisms and Contexts

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ABSTRACT: This study describes an example of design-based research in which we make theoretical improvements in our understanding, in part based on empirical work, and use these to revise our curriculum and, simultaneously, our evolving theory of the relations between contexts and disciplinary formalisms. Prior to this study, we completed a first cycle of design revisions to a game-based ecological sciences curriculum to make more apparent specific domain concepts associated with targeted learning standards. Of particular interest was using gaming principles to embed standards-based science concepts in the curricular experience without undermining the situative embodiment central to our design philosophy. In Study One reported here, the same first-cycle elementary teacher used the refined second-cycle curriculum, again with high-ability fourth graders. We then analyzed qualitative and quantitative data on student participation and performance to further refine our theory and revise the curriculum. In Study Two, another teacher implemented a further refined second-cycle curriculum with lower achieving fourth graders, including several students labeled as having special needs. We use the design trajectory and results to illustrate and warrant the creation of a situationally embodied curriculum that supports the learning of specific disciplinary formalisms. © 2007 Wiley Periodicals, Inc. *Sci Ed* 1–33, 2007

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> When I compare today's high school science textbooks with those of my 1930s high school textbooks, I am less than pleased. For one thing, they are as dull as ever and have no more literary merit now than they did then. Science is a grand human adventure, but you would not know it from reading science textbooks. In every science discipline there are stories to tell, ideas to explore and to try to understand, advances and disappointments to confront, applications to astound us or worry us, mysteries solved and new mysteries created—but that is not what comes through in science textbooks. (Rutherford, 2005, pp. 370–371)

INTRODUCTION

Modern society presents a host of decision-making opportunities in which citizens must consider scientific problems that have ethical, economic, political, and social implications. Scientific literacy—beyond memorizing specific facts, concepts, principles, and ideas as articulated in many state standards—involves using this scientific knowledge to negotiate and resolve complex societal issues (Driver, Newton, & Osborne, 2000; Ryder, 2001; Zeidler, Sadler, Simmons, & Howes, 2005). Central to our work is the belief that displacing to-be-learned content from the situations in which it has value undermines the very understandings that educators aim to foster (Brown, Collins, & Duguid, 1989; Dewey, 1938/1963). To be clear, we believe that understanding scientific concepts is critically important. However, especially for K-12 learners who might not come to school already valuing the learning of science, it might be conceptually and motivationally ineffective to make science content the focal point of the learning as opposed to presenting science as a tool for addressing other more engaging issues. In spite of the intuitive appeal of *situating* learning in contexts of use (e.g., Lave & Wenger, 1991), this goal has proven difficult to actualize, especially in the current U.S. sociopolitical school context with its emphasis on standardized tests.

The challenge inherent in enlisting rich contexts in schools is how to meaningfully relate experience, particular domain practices, and the accepted understanding of domain content, such that students develop an appreciation for the contextual value of the content while also beginning to identify the relevance of the underlying to-be-learned content when it is situated in other contexts. Or, as argued by Bereiter (1997, p. 286), "the main weakness of situated cognition is, it seems, precisely its situatedness." Conversely, as long as educators adopt a reverent attitude toward pure thought as the goal of education, they are likely to undermine the very understandings they wish to support. In fact, for us as science educators, the central question is not whether learners should engage rich contexts for learning science but, rather, how we can best support and engage active learners with these rich contexts. Toward this end, numerous projects have leveraged technology, and specifically the networked personal computer, to facilitate the establishment of rich learning contexts that provide associated tools and resources for supporting the learning/doing process (see, e.g., Barab & Hay, 2001; Blumenfeld, Marx, Soloway, & Krajcik, 1996; Fishman & Krajcik, 2003; Karlan, Huberman, & Middlebrooks, 1997; Kolodner, 2006; Linn, Clark, & Slotta, 2003; Linn, Davis, & Bell, 2004; Rivet & Krajcik, 2004; Roth, 1996; Roth & McGinn, 1998; Songer, 2006; Songer, Lee, & MacDonald, 2003; Tal, Krajcik, & Blumenfeld, 2006).

Building on this work, we go one step further by leveraging game-design methodologies and technologies to situate the learner and the content (Greeno, 1993; Lave, 1988). Truly situating the learner involves fostering a deep sense of embodiment in which the learner enters into a situation narratively and perceptually, has a goal, has a legitimate role, and engages in actions that have consequence—what we describe as *situative embodiment*. Situative embodiment involves more than *seeing a concept* or even a context of use; it involves *being in the context* and recognizing the value of concepts as tools useful for understanding and solving problems central to the context in which one is embodied.

Situative embodiment involves both a sense of projection into and identification with the situating context (Dourish, 2001); it involves the adoption of particular intentions that are bound up in the use-value of the content. It is just such socio-material embodiment that Gee (2003) and others have argued videogames can afford.

While simulations historically have been valuable in establishing a sense of perceptual or conceptual grounding, videogames and the worlds they help establish provide a new medium for supporting situative embodiment and advancing science education. Gee (2003), in his seminal book on learning from videogames, illuminated how well-designed games have the potential to establish a sense of embodied empathy for a complex system as players come to identify with their game character and the larger system within which this character interacts. Well-designed game play embodies players—perceptually, socially, and narratively—in a rich network of interactions and unfolding storylines through which they solve problems and reflect on the workings of the design of the game. In this study, we propose that videogames can provide science educators with a new tool for establishing the legitimacy of science content, situating learners in rich narrative contexts in which they adopt particular intentions and in which player actions result in story changing consequences.

Games can be thought of as designed experiences or ideological worlds (Squire, 2006) that establish a rich narrative context for meaningful learning/participation. To appreciate how videogame contexts provide a platform for supporting situative embodiment with respect to a particular context-of-use, consider some of the game features that Squire and Jan (2007) highlights as relevant to science education. First, games invite students to *inhabit roles* and take on identities that are a melding between the player identity and the game role of that player. This allows students to move outside their student role in the classroom into the role of an active participant-stakeholder. Similar to school, games also provide *challenges*. However, the challenges available in games allow for problem-based and player-defined goals—a possibility not always present in classrooms—that are meaningfully actualized in the game space. In this way, as particular actions result in system changes that help realize particular goals, the game world itself provides the learner a sense of intentionality and consequentiality. Properly designed game worlds can be thought of as *contested spaces* in which there is a spatially bound problem that changes over time based on player decisions as they move around the space. Last, games allow for the *embedding of authentic resources and tools* that are critical to success in the game space. These tools and resources are “situated” in terms of the requirements of the to-be-accomplished task. Through these features, digital games in particular have the potential to situate (embody) the content, the practices, and the learner within a virtual world.

Central to our argument is that a sense of situative embodiment changes the learner’s relationship to the underlying formalisms, and that videogame methodologies and technologies can help establish a narrative, perceptual, and social world that invites such embodiment. This article details the evolution of our curriculum and our related theory, designed to embody or ground scientific concepts and processes within a meaningful context and at the same time support generalizable understandings. It outlines the enactment of the initial second-cycle curriculum of an ongoing design study (see Barab, Sadler, Heiselt, Hickey, & Zuiker, 2007, for the first-cycle design study) and the modest transfer of content knowledge that occurred, then details subsequent revisions aimed at ensuring that new content knowledge would transfer even to the random and/or impoverished context of standardized achievement tests. In the revised second-cycle curriculum, we designed curricular activities that feature various embedded scientific *formalisms* (e.g., causal reasoning, systemic process analysis, hypothesis, eutrophication) that, through participation, may become contextualized, and upon reflection, abstracted.

Across implementations, we analyze both qualitative and quantitative data to answer the following research questions:

- What are the main challenges in designing a game-based learning environment that situates and legitimizes (*narratizes*) scientific formalisms?
- As learners investigate the game-based learning environment, what are the challenges in supporting their enlistment of scientific formalisms to meaningfully interrogate (*scientize*) the context?
- As learners are challenged to recognize and apply scientific formalisms in a myriad of contexts, how can educators best support generalization from specific, contextually bound experiences?

THEORETICAL GROUNDING FOR AN EMBODIED CURRICULUM

Central to this article is the idea of a situationally embodied curriculum; that is, a curriculum involving at its very core a perceptually and narratively rich context that does academic work. Such a situated or embodied perspective contrasts with views that advocate for students to be taught formal, abstracted disciplinary knowledge, unencumbered by contextual particulars that purportedly limit a given formalism's potential to generalize. For many, it is the "pure" form or abstraction away from context that makes disciplinary *formalisms* so powerful and applicable. In this study, we build on Nathan's (2005, p. 5) characterization of formalisms as "formal structure and abstract principles that underlie the conceptual framework of the content area." Formalisms refer to the hypothesized process or invariant structures that give rise to or explain a particular instance (the variant). Thus, for example, erosion is an invariant concept that can be enlisted to explain why clear cutting forests on the banks of a particular river may be responsible for the clogging of fish gills. It rests relative to the phenomenon, having an essence, but one that is continually contextualized in relation to the context—similar to Kant's notion of noumenon. In our thinking, it remains embodied when discussed in relation to a particular context, but becomes more abstracted when discussed with no explicit connection to a particular context.

The hypothesized power of the abstracted formalism, as opposed to understanding a formalism in terms of a particular instantiation, lies in its not being tied to the instance and, therefore, being generalizable across contexts. The problem, however, is that while these formalisms might do useful work for an expert in the field who appreciates their functional value, they are unlikely to have this same meaning for a student—even the "A" student who can correctly describe their formal structure (Schoenfeld, 1996). Students learning a formalism who are new to a disciplinary body of knowledge may be unaware of the contexts in which it has value and as such, we argue, might develop an understanding of the formalism that is inert. Inert knowledge, according to Whitehead (1929), is knowledge that students can use correctly to respond to a question in terms of a particular school context or testing situation, but they do not apply it or see its relevance to other contexts. Bringing students to see the beauty and power of science as it relates to the world and to themselves is critical to their deep learning and life-long commitment to science (Barab, Cherkes-Julkowski, Swenson, Garrett, & Young, 1999).

