Designing game-based learning environments for elementary science education: A narrative-centered learning perspective

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Abstract

Game-based learning environments hold significant promise for STEM education, yet they are enormously complex. CRYSTAL ISLAND: UNCHARTED DISCOVERY, is a game-based learning environment designed for upper elementary science education that has been under development in our laboratory for the past four years. This article discusses curricular and narrative interaction design requirements, presents the design of the CRYSTAL ISLAND learning environment, and describes its evolution through a series of pilots and field tests. Additionally, a classroom integration study was conducted to initiate a shift towards ecological validity. Results indicated that CRYSTAL ISLAND produced significant learning gains on both science content and problem-solving measures. Importantly, gains were consistent for gender across studies. This finding is key in light of past studies that revealed disproportionate participation by boys within game-based learning environments.

Keywords: Serious games, game-based learning, narrative-centered learning, science education.

1. Introduction

There has been significant development in game-based learning in the past decade. Of particular interest is the potential that game-based learning environments have for integrating effective problem-solving episodes with highly engaging learning experiences. Recent advances include theoretical developments [22,24], the creation of game-based learning environments for a broad range of curricula [39,66], and the emergence of technically advanced game-based learning environments for both education [13,27,40] and training [33].

Although historically limited empirical evidence was available in support of educational games [1,8,26,53,59], in recent years game-based learning research has matured. Empirical studies have demonstrated that students achieve significant learning gains from interacting with educational games in a range of subjects [9,33,41]. Moreover, there have been several randomized controlled trials [1,9,25,45,46], as well as quasi-experimental studies [3,27,40,57] conducted with students in classroom settings that indicate that game-based learning environments are effective.

For the past four years, the authors have been designing, developing and iteratively refining a game-based learning environment for upper elementary science education, CRYSTAL ISLAND: UNCHARTED DISCOVERY (Figure 1). Our efforts have been guided by the principles of design-based research and design-experiment methodologies [7,10,14]. It has been suggested that design studies are "test-beds for innovation" whose intent is to "investigate the possibilities for educational improvement by bringing about new forms of learning in order to study them" [10]. The project has brought together researchers from computer science, curriculum and instruction, science education, and educational psychology to build and systematically study the cognitive impact of 3D storyworlds.

Figure 1. CRYSTAL ISLAND: UNCHARTED DISCOVERY

This article reports on the design, development, and implementation of CRYSTAL ISLAND: UNCHARTED DISCOVERY. The article is organized as follows. First, we situate our work on CRYSTAL ISLAND: UNCHARTED DISCOVERY in the context of serious games and science education, and then discuss theoretical underpinnings in narrative-centered learning, problem solving, and engagement. Next, we discuss curricular, narrative interaction, and software platform design requirements. We then present the design of the CRYSTAL ISLAND: UNCHARTED DISCOVERY learning environment, and describe its implementation through a series of field tests and a classroom integration study.

2. Literature review and theoretical underpinnings

2.1 Serious games and science education

Three recent policy reports have advocated the importance of game-based learning for educational purposes. *Learning Science Through Computer Games and Simulations* [50] concluded that games offer great promise because they "motivate learners with challenges and rapid feedback and tailor instruction to individual learners' needs and interests" (p. 21). These findings were echoed by the *New Media Consortium's Horizon Report*, which identified game-based learning as a key technology with great potential for significant impact on education [32]. Finally, the *National Education Technology Plan* [65] called for "simulations, collaborative environments, virtual worlds, games, and cognitive tutors" and discussed how they "can be used to engage and motivate learners while assessing complex skills" [65]. Taken together, these reports make a strong case that game-based learning is prominently positioned to make a significant impact on the educational landscape.

In addition to policy-related knowledge, advances in game-based learning have also taken place in the educational research arena. In a recent systematic review of empirical evidence on serious games, Connolly et al. [12] identified 129 reports on the impact on learning and engagement. The most frequently found outcomes were related to knowledge acquisition, content understanding, and motivation. Although the field continues to suffer from fragmentation and lack of coherence [38], substantial progress is being made in terms of synthesizing types of games and investigating their learning outcomes, e.g., students' achieving significant learning gains [3,27,40,57].