What makes the curriculum situationally embodied is that any to-be-learned content is experienced initially and primarily in relation to a particular context of use. The idea of situative embodiment, for us, is not simply a perceptual surround; it involves a storyline that provides (a) legitimacy to the content and student actions, (b) a meaningful goal and set of actions for the learner, (c) a background against which learner actions have some consequence, and (d) a contextual framing that allows the learner to appreciate the use-value of the content being learned. The types of narratives we design are not simply stories told to passive listeners. Instead, they are transactive trajectories that unfold in relation to evolving student understandings and application of disciplinary formalisms. The argument advanced here, and one that is consistent with the wealth of work related to situated cognition (Brown et al., 1989; Greeno, 1993; Lave, 1988; Lave & Wenger, 1991), is that a context of use has the potential to change fundamentally the very meaning of the formalism. In a situationally embodied curriculum as described here, the learner is immersed in a narrative context of use and, through it, engages a formalism as situationally *embedded* in, *embodied* by, or *abstracted* from the socio-material context.

A formalism is considered *embodied* when it is experienced as part of a concrete situation; that is, the meaning of an embodied formalism is bound up in, and dependent on, its particular context of use. In an embodied formalism, the user is "seeing" or "living" the formalism. Thus, for example, if a student is examining the water quality of a river that is being compromised by erosion from cut trees along the bank, erosion as a formalism is considered embodied—even if the student begins to describe the local problem as erosion. Erosion is considered *embedded* when a student is engaged in a situation and draws on a formal account that has meaning and is described irrespective of the particular situating context of use. In this way, the meaning of the formalism erosion might be bound up in another context of use, or its reference might be more abstract, but it is enlisted by a student who is situationally embodied, and the formalism serves as a conceptual tool for addressing the situation. In other words, a formalism is considered embedded when it resides apart from the situation, perhaps as described in a textbook, but is enlisted to make sense of the embodied phenomenon. The important difference is that in the embedded situation, the student enlists the abstract formalism and applies it to bring meaning to an embodied instance of the formalism. In the embodied situation, in contrast, there is no separate instance or description of the formalism beyond the context in which it is being applied. An *abstracted* formalism involves applying an understanding of the formalism originally developed in relation to a particular context to other contexts of use. This type of cross-context application is often referred to as transfer (Detterman & Sternberg, 1993). Table 1 provides definitions of these and additional terms pertaining to the relations between formalisms and contexts.

Figure 1 further characterizes the relations of formalisms and contexts, in an attempt to advance an ontological framework that has pedagogical implications for situationally embodied curricula. In this diagram, diamonds represent formalisms and circles represent

TABLE 1
Different Epistemological Characterizations of Formalisms

Manner of Formalism	Relationship to Context-of-Use
Context independent	
Disembodied	When the formalism is *not* connected to an embodied authentic use situation
Framed	When the formalism is introduced and multiple examples are enlisted to further illuminate its characteristics
Context dependent	
Embedded	When formalism is enlisted as a tool in the context of a concrete situation for which it has value
Embodied	When the formalism and its meaning are bound up within the particular context in which it is being applied
Abstracted	When a formalism that is learned through enmeshment in a context-of-use is related to other contexts-of-use

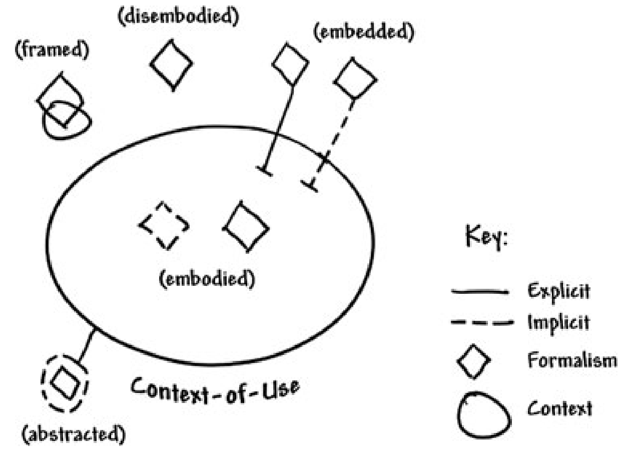

Figure 1. An ontological characterization of the relations between formalisms and contexts.

contexts. Solid lines in the diagram represent explicit formalisms, contexts, and connections, whereas dashed lines represent implicit ones. Central in the figure, illustrating its importance, is the context-of-use. A formalism is *contextualized* when the instruction focused on the formalism is situated within a context-of-use in which the formalism could usefully be applied. This stands in contrast to instruction that presents formalisms devoid of, or with only minimal, contextual framing—referred to as disembodied and framed, respectively. A problem that arises is that what is abstracted for an expert or a textbook developer may be disembodied for other people, including students.

Figure 1 also indicates that relations between an embodied formalism and a context can be implicit or explicit. Explicit refers to direct use of a formalism. Rather than merely being leveraged for understanding, it becomes the focus of attention in name and function. In contrast, implicit enlistment involves an appreciation of function but no particular explicit focus or labeling. Thus, for example, "embedded explicit" involves enlisting a resource such as a textbook diagram about erosion to make sense of a contextually embodied instance of the formalism. In contrast, "embedded implicit" might involve someone suggesting, without identifying the formalism by name, that a problem similar to the one being investigated is happening at another park and that understanding the other context might help make sense of the one at hand. In this latter case, erosion as a core concept is not being enlisted explicitly but rather is enlisted only through those characteristic processes that constitute its transferability as a formalism. Similarly, when someone is trying to make sense of a particular, contextual occurrence and is describing or experiencing the process that is unfolding, then the formalism being engaged is "embodied implicit." It becomes "embodied explicit" only when the person specifically focuses on or even mentions the process as one of erosion. Even then, the context and not the formalism remains the focus of attention.

In Figure 1, "abstracted formalisms" are represented by an arrow or tether issuing out from the context of use, with the formalism becoming explicit and the context from which it was abstracted being implicit. This stands in contrast to "disembodied formalisms," in which there remain no relations to any particular context of use, either now or in the history of one's experience. Figure 1 suggests that the relations between any formalism being learned and a particular context-of-use change the ontological status of the formalism itself; that is, when the focus of learning is first on the context-of-use, rather than on the disembodied formalisms, the very meaning of the formalism changes. Furthermore, and consistent with others who adopt a situated perspective of knowing (Brown et al., 1989;

Lave, 1988; Roth, 1998), a core argument of this paper is that learning should begin with this sort of embodiment.

THEORY TO PRACTICE

At the core of our argument, and consistent with the situated platform that inspires our work, is the belief that K-12 curriculum would be more useful, especially in helping learners understand the meaning and value of formalisms, if the academic content to be learned was embodied within interactive narrative contexts (Bruner, 2002; Ryan, 2001). Toward this end, we have been iteratively refining an ecological sciences curriculum that is based on an inquiry framework (Barab et al., 2007). The unit immerses students in a rich, interactive narrative about a serious ecological problem centered on a declining fish population. Using a graphical multiuser environment, students enter a computerized world and collect data, interact with their peers, and interview a number of virtual characters. The evolving storyline aims to engage students in the role of expert helper. As field investigators, students interview characters with different perspectives on the problem (activity one), collect and analyze data to develop a hypothesis about the problem (activity two), engage in a series of voluntary activities (missions one and two), propose an informed solution (activity three), and collaboratively provide advice on a related problem (mission three). As students complete activities, they have access to new resources, different forms of data, and to virtual characters that share additional information over time.

Observations of fifth-grade students using earlier versions of the curriculum indicated that, in general, students found both the narrative and the problem it revealed to be engaging. However, students interacted with scientific inscriptions infrequently. Consequently, while performance improved significantly on "proximal-level" assessment items that were closely aligned to our curriculum, there was only modest improvement on "distal-level" assessment items that were aligned to the targeted standards, independent of our curriculum. In addition, detailed examination of the enactment of various activities and their resulting artifacts revealed little evidence that students were enlisting scientific formalisms in their inquiry (Barab et al., 2007).

The challenge that motivated this study is thus how to position domain formalisms, such as eutrophication, within a curricular context such that they have rich contextual value and, at the same time, are explicitly identified by learners as formalisms that will have value in other contexts. Simply being able to discuss eutrophication in the context of the particular situation that we established was not our goal. In fact, the first cycle of our design work indicated that we had too much "situation" and not enough formalism. Therefore, a key goal in the two implementations discussed here was aiding students in understanding the relevance of the formalisms to this context and at the same time in appreciating their invariant properties as they are enlisted in other contexts. Said another way, whereas in the previous study we were able to demonstrate that a game-based curricular environment could be effectively used to *narratize* disciplinary formalisms, here our goal was to further support students in taking up disciplinary formalisms to *scientize* the context. This design challenge also pushed us to develop a more robust and nuanced theoretical characterization of formalisms and their relations to contexts.

METHODS FOR STUDY ONE

Overview and Context

As indicated above, the first-cycle implementation of our ecological sciences curriculum yielded significant gains on "cherry-picked" standardized items and on locally developed open-ended items that matched the content and context of the curriculum, but we failed to obtain statistically significant learning gains on a test consisting of items drawn at random from pools of items aligned with the targeted standards for elementary school science (Barab et al., 2007). These latter items more often used contexts that had little to do with water quality, and tended to use the formalisms in examples that had little surface relations with the water quality simulation at the heart of the curriculum. Following the principles of design-based research (Brown, 1992), we made theoretical improvements in our understanding, in part based on empirical work, and revised the curriculum accordingly. The first study of the second cycle that we describe below occurred in the classroom of the teacher who originally piloted the curriculum, albeit with a new group of students. Both studies reported in this article employed naturalistic inquiry methods involving quantitative and qualitative data as part of the design-based research focus.

The water quality curriculum was implemented in a fourth-grade class of high-achieving student who had been selected for inclusion in a systemwide program for gifted students; their school was located in a midwestern town in the United States. There were 23 students in the class, of whom 15 were girls. The teacher was exceptional. She had taught the curriculum to a previous class and was very comfortable with university educators conducting research in her classroom. The students had done other project-based, collaborative, and inquiry-based work, as well as other curricular units associated with the three-dimensional (3D) Web environment; however, they had not studied water quality. The particular unit we observed lasted 2 weeks, including the pairs of pretest and posttest assessments described below. We videotaped class and computer room segments throughout the 2-week intervention and conducted interviews in which students explained their reasoning and actions.

Curriculum

The unit was a water quality simulation that took place in the 3D virtual, multiuser environment known as Quest Atlantis (QA). Building on strategies from online role-playing games, Quest Atlantis combines strategies used in the commercial gaming environment with lessons from educational research on learning and motivation (Barab, Thomas, Dodge, Tuzun, & Carteaux, 2005). It allows participants to use an avatar to travel to virtual places to perform educational activities (known as quests), chat with other users and mentors, and build virtual personae. A quest is a curricular task designed to be entertaining yet educational. In the case of the aquatic habitat unit used in this study, there were three quests and a number of suggested class discussion activities that constituted the experience. Figure 2 is a screenshot of the 3D world students navigate during this exploration.