The serious games movement is responding to the desire to unite significant content with play as a way to promote 21st century skills [62]. The games within this genre layer social issues or problems with game play, helping players gain a new perspective through active engagement [29]. For example, Klopfer et al. in *Moving Games Forward: Obstacles, Opportunities, & Openness* [42] provide a conceptual path for educators and organizations interested in fostering the development of games for learning purposes. They make "a case for learning games grounded in the principles of good fun and good learning" (p. 1) and devote their efforts to motivating and informing educators and researchers who want to constructively participate, as creators and consumers, in the gaming domain.

There is a growing recognition that science classrooms are key to improving students' participation and performance in science [50]. While children enter school with curiosity about the natural world, many science classes fail to cultivate this interest into the scientific literacy needed to fuel our nation's progress. This has caused many experts to call for a new approach to science education, one that deemphasizes the rote memorization of "factlets" and the coverage of large bodies of content in favor of active engagement in problem solving and deep learning about core, cross-cutting concepts and processes [17,51].

The *Taking Science to School* report [17] asserted that K-8 students may learn deeper science knowledge when they engage in activities that are similar to the everyday activities of professionals who work in a discipline. This report presented four intertwined and equally important strands that define proficiency in K-8 science for all students: (1) understanding scientific explanations, (2) generating scientific evidence, (3) reflecting on scientific knowledge, and (4) participating productively in science.

Simulations and games are uniquely positioned to help educators realize this new approach to science instruction by enabling learners to see and interact with representations of natural phenomena and facilitate their development of scientifically correct explanations for these phenomena [50]. One of the key strengths of serious games is that they can allow students to observe, explore, recreate, manipulate variables, and receive immediate feedback about objects and events that would be too time-consuming, costly, or dangerous to experience first-hand during traditional school science lessons [67]. Nevertheless, it is clear that incorporating this type of technology haphazardly or in isolation can be ineffective [6,30]. The implementation guidelines offered by Smetana and Bell [61] are timely and prudent: innovative technologies should supplement and enhance (not replace) other modes of instruction, such as hands-on labs and activities currently included in many inquiry-based science programs.

2.2 Theoretical underpinnings

Three theories provide the foundation for the development of CRYSTAL ISLAND: UNCHARTED DISCOVERY: narrative-centered learning, problem-solving theory, and engagement theory. Following is a brief discussion of each theory and an example of how the theory is enacted in relation to the design of the game world.

2.2.1 Narrative centered learning

Mott et al. [49] introduced the theory of narrative-centered learning to game-based learning environments and virtual worlds by building on Gerrig's [23] two principles of cognitive processes in narrative comprehension. First, readers are transported; they are somehow taken to another place and time in a manner that is so compelling it seems real. Second, they perform the narrative. Simulating actors in a play, readers actively draw inferences and experience emotions prompted from interactions with the narrative text, or what Deslandes [15] refers to as emoting by proxy. In the same way that good readers employ a particular stance to achieve their reading purpose and goals, a game player may employ a stance in order to participate successfully in the game [64]. Barab et al. [4] define narrative-centered learning games as environments that "afford dynamic interplay between player and storyline, between knower and known, between action and understanding" (p. 525).

With the recent interest in game-based learning environments and virtual world creation, narrative is being appropriated as a dynamic tool for exploring the structure and processes of game-based learning related to engagement and meaning creation [5,48]. Of particular interest is the approach of using games as a means to connect disciplinary content to situations in which it has utilitarian or personal value for the student. To that end, Barab et al. [5] specifically focus on designing games that (1) legitimize the key disciplinary content to be learned, (2) position the person as an individual with an intention to transform the content, and (3) design the learning environment as a context in which actions are consequential.