Shown in the screen shot is Ranger Bartle, the park ranger. In videogames, such computerized bots are referred to as nonplayer characters (NPCs). The Ranger Bartle NPC is central to establishing the nature of the work the students are tasked with in this study. Students use arrow keys on their keyboards to navigate their way to him at the ranger station, where they learn about the park and can access scientific articles relevant to their task. As students move their avatars around the virtual world, they encounter a number of NPCs and other students who are similarly using avatars to move around the world, and they chat with and send emails to other students. Certain NPCs may also be programmed to send emails to follow up on actions taken and events experienced by the students.

As part of this unit, a rich narrative immerses students in a story about an area (the Taiga Park) with serious ecological problems and invites them to assume the role of field investigators. Students initially read about different viewpoints by clicking on NPCs. Each

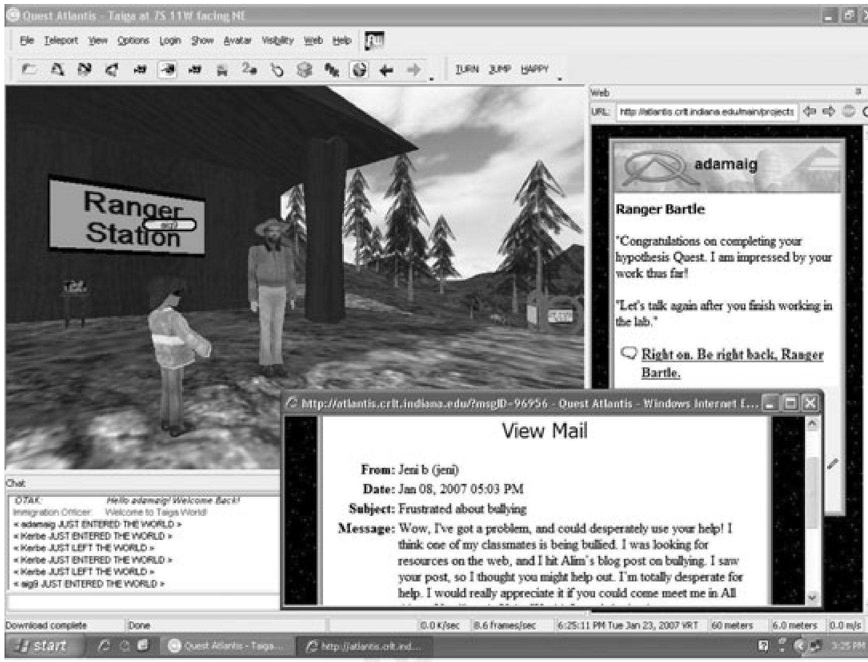

Figure 2. Screen capture from the Taiga virtual world.

NPC presents simulated dialogues that reveal a perspective on the problem. Drawing on these conversations, students report profiles of each group of users of the park and how they might relate to the fish problem (Quest One). Next, they collect and analyze data to develop an assertion about the causes of the problem (Quest Two) in order to propose informed solutions (Quest Three).

In doing these quests, students engage in a socioscientific inquiry process that involves three central, interrelated activities and continual reflection and revision of their understandings (Barab et al., 2007). For us, socioscientific inquiry refers to inquiry that considers more than scientific variables alone; it has to balance scientific data with socially relevant factors such as economic or political factors. Barab et al. (2007) suggest that in the Taiga unit, the process begins with immersion in a narrative with the goal of recognizing multiple stakeholders and identifying factors contributing to the fish decline. This is followed by a more substantial investigation that involves gathering and analyzing data and formulating hypotheses. Students then use their nuanced understanding to propose a solution that balances the scientific evidence with political and economic awareness.

The underlying narrative is further fleshed out as students navigate the virtual environment. The virtual world includes two rivers (one starting in the northeast and the other in the northwest) that run together in the center of the park (Figure 3 shows a two-dimensional (2D) map of the Taiga park). Different perspectives are learned by navigating one's game avatar around the world to any of the 13 NPCs. Students must explore the Taiga context to find each of the different virtual characters in order to gain a full appreciation of the happenings in Taiga.

An important aspect of fostering socioscientific inquiry is that during the learning process the narrative "unfolds"; that is, the narrative is revealed over time based on student choices. In the case of the Taiga, students began with a printed letter from Ranger Bartle asking for

Figure 3. A 2D map of the Taiga park.

their help. They then log in and navigate their avatar through the 3D environment, clicking on virtual characters who share information. For example, in the beginning of the simulation after clicking on Lim, the logging mill manager, the students respond to a dialogue tree, and Lim's follow-up response is based on choices made by the student in the dialogue tree:

> Manager Lim: "Welcome to our little piece of the Kongakut. I am Lim. We're just a small operation now, but we are growing. Did you know that we added twenty new jobs to this area last year? I'm very proud of our logging efforts."
> Student Choice A: I thought this was a national forest, why do you call it "our" little piece?
> Student Choice B: You have a very impressive operation here. Could you give me any more information about this area?

If a student chooses the first question, then Lim responds defensively and provides less information than if students ask the more polite second question. Further, after completing the first quest, Lim responds to the student with additional new information. Lim tends to ascribe the water quality problem to acid rain. In contrast, Norbe (the leader of an indigenous group) and Maria (a park visitor) blame the loggers. Sara, the girlfriend of a logger, defends the loggers:

> Sara: From what I understand, everyone is anxious to hear your report. I know the loggers and the people here at K-Fly really want to make sure the park remains healthy. Financially, the loggers invest more than any other group to keep the park healthy. My boyfriend tells me that Ranger Bartle might have had to shut down the park if the loggers didn't pay as much as they do to log here.

Thus, the narrative presents the complex, interrelated nature of ecological conditions and the need to balance competing demands that are essential components to meaningful inquiry into complex scientific issues that involve broader social, economic, and political factors (Sadler & Zeidler, 2004).

Some of the domain formalisms in the Taiga unit are associated with testing the water samples that students gather as part of the second quest. The water samples are collected at different sites on the river (see Figure 3) and brought to a laboratory, where they are assigned values for the different indicators. Students have to analyze each sample's chemical indicators of quality for the various river fish present in the context, including dissolved oxygen levels, turbidity, phosphates, nitrates, and pH. Students also collect some information about acid rain that is meant as a red herring. While data from our previous study indicated little direct student interaction with domain formalisms, the narrative itself was quite compelling, and the few formalisms with which the students interacted supported rich conversations. In revising the curriculum for the present study, we worked to ensure that the activities and dialogues with virtual characters illuminated the associated formalisms. In this sense, this revision contains more embodied formalisms. In addition, we included more textbook-like resources (or embedded formalisms) that are accessible to the students through the environment but are initially introduced through the narrative as they become relevant to the students' thinking.

Data Collection and Assessments

We observed the class directly over all eleven 1-hour class periods across 2 weeks, compiling data from field notes, multiple video cameras directed at individual learning groups, interviews with students and the teacher, documents and artifacts, and retrospective recall analysis. Consistent with previous work, our data collection was targeted toward (a) documenting practices (e.g., uses of tools such as graphs or charts, problem solving, student inquiry) and resource use (e.g., tools used, formalisms appropriated); (b) capturing discussions among students and between students and teacher; (c) documenting the progress of student work; (d) following the same students, artifacts, actions, and procedures over time; and (e) supporting and refuting emerging hypotheses about how practices, resources, task constraints, task manifestations, and student understandings evolve over time (these methods are elaborated in more detail in the report of the first cycle in Barab et al., 2007). The focal topics were redefined during fieldwork, group meetings, and increasingly focused data collection and analyses. In constructing and triangulating interpretations (Guba & Lincoln, 1983), we looked across these various sources of data.

Similar to the first design cycle, we employed a "multilevel" assessment strategy to gauge the intervention's effectiveness (Hickey, Zuiker, Taasoobshirazi, Schafer, & Michael, 2006). In this strategy, targeted core intervention goals, state-learning standards, and core science concepts are used to "align" activity across three levels of knowledge assessment. The core intervention goals included engaging students in inquiry-based reasoning, supporting student understanding of science content knowledge, and developing an appreciation for socioscientific inquiry. The four targeted state content standards were as follows: (a) evaluate the validity of claims based on the amount and quality of evidence cited; (b) explain how the solution to one problem, such as the use of pesticides in agriculture or the use of dumps for waste disposal, may create other problems; (c) recognize and describe that systems contain objects as well as processes that interact with each other; and (d) demonstrate how geometric figures, number sequences, graphs, diagrams, sketches, number lines, maps, and stories can be used to represent objects, events, and processes in the real world, although such representation can never be exact in every detail. In addition to the broad standards, we wanted students to understand key scientific concepts, including hypothesis generation, chemical indicators, eutrophication, erosion, point-source pollution, water quality indicators, and watershed dynamics.

While understanding the process of, for example, eutrophication was necessary in order to submit quality responses to the various quests, we tried to avoid overwhelming students with details that were not critical to the reasoning needed to succeed in the curriculum. For example, an understanding of pH at a chemical level was not necessary for our use of pH as a relative water quality indicator. In our context, pH was only relevant in relation to other indicators such as nitrates and phosphates as a way of understanding the quality of the water at a particular location. Students only needed to understand which pH values were problematic and what process might cause pH values to be significantly different from a neutral value of 7. This information was provided through discussions of watershed run-off from agricultural and pastoral farm operations or was available through in-game computer links. The narrative aimed to make the students' understanding of pH more meaningful while simultaneously exploiting that understanding to help them more meaningfully explain the impact of a particular group's actions on the watershed.

These goals, standards, and concepts were used to structure assessments of knowledge at each of three increasingly "distal" levels. Each level is positioned along a continuum defined by increasing generality and/or abstraction from the enactment of specific curricular activities (cf. Snow, 1974). The *close*-level "activity-oriented" outcomes were the evidence of scientific reasoning in the artifacts that students produced and submitted in each of the instructional tasks (essentially the text of student Quest submissions). This level primarily looked at students' use of embodied and embedded formalisms in their work. The *proximal*-level "curriculum-oriented" outcomes consisted of gains on an assessment consisting of "cherry-picked," released test items that used a water quality context similar to that used in the curriculum. Finally, the *distal*-level "standards-oriented" outcomes consisted of gains on "far-transfer" assessment consisting of standardized items drawn at random from larger pools of items that were aligned to the four targeted standards.