2.2.2. Problem solving

Perhaps one of the most promising goals for games is their use in fostering problem-solving skills, which are often considered a critical 21st century skill. The *Partnership for 21st Century Skills* [55] claims that the capacity to problem solve separates students who are prepared for increasingly complex life and work environments from those who are not. Problem solving is also supported by research by Levy and Murnane [43], who, after conducting a content analysis of emerging work skills, concluded that the nation's challenge was to prepare youth for the high-wage/high-skilled jobs that involve *expert problem-solving skills* and *complex communication*.

Science education has a long history of problem-solving research. According to Newell and Simon [52], solving well-structured problems is a linear process and consists of two distinct stages: generating a problem representation or problem space, and developing a solution by working through the problem space. A recent study highlighted the importance of hypothesis testing strategies within the problem space in relation to student learning outcomes [63]. A significant difference between classroom and real-world problem solving is the nature of the problem space. Classroom problems are usually well-defined story problems whereas in the workplace, as Levy and Murnane [43] suggest, people are increasingly being required to solve complex, ill-defined problems. Well-structured classroom problems require the application of a finite number of concepts, rules, and principles being studied to a given problem situation that has a well-defined problem space, obvious solution paths, and accurate answers. In contrast, workplace problems are frequently ill-defined because they have divergent solutions, require the integration of several content domains, possess multiple solutions, solution paths, and multiple criteria for evaluating solutions [36,37]. Although it seems plausible that learning to solve well-defined problems will transfer positively to solving ill-defined problems, several studies have demonstrated that this is not the case [18,35]. In fact, Dunkle et al. [16] determined that performance in solving well-defined problems is independent of performance on ill-defined tasks, with ill-defined problems engaging a different set of epistemic beliefs. Additional research has demonstrated that solving ill-defined problems called on different skills than well-defined problems, including metacognition and argumentation [28,58]. More experiences with the cognitive complexity and social dynamics that mirror or at least approximate those of the workplace will better prepare students to be successful.

In *Ready, Set, Science! Putting Research to Work in K-8 Classrooms* [47], a synthesis of the *Taking Science to School* report [17] aimed at practitioners, it is recommended that the science education community provide science problem-solving experiences in elementary school and argued that the belief that young students are not able to handle cognitive complexity is unfounded. The CRYSTAL ISLAND learning environment is designed to provide a context for elementary students to encounter cognitive complexity and address the science education community's desire to help students learn to problem solve in both well-defined and ill-defined game contexts. Complexity in CRYSTAL ISLAND takes three forms: the learning environment's problem-solving space supports multiple pathways toward a solution; transfer is assessed through ill-defined problems; and students solve problems collaboratively [21].

2.2.3. Engagement

In addition to problem solving, one of the most interesting current discussions in the learning sciences concerns the importance of student engagement relative to achievement in STEM disciplines [11,19,44]. However, there is no clear agreement on an operational definition of this construct or how best to assess it. Engagement may be viewed on a continuum from immersion in a specific STEM task to long-term commitment and persistence in STEM disciplines that could lead to STEM career involvement. Jolly et al. [34] suggest that engagement is having an orientation to the sciences or quantitative disciplines that includes such qualities as awareness, interest, and motivation. Another definition by Skinner and Belmont [60] focuses on more subtle cognitive, behavioral, and affective indicators of student engagement in specific learning tasks. They claim that students who are engaged "select tasks at the border of their competencies, initiate action when given the opportunity, and exert intense effort and concentration in the implementation of learning tasks; they show generally positive emotions during ongoing action, including enthusiasm, optimism, curiosity, and interest" (p. 572). Fredericks et al. [20] assert that engagement should be viewed as a multidimensional construct that unites the three components of behavioral engagement, emotional engagement, and cognitive engagement in a meaningful way. While engagement is an exceedingly complex phenomenon and is not yet well understood, it is no doubt paramount for young learners and is a prominent design feature in the CRYSTAL ISLAND game world.