For this study, students completed eight proximal assessment items (two per standard) divided equally between multiple-choice and constructed response formats and twelve distal multiple-choice test items. While the proximal items targeted the conceptual resources aligned to the curriculum and the standards, the distal items targeted a broader sample of resources aligned to the standards only, with explicit disregard for the curriculum. For example, an item might address the above four standards in terms of a different context such as a tropical forest or in terms of a relatively abstract and decontextualized representation of erosion. Insofar as this broader sample or pool of items reduced or eliminated curricular bias, the distal measure provides data on a broader set of claims about learning and transfer, including claims that participating in the particular curriculum would impact performance on external achievement tests aligned to the targeted standards.

The distal measure, by design, assessed some concepts and many facts that the QA intervention did not target. In constructing the distal measure, we pooled 10 or more items for each of the four target standards then randomly selected only two items for inclusion. This randomization enables valid comparisons with other curricula, including earlier versions of our curriculum; it also constitutes a valid proxy for high-stakes tests, serving a broader research goal of evaluating whether curricular enactments support transfer to externally developed, high-stakes achievement tests (Hickey & Zuiker, 2003). Thus, the 12 distal-level items comprised a "far-transfer" measure of learning. This is a challenging one for a specific, short-term intervention to impact.

Last, at a "close" level, students answered extended-response questions as part of their exploration of the QA space. Each of the three quests detailed above required students to submit written statements that varied in length from a few sentences to multiple paragraphs. We used these submissions as evidence of students' enlistment of domain formalisms to navigate the complexities of the virtual socioscientific issue. We employed inductive strategies to interrogate these data with the intent of identifying emergent themes characteristic of socioscientific reasoning. In particular, we looked for evidence of how students attempted to balance economic and ecological concerns, considered scientific data and other information, appreciated the underdetermination of data in socioscientific contexts, and considered the complexity of the situation. We also endeavored to maintain sensitivity to patterns reflective of socioscientific reasoning that had not been identified a priori.

Data Analysis

Our analysis of the field notes, interviews, and video recordings targeted the joint goals of crafting a rich account of the experience and using our observations to evolve the curricular and theoretical frameworks. Given the volume of digital data, we did not transcribe all of the video and audio recordings, but instead relied primarily on our field notes and then purposively buttressed these with selected digital data. While we tried not to impose structure overly on the data, we were also interested in students' use of formalisms both in classroom discourse and submissions, and whether the task, other students, or the teacher initiated their engagement with formalisms. In particular, we aimed to consider the refinements from the initial development and implementation during first cycle design work in relation to this second cycle study, which was implemented under similar circumstances, especially with regard to how the curricular revisions initiated use of the formalisms in student practices.

We frequently debriefed after a class period, and periodically met at the university to relate particular happenings as they pertained to and advanced our evolving theoretical framework about formalisms and our strategies for enlisting them in the curriculum, both in terms of organizing the 3D space and supporting classroom discourse. Our analysis of the student performance on the close-level assessment and distal-level test followed standard methods. Student scores for the number of items correct on each measure were analyzed using one-sample t-tests.

CASE DESCRIPTION AND RESULTS: STUDY ONE

Qualitative Description and Outcomes

After reading and discussing a Park Ranger's solicitation to resolve the ecological problem, students explored the digital park and talked to 13 characters. These perceptual and narrative features immersed students in a virtual world that they consistently described with first-person accounts about where "I" went or what a character told "me." In interviews, the teacher suggested that students displayed an uncommon enthusiasm toward the curriculum. Moreover, she reported that many students discussed the scenario during lunch and recess periods. In this sense, the curriculum immersed students in the digital experience and engrossed them not only during science class but, at times, beyond it as well.

At the same time, it was also necessary for the teacher to coordinate the curriculum in key respects. She facilitated student–computer interactions, addressing individual questions and comments and interleaving the invariably computer-centered activities with brief whole-class discussions beforehand and afterward. She also inserted classroom activities in anticipation of inefficiency or confusion at three different times. In preparation for the first of these, she organized students into small groups to complete the first quest, which asked students to summarize each user group's perspective. Each student group collected information about a subset of characters, then all groups shared notes during a period-long exchange of information. This strategy created multiple subtasks that streamlined the activity, but also shifted some first-hand virtual experiences to second-hand summaries.

This sequence, from the ranger's opening letter to the student overviews, lasted five class periods and oriented students to the complexities of the declining fish population.

As part of Quest Two, students revisited characters and conducted scientific analyses on water samples. Students publicly interrogated character comments this time, identifying specific remarks as either fact or opinion. These encounters, coupled with those in Quest One, further resolved the fish problem into details about the practices of the logging company, the fishing outfit, and the indigenous community and underscored the value of scientific study. Before students generated and analyzed data, however, the teacher inserted the second classroom activity in order to discuss the to-be-featured indicators of water quality (e.g., dissolved oxygen, turbidity). She verbalized a strategy for identifying unhealthy measures of some indicators and for interpreting their meanings, then students returned to the virtual space to generate data for three sites along the river. After three class periods of continued analysis, most students had submitted assertions about the causes of the problem based primarily on the scientific data but also on the facts and opinions gathered and discussed throughout the 10 periods of the curricular experiences.

Last, based on information about the user groups and the scientific analyses of water quality, students developed solutions to the problem. At the start of this final quest, the teacher interleaved a third classroom activity in which she reviewed the problem and assisted students in developing aspects of their solutions. Pairs then discussed and wrote across three more class periods in order to propose and submit balanced solutions to the fish problem at the end of the eighth day.

Quantitative Outcomes

The curriculum-oriented proximal-level assessment included eight multiple-choice items, each worth one point. The class' mean score increased from 5.2 on the pretest to 6.6 on the posttest. Given a pooled standard deviation of 1.4 across the pre–post proximal measure, this gain represented an increase of approximately one standard deviation. A one-sample t-test indicated that this gain was very unlikely to have occurred by chance, given the overall variance in gains [$t(19) = 15.77$, $p < .01$]. This provides evidence that the students learned about the concepts detailed in the intervention in a way that transferred to standardized items targeting that same topic but in a more general context.

The standards-oriented distal-level assessment consisted of 12 multiple-choice items aligned to the four targeted standards without regard for curricular resonance. Students averaged 8.15 items correct in pretest and 9.4 items correct in posttest out of a possible total of 12. This gain of 1.25 points occurred in light of a pooled pre–post standard deviation of 1.6, representing an increase of approximately 0.8 *SD*. A one-sample t-test showed that this gain was unlikely to have occurred by chance [$t(19) = 18.91$, $p < .01$]. This provides evidence that our continued refinements of QA had left students with ways of knowing that would transfer to externally developed, high-stakes achievement tests. Impacting scores on an assessment that is twice removed (once in context and once in representation of the content) from the curriculum is an ambitious and seldom attained goal for specific curricular interventions such as this. Acknowledging these quantitative gains, below we report our more detailed analysis of the close-level data, leading to another round of curricular revision.

Analysis for Curricular Revision

In this section, we briefly report both the collective impressions developed as the implementation progressed and the results of the informal reviews and analyses conducted afterwards, which together informed our refinements for the curricular design in Study 2.

From the outset, many students suspected that the logging company alone was at fault and developed corresponding degrees of bias that overly simplified the complexity of the scenario. The first quest required students to describe and summarize the narrative, ensuring that students understood the narrative dilemma. Consequently, students synthesized the narrative from others' accounts, which had the effect of simplifying the richness of the scenario further. As reflected in their Quest One submissions, students converged on very similar summaries and a unanimous speculation that the different uses of the watershed all contributed to one single problem: "clogged" fish gills. Therefore, while students framed each group of park users' relation to the problem in ways consistent with the narrative and attempted to detail its underlying causes, our analyses suggested a need to redesign the narrative and tasks in order to preserve the complexity of the problem.

With the introduction of water quality indicators in the second quest, student submissions demonstrated noteworthy changes in light of the scientific evidence. They abandoned the idea of clogged gills in exchange for indirect effects related to the water. In comparison with collected submissions from the previous cycle (Barab et al., 2007), water quality indicators and, in two cases, the notions of eutrophication and erosion played greater roles in student explanations. However, the students did not reexamine the problem in light of the formalisms underlying the particular indicator shifts; that is, they would report problematic indicators but would usually not describe the underlying processes that might have produced those indicators. Moreover, individual student submissions varied greatly in their interpretations of the indicator profiles, and few organized their interpretations in terms of relevant details of the park user groups, instead just listing abstracted values. Their final submissions also reflected an ongoing struggle to enlist the formalisms deeply and consistently, and their solutions addressed impacts in isolation, suggesting minimal appreciation for the interdependence of the multiple systems present in the scenario. Thus, we sought to redesign the virtual environment in order to better connect formalisms to the narrative context without diminishing the immersive experience.

Student enthusiasm, conversations, and mention of environmental particulars indicated deep narrative engagement, even if it adopted a fairly common viewpoint on the narrative—the loggers were at fault. Of greater concern, however, was that we witnessed few examples of the underlying formalisms being discussed explicitly or even implicitly. Instead, we observed three class periods in which the teacher spent over half of the class time leading discussions or providing lectures on the underlying formalisms. While the teacher did an admirable job connecting these conversations and lectures to the Taiga problem, there was little indication in these sessions that the students were also enlisting the domain formalisms to engage in meaningful inquiry. Two of the researchers probed students by informally questioning their understandings; both reported that the students were not able to participate in even modestly sophisticated discussions about the underlying domain formalisms. This observation was echoed in student work that failed to invoke scientific formalisms in explaining the cause of the problem. It seemed that the formalisms were not being enlisted as a tool for interrogating and explaining the narrative. Given that our next implementation involved a less academically advanced class, we became concerned about how to increase engagement with the underlying formalisms.

STUDY TWO

Overview and Context

Following the first implementation in this cycle, we used the data and our evolving theoretical understanding to modify the curriculum again. Of particular interest was how to embed more of the target formalisms within the curricular experience, as opposed to having them be introduced by just-in-time lectures from the teacher. We also wished to implement the curriculum in a nongifted classroom, to see whether the Taiga intervention could benefit ordinary students' learning about water quality. Similar to the first study and consistent with its design-based research methodology, we collected and analyzed data to understand the impact of the curriculum and to advance our theoretical framework around formalisms. A particular challenge in our redesign was determining the best way to introduce formalisms such that they were embodied or embedded in the context.