3. Establishing design requirements

Designing a narrative-centered learning environment for STEM education is a complex enterprise. To devise a system that creates learning experiences that are both effective and engaging, the project team addressed two sets of design requirements: curricular and narrative interaction. For several years prior to the inception of the project, our team had been involved in the design and development of a narrative-centered learning environment for middle school science, CRYSTAL ISLAND: OUTBREAK, which was designed with a curricular focus of microbiology [57]. Building on the experience of the middle school CRYSTAL ISLAND project, the team mapped out the curricular and narrative interaction requirements for the CRYSTAL ISLAND: UNCHARTED DISCOVERY environment. Each of these is discussed in turn.

3.1 Curricular focus

A critical set of design requirements to address is the curriculum. Because of the affordances of virtual environments for spatial cognition, it was determined that of the science units of the upper elementary science curriculum, the CRYSTAL ISLAND: UNCHARTED DISCOVERY environment would support the Landforms unit. It was designed to support globally relevant skills for science literacy and also address a key component of the Landforms unit, "Maps and Models," which is required by upper elementary science curricula at both the state and national levels in the United States.

Despite the real-world utility of map interpretation [2], becoming a skilled map user is cognitively challenging. It is difficult for students to connect what they see in the world to map elements. Understanding space-to-map and map-to-space relations is an important but complex skill to acquire, as is the ability to utilize map elements (including scale, directions, and symbols) and to master projective and metric concepts. To address these challenges, it was determined that the CRYSTAL ISLAND: UNCHARTED DISCOVERY environment would be designed to teach map skills through a broad range of guided map interpretation and navigation experiences through unfamiliar, complex terrains in the learning environment's virtual uncharted island. It targets four learning objectives:

- Identify common landforms including the following: *delta*, *plateau*, *river*, *waterfall, tributary,* and *volcano*.
- Explain that models can represent objects that are very large and processes that occur over long periods of time, and that models often represent features of the earth at a manageable scale.
- Recognize that maps are a kind of portable model representing landforms and human structures.
- Use a map and map elements (e.g., key, scale, compass rose, grid) to navigate and wayfind in a 3D environment.

The CRYSTAL ISLAND virtual environment was designed to support map reading and navigation skills, such as those required to correctly respond to the item in Figure 2.

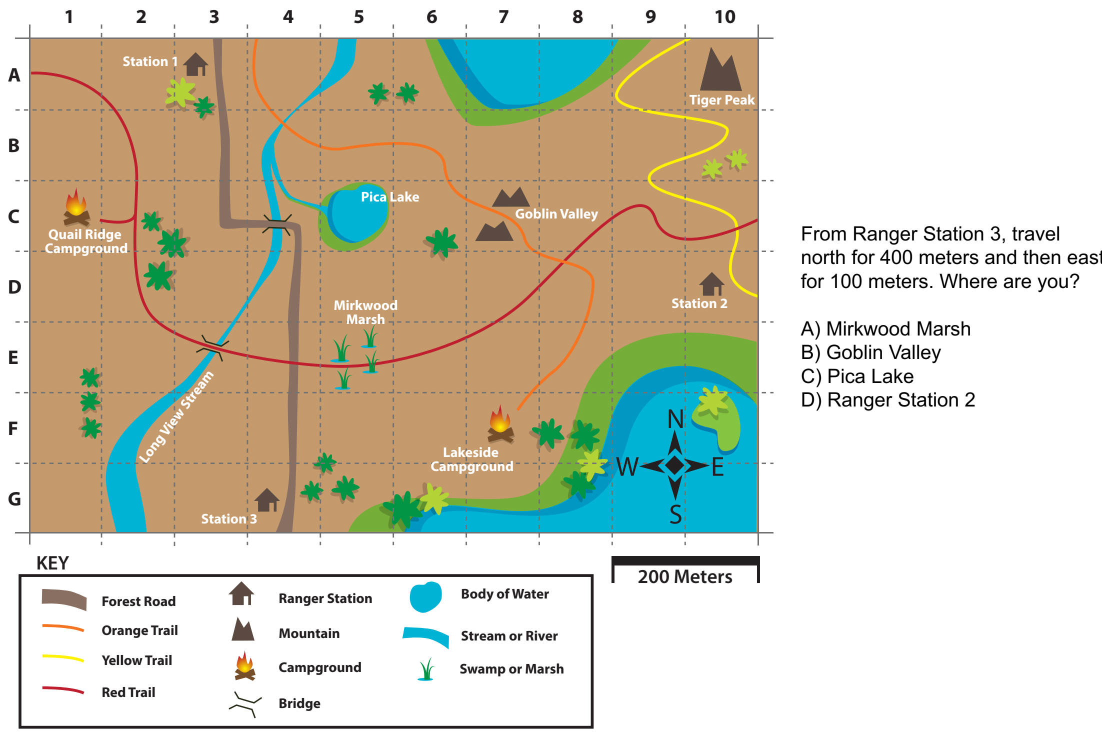

Figure 2. Map Skills Content Test Item

3.2 Determining narrative interaction requirements

When designing narrative-centered learning environments, the second set of requirements centers on the narrative problem-solving interactions that a learning environment will support. To ensure that the narrative and its interactions would most effectively support the target audience, the project team conducted two focus group studies: one with students, and one with teachers.

The primary goal of the Student Focus Group Study was to gather data that would inform the design of key narrative elements of the CRYSTAL ISLAND narrative. The study was conducted in two sessions in a fifth grade classroom in the project's lead partner school, a highly diverse urban elementary school with a large free-and-reduced-lunch population. Emphasizing students' gaming experiences, the study focused on the following design features:

- *Plot:* The eighth grade microbiology version of CRYSTAL ISLAND revolves around a science mystery; would an open world environment be more effective for fifth grade students?
- *Characters:* How should characters behave? How should they collaborate with each other? How should characters communicate with the student? Should students be able to create customized avatars?

- *Setting:* How should the island setting be designed to best support the curricular content (e.g., larger area to support map reading and creation activities, particular landform features such as rivers, canyons, mountains, volcanoes, etc.)?
- *Interface & Controls:* Should the controls be a combination of keyboard and mouse movements? Should gamepads be supported? Should it be a first person or third person view? What onscreen elements should be displayed (e.g., map, score, health, selected items, etc.)? How should students communicate with characters and other students?
- *Gameplay:* Should the player have health? How should the player collaborate with other players? How many players should be allowed in the game? Should the player collect money to purchase items? What types of items would be useful (e.g., tools, cards, power-ups, etc.)? Should players be able to trade items? Should there be different levels? Should there be an ending? Should the player be able to save and continue? Should there be a "leaderboard" to track students' performance?
- *Curriculum:* What are some ideas for integrating landform content within the game? Are there mini-games or micro-games that work well for this content? Which topics seem like they would work especially well for a game environment?

In the sessions students took surveys and interacted (as a group) with the eighth grade version of CRYSTAL ISLAND to provide a concrete point of comparison. The sessions began with participant surveys that included demographics and game playing experience. Then the students interactively brainstormed features of the new learning environment. Finally, a discussion was facilitated regarding which topics in the curriculum that students found to be the most challenging to learn in typical classroom activities, what would they find to be most helpful in learning this content, and what activities might work well in a game? At the conclusion of each session, the team showed the students brief videos of games that were popular with elementary school age students and discussed the relative attractions of various features.

The study yielded a broad range of design recommendations. It was found that the students had substantial game playing experience. Almost all of the students indicated that they frequently played games on personal computers, most of the students had experience playing browser-based games, and most had been playing games for approximately four to six years. Further, all of the students indicated that they played multiplayer online games, with action-adventure ranked one of the types of games students most preferred to play. Taken together, the findings pointed toward the new CRYSTAL ISLAND learning environment being designed as an action-adventure game.