The second study took place in a fourth-grade inclusion class located in the same school as Study One. Coincidently, there were again 23 students, 15 of whom were girls. The teacher was in her first year and had been using Quest Atlantis with her students for approximately 3 months. She had seven students labeled as special needs, five of whom were non-White, and was considered to have the lowest functioning students at that grade level in the school. She was also implementing the water quality unit, although a number of changes had been made to it based on the results from Study One reported above. We communicated to the teacher that our role was to capture video data and respond to any technical issues, but that we were not going to offer lesson advice or be a resource for the students.

Revised Curriculum

A key focus in the curricular revisions was maintaining the high level of narrative embodiment of the previous version while facilitating closer attunement to the underlying formalisms. Bruner (2002, p. 11) suggested that good stories are "subversive in spirit, not pedagogical." Our challenge was how to do both; that is, capture the imagination of the student at the same time using the context more successfully to advance particular curricular aims. We were not simply using narrative as traditionally conceived; rather, we were using a computer-gaming engine that allowed for the creation of an interactive narrative. This broader frame of work had implications for how we would redesign the curriculum to increase meaningful participation and transferable understandings. In particular, we added more interactive rule sets, more embedded pedagogical scaffolds, more narrative storyline, more collaborative participation structures, and, consistent with our multilevel assessment, we introduced multiple levels of interaction with the formalisms.

The first task was to increase the narrative's complexity to implicate multiple groups of Taiga park users. For example, the indigenous people in the northwest corner of the park were more directly critiqued for the amount of fertilizers they were using on their fields, which were directly adjacent to the river. In addition, some anglers were more directly implicated for holding their fishing competition during the spawning season. In addition to modifying the main storyline, we added subplots that provided students with multiple representations of the underlying formalisms (discussed below) that might emerge based on student choices and accomplishments. Salen and Zimmerman (2004) outline the power of interactive rule sets as used in games to establish play, engagement, and a sense of agency in which the game rules structure participation and give meaning to player actions. The interactive rule sets were also useful in establishing pedagogical agents. For example, instead of simply receiving the data results when they brought their collected water samples to the laboratory, the students now had to work with the lab technician to conduct various analyses with his support. On the basis of the quality of their interactions, they would receive different forms of acknowledgment and even different information.

Our overall framing of the experience was more consistent with how video games frame tasks, presenting the different curricular activities as a sequence of well-bounded "missions," each with different reward structures (Gee, 2003). We also added other game-like interactions through which students would uncover "mystery" files and complete tasks that would "unlock" new functionalities. These included seemingly trivial interactions in which students collect game rewards as well as deeper interactions through which they gain status while also gaining insight into particular formalisms. As one illustration, students find pieces of paper; the blurry images suggest that they are too wet to read but that they may be dry later. When students return later, the dry papers reveal diagrams depicting problematic processes related to land use along a river, including erosion and eutrophication. In another instance, students must obtain a credential from the lab technician before they can use the lab equipment to analyze their water samples. The technician will only certify those who demonstrate that they understand how to interpret the data the machine outputs. We also designed more collaborative activities, in which groups interrogate a particular finding, data set, or claim and then collectively pose a solution.

Beyond evolving the narrative, interactive rule sets, and pedagogical agents, we also wanted to facilitate multiple types of interactions with the underlying formalisms. The idea was to provide multiple representations of the core formalisms, such that students would experience them in different contexts with different relations to embodiment. These different levels represent efforts to develop increasingly rigorous scaffolds for understanding formalisms and to provide students opportunities for thinking deeply about the relations among formalisms and the variable contexts in which they are embedded. As such, coordinating representations and contexts in and across missions became a focal point for design revisions and theory development. For example, once students provide a solution to the main storyline they collaborate to gain access to a locked cave in which they provide a shared recommendation to a distraught computer character on a problem that has much overlap with the Taiga fish problem but in a different context. These changes, we hoped, would maintain the concrete examples of the scenario yet rearrange the immersive experience in ways that would begin to reveal the "polycontextualization" of formalisms and their "functional interdependence" across contexts (Zuiker, Barab, & Hickey, 2007).

Toward this end, we coordinated context-formalism connections through a design process intended to bring into alignment the context and the necessary formalisms. This process involved building a table of activities in which we placed all the science concepts and the core standards in rows and had columns for embodied, embedded, and abstracted. We then went through the space and documented all the instances in which the target science standards and core concepts were treated as embodied, embedded, or abstracted. For example, collecting data about water quality indicators and working with the technician were considered embodied instances; reading documents on the computer or in other manuscripts found in the space were considered embedded; and using one's understanding of indicators to help a game character make sense of a similar contexts was considered abstracted. At times, establishing these connections meant refining a task such that it more clearly aligned with the standard or concept, and at times this required the development and opportunistic placement of resources. For example, realizing that one standard was underrepresented led us to redesign an activity with more explicit resources targeting that standard. Also, we distinguished between times when the formalism would be enlisted by students in the context of the core mission and when it was presented as part of a secondary mission. In some secondary missions, as in the cave activity briefly mentioned above, this meant providing brief activities in which students had to enlist the formalism in relation to a different problem in an altogether new context. These new problems maintained continuity with the narrative and the student's role as field researcher, but required students to leverage the formalisms differently.

An important goal of the activity was to have students generalize the underlying conceptual meaning of the formalism such that they focused on its cross-referential meaning. We added optional, secondary activities that presupposed the context in which a formalism was embedded (e.g., sketches or diagrams of erosion). This allowed students to interact with more abstract representations of the underlying formalisms, but in the context of a narrative that situated the components of the formal diagram; for example, children would discuss how the diagram represents algae blooms caused by nutrient excess from the land practices of the indigenous people in the Taiga storyline. In this way, students could leverage their experiences with Taiga to recognize abstract formalisms, eventually applying these to related contexts. This process, known as *concrete fading*, has become an important design principle in our work (Goldstone & Son, 2005; McNeill, Lizotte, Krajcik, & Marx, 2006). In summary, and consistent with the levels of assessment being employed, we included activities that provided experiences in applying formalisms that were part of the core Taiga context (close and activity oriented), other activities that presupposed the Taiga context and invited students to apply embedded core formalisms in an aspect of Taiga not taken up in the core narrative (proximal and curriculum oriented), and still other activities that entailed the Taiga context and invited students to apply those formalisms in new abbreviated contexts (distal and standards oriented).

Data Collection/Analyses

Data were collected over a 1-month period through direct observation and field notes, and multiple video cameras were again used to record student groups. However, this time the focus was more explicitly on applications of the formalisms around each of the three activity contexts. We traced the application of formalisms across the curriculum, focusing on each activity in terms of the relationships between context and formalisms in order to capture when formalisms were discussed or applied, and under what conditions this occurred.

Specifically, we went through the data and identified examples of the manner in which a formalism was engaged. Given that there were over 6000 minutes of recorded data, rather than sift through all interactions we used the field notes to identify particular times for particular groups in which an illuminative event was noted. The episodes presented in the next section were chosen because they illustrate the target phenomenon in a way that is representative of the local implementation, and because they were deemed generally useful in terms of issues that would have (experience distant) relevance to other researchers (Geertz, 1983). In addition to the transcribed episodes, we also examined other forms of data such as student work submitted, relevant field notes, and work from other students related to the episode. This allowed us to describe the particular episode and the design features that contributed to its emergence more meaningfully.

In addition, two new proximal-level short-answer items were added to the assessment to consider scientific inquiry involving broader social, political, and economic factors more directly. A brief scenario was used to characterize a complex problem, and the items asked students to offer solutions and justifications for those solutions. These items presupposed the Taiga context and invited students to apply targeted formalisms while balancing economic and ecological concerns and appreciating the underdetermination of scientific data in complex human contexts. On a related note, we believed that students in Study One were synthesizing commonalities and simplifying interrelations when recognizing ambiguity and appreciating complexity were necessary. Therefore, we changed some activity goals. For example, whereas the first activity required students to "describe how everyone uses the Taiga" in Study One, students in Study Two had to "write an educated guess (hypothesis about the cause of the fish problem and describe why you think your guess is correct," focusing on analysis exclusively. Students still completed descriptive tasks, but these were translated into interactive debriefings, frequently with questions from the pedagogical agents—NPCs.

Qualitative Description

As with Study One, the teacher typically began periods with short whole-class briefings and ended them with somewhat longer debriefings in which several students shared their strategies and reported their findings for that period. However, each period primarily consisted of individual student interactions with a computer and conversations with peers in the classroom. After six periods, students wrote and submitted their hypotheses, which had been a common topic in the debriefings. Students then worked with empirical evidence to test their hypotheses, including two periods centered on earning a lab credential. The teacher interleaved the virtual experience with two period-long classroom lessons on indicators. In the first lesson, she assembled materials to illustrate indicators; for example, she used litmus paper to demonstrate different pH values. In the second lesson, she generated data for a pretend Taiga called *Paiga* and asked students to interpret the data and their relationship to the broader fish problem. It was in the second week that students began to link the water quality indicators to user group practices along the river, connecting nitrate levels, for example, to fertilizer-intensive farming practices or linking turbidity to logging near riverbanks. During the final 3 days of the 3-week curriculum, students visited the laboratory twice a day in order to finish writing the second activity and to collaborate in writing the third.

Quantitative Analysis

For the proximal items, we combined the eight standardized assessment items and the two short-answer items. To reiterate, the proximal-level assessment required students to employ invariant properties of the conceptual resources supported by the QA intervention, but the wordings and graphic representations that invoked these resources varied by degrees from their representations in the learning environment. Whereas the multiple-choice items were scored as right or wrong, the short-answer responses were scored using a conventional scoring rubric. Two raters attained a .92 correlation, indicating high reliability, and reconciled scores were used. A t-test comparison using the combined scores indicated that gains were unlikely to have occurred by chance [$t(17) = 10.05$, $p < .001$], with combined scores indicating a shift representing approximately two–three items. Again, while the multiple-choice scores were proximal and curriculum oriented, they were multiple-choice items culled from state and national standardized tests.

The distal-level assessment included 12 multiple-choice items aligned to the four external standards. The class's mean score increased from 5.2 on the pretest to 7.3 on the posttest; given a pooled standard deviation of 2.8, this gain of 1.8 represents an increase of approximately 0.6 *SD*, a gain that was unlikely to have occurred by chance [$t(17) = 9.41$, $p < .001$]. This provides strong evidence that QA intervention supports transfer to externally developed, high-stakes achievement tests. Again, it should be noted that impacting scores on randomly selected standardized test items that are twice removed (once in context and once in content representation) from the curriculum is an ambitious and seldom attained goal for specific curricular interventions.

COMPARISON OF STUDY ONE AND STUDY TWO

In this section, we reflect on the two case studies in response to the initial research questions, drawing attention to the contributions of this work beyond those of other project-based learning contexts featured in the science education literature. For each question, we discuss the studies in terms of our evolving design work and theoretical appreciation for the reciprocal relations between content and context. In so doing, we show how narratives can ground formalisms with meaning and how formalisms can imbue narratives with meaning (Sfard & McClain, 2002). We then discuss how we evolved the curriculum with the goal of expanding the reach of student understanding such that they engaged the invariant meanings of the scientific formalisms such that they could be extended to other contexts.

Using Narratives to Ground Formalisms

RQ1: What are the main challenges in designing a game-based learning environment that situates and legitimizes (*narratizes*) scientific formalisms?

A core focus of our work was to establish a rich context through which scientific formalisms are embodied, embedded, and eventually abstracted. Our initial challenge was to develop a compelling narrative that situationally embodies the curricular experience. This involved establishing a narrative with some sort of dramatic arc, in that there is a plot, characters, setting, and mystery or problem to investigate (Aristotle, 330 B.C./1992). However, instead of a narrative about someone else's experience, we used gaming technologies to build a narrative in which the player was protagonist and in which player actions impacted the unfolding of the narrative (Stern, 1998).

In Taiga, this involved a story about a park that was having ecological problems, in that the fish in the river were dying; the student took on the role of ecological scientist. This was a socioscientific narrative, in that understanding and solving the problem required the student to enlist scientific practices and apply formalisms. The formalisms were situated within a storyline that imbued them with particular meanings. For example, it is one thing to read a dictionary definition of eutrophication or to interpret a diagram illustrating the interacting components; it is quite another to learn their formal meanings in order to explain a specific problem such that the symbols in the diagram represent "people," rather than hypotheticals. In this way, students did not simply come to understand the formal relations among some decontextualized elements, but rather student understandings of the formalisms were embodied in terms of the conceptual work they did on the narrative.

This idea of narrative embodiment, as one aspect of situative embodiment, is different from perceptual embodiment because it emphasizes semantic or narrative rather than only sensory or perceptual grounding. However, it does similar work in terms of grounding domain formalisms. For example, in his interview with students, the leader of the Taiga indigenous community, an NPC named Norbe, lobbies a complaint that works to arrange situative embodiment around erosion. "There is much more sediment coming into the stream since the logging began. That must be causing the problems downstream." In Study One, students synthesized multiple statements such as this in order to profile how each group might contribute to the fish problem. One student enlisted the comments of Hildalgo, a logger NPC, in summing up the role of the logging company: "The loggers are being blamed because some people think that some of their soil is getting in the river. Hidalgo does admit that he knows that some of the loggers' soil does get in the river, but not much." It is our belief that situationally embodied science activities are at least if not more important than perceptual grounding for supporting learning; that is, narratively engaging the situations of use are as important for learning science as are having students perceptually see the concept. Using the analogy of learning mathematics, while Cuisenaire rods are useful, having a situation in which mathematics has practical application is also necessary if we want mathematics to become more than a "school" content.

It was clear in our analysis of the data that students were situationally embodied in the storyline, talking about the characters and the different perspectives. As noted in our analysis of Study One, however, student summaries and their formulations of scientific analyses and problem solutions infrequently eclipsed implicit appreciations of erosion, amounting to the seemingly inescapable situatedness (lack of transfer) that concerned Bereiter (1998). Students supplied rich descriptive accounts of the park narrative, but they were not enlisting the formalisms as reasons to justify arguments. It was as if their engagement with the underlying concepts was at an implicit level. As such, the quest submissions were contextually rich and there were even some proximal-level gains, although not significant distal-level ones. In response, we increased the number of opportunities for students to enlist embodied explicit formalisms (e.g., by having the NPCs directly refer to the process of erosion) and also embedded explicit resources (e.g., computer-linked resources that were explicit, formal descriptions of the underlying scientific concepts as one might find in a textbook) in Study Two.

Our design commitment dictated that these explicit representations be integrated as part of a user-engaged trajectory so they would be accessed in response to a particular intention for which they became resources. For example, one of the NPCs suggests to the student that eutrophication (embodied explicit) by the Mulu territory might be part of the cause of the fish decline. The student is then encouraged to go to the computer in the technician's laboratory and read through the linked documents (embedded explicit) so that the student can explain the problem to Ranger Bartle. In addition, students are asked to interpret particular data; that is, instead of simply describing what they find (descriptive stance), they are asked to analyze and interpret particular data sets showing how the data supported or refuted their hypothesis (critical stance). A major challenge in using narrative to imbue formalisms with meaning revolves around critical participation with the narrative. Where students in Study One collected and summarized aspects of the narrative, Study Two positioned the narrative in relation to an overarching formalism– hypothesis generation. Our intention was to shift student engagement from synthesizing a multidimensional scenario to developing and refining a position on the scenario as it unfolded.

In Study One, the initial submissions were homogeneous; all defined the same points, and no critical work was done beyond describing the relevant particulars. The second submissions again simply reviewed the data, doing little critical work to define the underlying cause. The final submissions tended toward overly simplistic solutions that did not take full account of the rich data and complex socioscientific complexities mentioned in the initial submissions. In contrast with Study One, Study Two initial submissions featured a range of direct and indirect problems related to Taiga user group practices rather than a single direct effect (i.e., clogged gills). This was in part because the shifting of the tasks from descriptive to analytic required moving beyond surface details to identify underlying causes. Later submissions, however, converged on similar interpretations organized around the targeted formalisms. In contrast to the minimal turbidity analyses by students in the gifted class in Study One, one girl in Study Two provided an explanation of turbidity in terms of her initial hypothesis:

> The indicators *do change* because Sites C and B's Turbidity were both bad. The changes do not show that there is dirt in the fish's gills, that was also part of my old hypothesis.

She continues her formulation with details about problems suggested by other indicators, then returns to the bad turbidity measure at Site B mentioned in her comment above:

> There is also a problem with Site B. The problem is that the Loggers are cutting down trees that are too close to the river and the trees might be holding the dirt and the soil from getting into the river. The dirt and the soil that gets into the side of the river will cause erosion on the side of where it is coming from.

These thoughts incorporate scientific data about turbidity and a targeted formalism (i.e., erosion) to connect the activities of groups around the river to the fish problem. It is consistent with and more explicit than most Study One submissions, and is also representative of the class because most students directly connected values of turbidity and the concept of erosion.

Another student similarly integrates his analysis of water quality indicators with evolving hypotheses about the fish problem:

> The data can support my hypothesis and I am pretty sure that it is correct but I now have a new one. I am also thinking that the loggers are part of the problem. I think that the trees in the water are harming the turbidity. The soil is also harming turbidity. That is not good because it can start erosion and it will kill the fish. If both the Mulu and the Loggers harm the fish from the top of Taiga, it flows downstream and kills the fish downstream. Then, the fishing tournaments are canceled because they see less fish.

As with the first student from Study Two, this boy links the logging company to two formalisms—turbidity and erosion. Most students generated similarly detailed and focused analyses in relation to both their initial hypothesis and the water quality indicators. Many also connected the idea of erosion explicitly to turbidity and described another key idea, eutrophication, in relation to issues with other indicators. We argue, however, that students in Study One for the most part did not achieve these deeper insights into the narrative, and we argue that productive situative embodiment requires the reciprocity we address in the next section; that is, using one's evolving understanding of the formalisms to reinterpret the narrative. In this way, just as the narrative "storyizes" the formalism, the formalism reciprocally can *scientize* the narrative (Abrahamson, 2004).

Using Formalisms to Interrogate Narrative

RQ2: As learners investigate the game-based learning environment, what are the challenges in supporting their enlistment of scientific formalisms to meaningfully interrogate (*scientize*) the context?

Fostering reciprocity between formalisms and the situating storyline requires not only using narrative to advance understanding of formalisms but also turning formalisms back onto the narrative. In this way, the formalism has the potential to establish a gaze (Focault, 1975), that is, a way of seeing a particular narrative through domain-colored glasses. Just as an architect entering a building immediately perceives structural aspects that may be unnoticed by others, an ecological scientist observing a watershed will perceive certain features and potential interactions. An appreciation of domain formalisms can structure one's understanding of a context in very different ways compared to someone who does not have such an appreciation. As we observed in Study One, our own narrative led nearly all students to speculate initially that farming and logging were directly clogging fish gills, regardless of their understanding of a particular formalism. Furthermore, many later summed up the problem by comparing the water quality measures they generated without drawing connections to the underlying causes or their implications for the problem and the Taiga community. Therefore, we designed for the enlistment of formalisms in a critical sense in order to challenge the ambiguity of the prevailing narrative and to reify it in terms of formalisms.

In Study Two, we leveraged gaming strategies to integrate embedded formalisms into the narrative in several ways. We added more interactive rule sets, more embedded pedagogical supports, and evolving roles. Each of these roles was carefully paired with appropriate formalisms. Much of the information was the same for each study; however, we engineered connections to the narrative quite differently. In addition, we took advantage of the playful, interactive context to have nonplayer characters introduce explicit formalisms. In the first study, we used explicit formalisms minimally and, when we did employ them, their use was more of a telling than integrated into the trajectory of participation. In the second study, we tailored the relationships among the formalisms by layering them into key aspects of the scenario and with quite explicit connections. It was our hope that their embedding would work to recast the narrative in terms of an underlying structure that they revealed. A noteworthy example relates to the introduction of water quality indicators.

In both studies, once students had developed an appreciation for what people in Taiga park said about the problem, they learned about indicator levels. This required that students collect water samples from different areas in the virtual space and bring them to the laboratory for analysis. In order to analyze samples and generate data, however, students in Study Two had to earn an authorization card by working with the resident technician—NPC. The technician served as a pedagogical agent who asked students to help him conduct various analyses. In doing this, the students went through a series of activities in which the technician first modeled the process, then he coached them on how to interpret the data, and finally he faded support such that the students conducted their own analysis.

We have already argued that the more analytical goals in Study Two improved the depth and focus of student interpretations. We argue further that tailoring the embedding of formalisms also contributed to these improvements. In the interactions between the technician and the students, for example, the technician used the authentic language of the formalisms. Thus, for example, instead of talking about cloudy water, he discussed turbidity (embodied explicit). As mentioned above, he (and sometimes other game characters) also suggested that students go read about potentially relevant concepts on the in-game computer. Students would then read "textbook" descriptions of concepts such as eutrophication, with the goal of building an argument about why the fish were dying. One special needs student who was literally failing his other class assignments formulated a rich interpretation about the cause that uses the technical language:

> My hypothesis is cows are using the bathroom by the river and it is being swept into the river. This may be causing the fish to die because the Nitrates and Phosphates are high. Nitrates cause overgrowth of aquatic plants, which takes away oxygen from the water which makes the fish die.

This student connects dialogue about cow manure in rainwater runoff to high levels of nitrates and phosphates in one water sample, and then partially describes a process of eutrophication. The excerpt reflects an evolving, deeper understanding of his initial hypothesis and incorporates two of the embedded formalisms to confirm and advance his inquiry into the problem.

A key moment along the way to this formulation illustrates the value of the scaffolding incorporated into the second study. In the following excerpt, Tom, the student whose submission we just presented, was observed developing that submission while completing analyses with the technician and talking with another student, Bob.

> Tom: Nitrates . . . nitrates! . . . nitrates . . . nitrates. Oh, this has to be from the Mulu. Result C—nitrates is bad.
>
> Bob: It doesn't have to be from the Mulu.
>
> Tom: Uh huh. It says its caused by manure right here. See look. "These chemicals can come from run-off from farm fields and manure." [read from a webpage linked to the technician] Yes! Tom's hypothesis is correct. [pause] Oh, cool. I've got my indicator definitions. [opens a resource embedded in the technician sequence] "Nitrates are very important for plant growth. Nitrate values less than 0.3 are excellent and nitrate values greater than 2.0 are poor. Too much can cause so much plant growth the stream becomes polluted with decay. Sources of nitrates include runoff from farm fields and from manure." Oh wait, now it says phosphates "include soil erosion, manure, and farm fields." So phosphates and nitrates.

Tom refutes a peer's challenge before connecting phosphates to manure, which he incorporates into his second quest submission. The game-like interaction with the technician organized the brief interaction between the two boys and also advanced Tom's understanding of the fish problem. It is important to note that while students did have access to 'textbook' descriptions of what chemical indicators mean and relevant water quality concepts, in the second study these were not available until other tasks had been accomplished, such that they became just-in-time information relevant to the immediate goals in which the information had value.

Extending the Reach of the Content

RQ3: As learners are challenged to recognize and apply scientific formalisms in a myriad of contexts, how can educators best support generalization from specific, contextually bound experiences?

Given the modest distal learning gains in Study One, the final question we explored in these studies was how to leverage the variance–invariance relationships illuminated through situative embodiment with the Taiga scenario to support productive transitions into other contexts. Much like the process of reifying a rich context in terms of formalisms, we also aimed to concretize the process of reifying embodied and embedded formalisms across contexts. In this sense, we wanted to both support and understand student learning by further engaging context-formalism reciprocity across contexts. By extending the participation trajectory beyond the immediate scenario, we aimed to support a process of abstraction through "liminal" activities that displaced students "betwixt and between" their role in Taiga and prospective role(s) beyond (Zuiker et al., 2007).

Specifically, we included two new shorter missions that ran parallel to the Taiga scenario in Study Two. The problems that students solved in these missions were different from, but complementary to, the central Taiga narrative. These missions occurred in a distinct space in Taiga, but they were woven into the narrative by incorporating in the first of these missions a "rookie" NPC Quester who asks students for help with his own quests and, in the second, a "veteran" Atlantian council member who asks for support after students have completed the Taiga mission. Equally complementary were the alternative contexts in which the same formalisms applied (e.g., polluted drinking water). These two missions were designed to imbue participation (i.e., the students as field investigators) as both competent and increasingly central to the broader Atlantian narrative. These design strategies of leveraging parallel episodes constitute an effort to foster "liminal" activities that embody the formalisms of the immediate scenario in a complementary context to support enlistment of the reciprocity between the formalism and the Taiga scenario for engaging with different contexts (Zuiker, Hickey, Kwon, & Barab, 2005).

Both secondary missions used increasingly abstracted representations of the formalisms (essentially an embedded multiple-choice item) to challenge students to examine their situated experience differently. In the sequence of excerpts below, Mary, Brenda, and Dionne first consider different information that might serve as evidence for choosing one or another water filter.

Mary: I think we should choose either B or C.
Brandy: I don't think B would kinda work because it's a commercial that's telling you so they're trying to sell something so they don't really know that it's the best in town. They're trying to assume it's the best in town cuz we have to have another commercial and somebody has to try out one of them. People have to try out that one and if somebody comes out with another one than they have to try out that one.
Mary: I think its c because a store in one town sold filter from both company, and people who used both like HydroClean the best. So it's the people not the commercial
Brenda: yeah
Mary: because commercials can be like
Brenda: maybe Atlantis is democratic.

They consider the information in terms of facts and opinions about water filters, dismiss commercials as biased, and value consumer purchasing as evidence. Equally important, they enlist the filter problem to speculate further about the broader context of the Quest Atlantis narrative. Moreover, Mary resituates the scenario into a real-world context in order to clarify Dione's confusion.

Dione: What does it mean?
Brandy: a store in town
Mary: let's say, for example Marsh [a regional grocery store] sold water filters from Hydroclean and Clear Water, but let's say your mom and dad used both but they liked better HyrdoClean filters better than Clear Water filters. Get it?
Dione: yeah.

In summary, these parallel missions were designed to extend context-formalism reciprocity to the broader scenario of Quest Atlantis and beyond. The excerpts above suggest a productive transition in which students not only critically engaged an alternative context but extended it themselves. At the same time, the Study Two teacher also facilitated the transitions by bridging contexts directly, introducing water quality data from a fictional *Paiga*. Through both designed and improvised scenarios, the use of liminal episodes that require students to abstract formalisms in terms of their underlying invariant structures and apply them to different contexts proved to be an important strategy to support productive transitions into other contexts.

SUMMARY AND DISCUSSION

This program of research is an example of design-based research (Brown, 1992; Cobb, diSessa, Lehrer, & Schauble, 2003; Edelson, Gordon, & Pea, 1999) in which we made theoretical improvements in our understanding, in part based on empirical work, and used them to revise the curriculum and our evolving theory. Too often in school contexts, it is assumed that learners will appreciate the functional value of a formalism in isolation from the practices for which it is only one tool. This assumption is reflected in curricula that apportion little or no time for richly situating formalisms, let alone integrating them with broader practice (Roth, 1996). While simplistic examples might be mentioned, no true contextual grounding is established or enlisted. It is this lack of grounding that others have suggested is the cause of Whitehead's inert-knowledge problem (Nathan, 2005). When formalisms are presented without proper grounding in authentic contexts-of-use, they run the risk of becoming disembodied facts to be memorized without application (Whitehead, 1929). In contrast, when they are learned to address problematic situations within a particular context they become embedded tools that are more likely to have functional value from the perspective of the learner (Cognition and Technology Group at Vanderbilt, 1993).

From a curricular design perspective, teachers need to establish rich narrative contexts through which domain formalisms can be experienced. However, returning to our levels of practice, it is also necessary that these experiences move beyond simply supporting engagement within one particular context. In order to have transferable value, they must also support practices of the abstracted type. This implies that the task of curricular experience is to situate students within a rich context through which relevant formalisms become embedded and embodied initially and then abstracted across a range of other contexts. Relating context and content through embedding in a particular context is one of the necessary types of practices in our multilevel curricular ontology. Extending the ideas detailed in Hickey et al. (2006), in the second study we used representations that framed the core narrative context closely; other less contextually grounded representations framed it proximally; and still others with little explicit context framed it distally. Each of these frames balances content and context differently as we have done in the curriculum reported here, our pedagogical move is to establish a situation in which the learner is immersed first and, through it, engages a formalism as *embodied*, *embedded,* or *abstracted*.

Returning to our three research questions in light of our theoretical frame of situative embodiment, we can see emergent tensions across the two studies. Embedded resources in Study One tended not to be embodied in the curriculum, instead becoming relevant only through minilessons initiated by the teacher in relation to the context of use. These moments frequently involved explicit discussion about the formalisms, sometimes explicitly referencing the context of use and other times focusing more on understanding a formalism in terms of its implicit connection to a valued need that the Taiga context defined (e.g., when the teacher gave a just-in-time lecture on dissolved oxygen). In Study Two, we developed a richer appreciation for the design needed to embed formalisms and translated the core concepts into conceptual tools that were explicitly linked in the space such that they would become available for the activity.

It is our belief that one should begin any instructional episode with a level of embodiment. Too much explicit, even embodied explicit, content can become like a school assignment and runs the risk of the formalism being perceived as content to be memorized. The design tensions framework illustrated in Figure 4 illuminates the challenges in balancing the quality of context (noisy vs. tailored) and the quality of formalisms (explicit vs. implicit). Balancing the curricular experience across these four quadrants seems like a key challenge of instructional design and is an important tension to examine in future research. Having too much explicit formalism runs the risk of the experience being overly school-like, while too much focus context can be inefficient, especially given the current focus on facilitating students in accumulating standards. The focus of learning context reported here, rather than on the disembodied formalisms, comes to be on a particular context-of-use in which

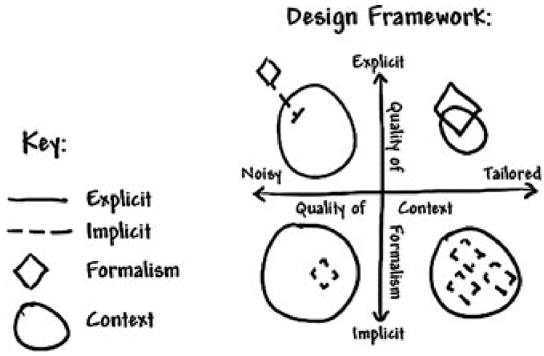

Figure 4. Design framework highlighting the tensions of designing an embodied curriculum (adapted from Barab & Roth, 2006).

the formalisms do important work (e.g., helping to illuminate underlying problems in the context). Beginning with this sort of embodiment, one can then situate various formalisms such that they have use value.

Figure 4, as a curricular design document, provides an instantiation of the tension one has to balance when designing a contextually rich learning environment. The goal is to evolve the curriculum in relation to the core embodiment. To the extent that a particular formalism is not connected to the core context-of-use, it runs the risk of being a disembodied fact to be memorized, with no contextual anchor from which a student can see its authentic application. It is the intentions that emerge from the context-of-use that serve to transform a particular formalism from a disembodied fact to an embedded or even embodied one. In building a particular context-of-use, one has to examine what intentions are likely to emerge from the core context and how satisfying these emergent intentions requires and validates a particular formalism as a useful tool. Finally, consistent with our multilevel curricular ontology, we also believe that some level of concrete fading is necessary to support deep transfer of the underlying concepts. It is for this reason that we begin with a level of embodiment and then work toward more framed representations of formalisms, a trajectory that is consistent with the close, proximal, and distal levels of assessment discussed by Hickey et al. (2006).

Design Principles for Embodying Formalisms

Our increased success across implementations demonstrates that gaming methods and technologies can be used in schools to focus on academic content in ways that are quite engaging to students. However, building compelling narratives that embody formalisms through authentic contexts-of-use is not enough if the goal is to enable students to enlist those same formalisms in other, different contexts. Design for polycontextual embedding requires cutting across multiple contexts *and* coordinating these traversals. The following paragraphs summarize four steps that we used in designing a context that established a sense of situative embodiment that was pedagogically useful for science education: establishing embodiment, illuminating content–context relations, fostering an analytical stance, and developing multiple representations of formalisms.

Establishing Embodiment. The idea that important disciplinary content and processes can be situated as tools and resources for addressing authentic problems has a rich history that can be traced back at least to the beginning of the century (see, e.g., the works of

Dewey, 1938/1963, and Whitehead, 1929). More generally, there is a rich body of literature suggesting that a useful pedagogical move is to situate formal concepts within rich contexts and narratives such that students appreciate their value in understanding the world (Bransford, Brown, & Cocking, 2002; Brown et al., 1989; Cognition and Technology Group at Vanderbilt, 1993; Greeno, 1993; Lave, 1988). However, new technologies and game-design methodologies afford virtual worlds that engage students in narratives with unfolding trajectories in which the learner becomes both player and author (Gee, 2003; Steinkuehler, 2006). These tools and methodologies provide educators with a new curricular tool for situating disciplinary content, one that affords agency and embodiment.

As outlined above, embodied participation involves a form of being within some physical, perceptual, or narrative space. Being embodied implies a type of literal or conceptual presence. Unlike other contexts in which students are doing an assignment required by the teacher, for the teacher, our students interacted with nonplayer characters in a fantastical environment that afforded them a legitimate and important role as ecological scientists and where their actions have consequentiality. In short, the context fostered a sense of embodiment that gave value and meaning to their actions.

Illuminating Content–Context Relations. As an initial strategy, is it central to establish a rich perceptual and/or narrative grounding. Designs must begin with well-crafted environments and nested affordances, then coordinate emergent relationships between the situation and relevant formalisms. As part of this grounding, our embodied curriculum invited students to assume the role of a field investigator in Atlantis as they engaged the virtual park and its waterway. However, while being in this role situated them within the park dynamics, it was also our commitment to facilitate critical reflexivity with their role so that students reflected on how their various actions affected park dynamics. In this way, our design was intended to support both productive and critical action. Balancing an analytical stance with a productive one is an important challenge for educators designing curriculum that supports situative embodiment.

In the terms of Gibson's (1986) ecological psychology, we aimed to support students in developing invariance–variance attunement. This attunement required students to have a deep appreciation of the way the contextual particulars (variance) and the underlying formalisms (invariance) relate, while also recognizing aspects of the formalism that have potential value to other contexts (Barab et al., 1999). In this curriculum, solutions involved learning, for example, about the process of eutrophication in order to make claims about the role of the indigenous people in contributing to the Taiga fish kill problem. The deliberate interweaving of context and content enabled us to arrange the likelihood of some relations and the likely preclusion of others, and in this way it began to illuminate concepts like erosion and learning standards about the value of scientific evidence to support claims. The challenge was to establish an analytical stance without undermining the students' sense of situative embodiment.

Fostering an Analytical Stance. To establish an analytical stance, students needed to move beyond summaries of information toward analyses of it. Participant roles incorporated a participative status in relation to the experience, one that instantiates a position or emerging disposition (cf. Gresalfi & Cobb, 2006). In addition to the cognitive work that such repositioning does, it also provides agency to one's experience with the existing narrative (Gee, 2003). For example, in Study One students simplified a complex narrative but did not meaningfully engage the complex analytical work necessary to expose the underlying deeper structures. To an extent, they were regurgitating someone else's narrative rather than creating their own analytical relations to the narrative. In contrast, in the second study, students needed to formulate an initial hypothesis derived from a synthesis of the characters' many perspectives. This led to divergent positions that students debated in groups and during whole-class debriefings. These debates appeared to address many misinterpretations and ultimately led to a more well-grounded interpretation of the problem.

This analytical stance was not a theoretical or even curricular assignment, but instead was a first move in taking on the role of field scientist and providing Ranger Bartle with necessary information. We enlisted gaming technologies and methodologies to coordinate what Barab and Roth (2006) referred to as *attunement trajectories*. Correct interpretations across a series of increasingly complex tasks granted the students higher status in the laboratory and entitled them to conduct their analyses. At the same time, these relatively sophisticated and consequential episodes added to an already intricate experience. Therefore, in the final curriculum used in Study Two, we introduced pedagogical agents, for example, the technician who urged students to read explicit descriptions about relevant processes and facts that could help them better understand what was happening in Taiga. Meanwhile, other characters provided general guidance based on data logs of what a particular student had done in order to resolve confusion about curricular goals. Alternatively, in the case of Ranger Bartle's young apprentice, we positioned students in the role of expert helper, forcing them to take on a position of expertise and power with respect to their understanding of the problem.

Developing Multiple Representations of Formalisms. The fourth way we made the narrative space more pedagogically useful was by embedding derivative narratives. Rather than enmeshing content in a single context, we aimed for *polycontextual intermeshment*. We did so using *liminal* episodes in which students experience the same content across multiple contexts. Although we situated most of the curricular activities in the park's fish problem, the activities and the meaning of the to-be-learned formalisms branched into multiple other narratives. We characterized these strands as "missions" and leveraged them to foster analytical stances that related to the scenario by enlisting different representations of the same context and framing different contexts with the same participation role (cf. Engle, 2006). One of these contexts used derivative narratives that abstracted the rich immediacies of the experience in terms of scientific formalisms. The other fostered connections with abbreviated contexts presented through the broader Quest Atlantis narrative, subtly extending the student's role from the immediate scenario into the wider backstory of mythical Atlantis.

Other examples of polycontextual intermeshment were having students serve as advisors and make recommendations on activities in which they had to determine best solutions when presented as multiple-choice items. The items closely mirrored those on high-stakes achievement tests that the students encountered on the pre–post measures and would subsequently encounter in their district science test, suggesting an interesting and potentially powerful way of ensuring enhanced achievement. Alternatively, students used the same underlying concepts they were learning in the core narrative but enlisted the formalisms to provide advice on different contexts. This provided multiple representations of the core formalisms, allowing students to experience them in different contexts with different levels of embodiment. For example, during the data interpretation phase of the investigation, students would go to an in-game computer terminal where they would read explicit descriptions of the relevant concepts, such as eutrophication, erosion, and chemical indicators. This helped students appreciate the formalism's context of use and increased the likelihood that students would appreciate that underlying domain content (e.g., dissolved oxygen, eutrophication, using evidence to support claims) in other contexts.

IMPLICATIONS

In our view, an effective curriculum for elementary students begins with enmeshment through narratively engaging activities that establish the need for embedded formalisms and embodied participation and that eventually provide opportunities for working across contexts. The key is effectively balancing the curriculum so that it supports the emergence of practices at multiple levels of embodiment, including applying the underlying formalisms to problems close to the narrative, to those that are proximal, and finally to those that are more distal. If the learner has little experience with the situations in which the content being taught has value, then the instructional context should be further elaborated such that it facilitates more student enmeshment and subsequent embodied and embedded practices. With reference to Figure 1, if the learner has a lot of experience and simply is trying to develop more specialized understanding of formalisms, then the emphasis might more usefully be placed on framed experiences, with the idea that any presentation of domain formalisms will become embodied by the learner. However, for learners new to a domain, we believe that a richer form of experience in which the learning is grounded in a particular context-of-use is necessary.

In this article, we overviewed the challenges and opportunities of developing and implementing a curriculum that engages students effectively in a situation from which they could develop transferable knowledge of domain formalisms. Over the course of a 2-year design process, we developed an increasing appreciation for the complexity of aiding students in enlisting formalisms that are situated in a rich narrative. We found game-design methodologies and technologies particularly useful in supporting a consequential form of embodiment in which participants engaged as protagonist in an unfolding story that required understanding and applying scientific formalisms. It is our belief that when formalisms are situated within rich narratives, the contextualization has the potential to change participants' interpretation of the formalism: from a fact to be memorized to a powerful tool that can be enlisted toward the actualization of meaningful ends (Brown et al., 1989). It is a challenging balancing act to maintain a compelling narrative while ensuring that students develop a sufficient appreciation of the underlying formalisms and their various contexts of use.

The use of gaming technologies and design methodologies allowed us to design a world in which students had a legitimate role in uncovering and solving an ecological mystery. We incorporated interactive rule sets that acknowledged student progress and rewarded productive scientific practices. This participation role therefore featured interactivity and also the relative status or prestige associated with the goals of a field investigator. Participation roles proved critical as we worked through our first design strategy, illuminating content–context relations. More generally, role-playing is a powerful design move for engaging students in meaningful interactions with designed environments for learning. We assert that curriculum designers spend too little time thinking about the roles that students adopt as they interact with the curriculum. It is through these roles, however, that the curricular targets have the potential to be something more than "content." The content can become a conceptual tool for acting on situations. While authentic immersion in real-world contexts might be more desirable in some cases, K-12 educators do not necessarily have access to authentic water quality problems and data. Even if they did have the field trip funds, it is difficult to find actual locations where the natural dynamics are unfolding such that they are pedagogically useful, especially given the abbreviated time frames of classroom learning.

The process of translating theory to practice and using theory to account for practice provided us with a powerful methodological tool, especially when used in the context of design work. Through our design framework, we were able to evolve theory grounded not only in practice, but in a visionary frame—one that allowed us to test not only what exists in schools but what could exist. Toward this end, we have enriched our understanding of what constitutes a curricular unit, enlisting narrative storylines, interactive rule sets, pedagogical scaffolds, and a multilevel appreciation for formalisms to simultaneously develop rich contexts for situating underlying formalisms and at the same time support the learner in appreciating the invariant aspects of the formalisms. In this way, as situativity theorists, we are working theoretically to "have our cake," and in the context of a standards emphasis in schools, be able to pedagogically "serve it to others" as well.

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