Complementing the Student Focus Group Study was a Teacher Focus Group Study. The purpose of the Teacher Focus Group Study was to gain insight into the fifth grade teachers' perspectives on the needs of the curriculum in the classroom, to understand what support materials they currently used, and to understand what areas were the most challenging for students and teachers alike. The study was conducted with classroom teachers as well as with special programs teachers and staff. The session was recorded, and a transcript was prepared. The Teacher Focus Group was structured around the following questions:

- If you have experience with game-based educational software, please take some time to reflect on your experiences. What aspects of the software have proven most useful for you? What things would you consider removing if you could? How would you change it?
- What are the areas (both skills and content) in which the students struggle the most?
- What should the game/virtual environment we create do? Reinforce content covered in the modules? Fill gaps in student understanding? Engage students in otherwise inaccessible content?
- What ideas do you have about assessing student learning in this virtual environment?
- Game-based educational software is often designed for use over multiple sessions and in informal settings. How would you envision the best use of the software from this perspective?
- Game-based educational software can be used in informal settings. How would you envision the best use of the software outside of the classroom, e.g., in after-school programs or at home?

It was found that there was a consensus among the teachers that game-based learning environments could be very beneficial. The discussion ranged from issues in supporting collaborative learning and criticisms of existing educational software to specific recommendations for learning functionalities (e.g., virtual notebooks) and suggestions for dealing with the broad range of abilities that have emerged at the fifth grade level. Suggestions were also made regarding including capabilities that parents could utilize and the importance of taking into account the impact of potential gender differences.

4. Narrative-centered learning environment design

After the initial design requirements were in place for the narrative-centered learning environment, design and development commenced. Addressing the findings from the focus group studies, CRYSTAL ISLAND: UNCHARTED DISCOVERY was designed as an action-adventure learning environment that integrates elements from adventure games (a rich storyline, a large cast of characters, exploration, and situational problem solving) with elements from action games (time pressure, obtaining power-ups, and collecting objects). It features a science adventure set on an uncharted volcanic island where a group of stranded explorers are trying to contact the outside world for rescue. The curriculum underlying CRYSTAL ISLAND's adventure is derived from the North Carolina Essential Standards for Science landforms curriculum with a focus on maps and models. In CRYSTAL ISLAND, students play the role of the protagonist who undertakes a series of quests to develop the skills to locate and build a communication device that is needed to send out an SOS distress signal. Using their selected avatar, students explore the island from a third-person point of view. In the storyworld, players can manipulate virtual objects, converse with non-player characters, and use resources such as a virtual tablet computer to complete the adventure. Students are asked to complete multiple quests that develop skills in problem solving, map reading, and navigation during the course of their adventure.

CRYSTAL ISLAND's narrative is set on a fictional island in the Oceania region of the Pacific Ocean, where the explorers have established a new life after being shipwrecked by a powerful tropical cyclone. The game opens with an introductory cinematic depicting the explorers struggling at sea, their stranding on the island, and the start of their new life in a small village. The game begins with the student located on the beach where she learns how to control her character in the virtual world, as well as how to use the virtual tablet, a multi-functional computing device that provides a set of tools for students to use throughout their quests, including apps such as a camera, journal, and map. Upon successfully learning how to control their character and use their virtual tablet, the student is introduced to the village where the explorers live. The student meets the mayor of the village, and initiates a conversation with her. The conversation with the mayor, as well as with other non-player characters, takes place through a combination of non-player character dialogue and player dialogue menu selections. The mayor explains that she needs the player's help exploring the island. After speaking with the mayor, the student has several options for developing her problem-solving, map reading, and navigation skills. Inside the Community Hut, she can speak with the village's teacher, who asks her to undertake quests that require her to develop her map reading and navigation skills.

The first navigation quest involves navigating to specific coordinates on the map and collecting the flags that her teacher has placed at these locations while leaving his decoy flags. The second navigation quest asks the student to navigate using both direction and scale to specific locations on the island, e.g., 200 meters west and 50 meters north, and take photos of the animal life she finds there. Alternatively, inside the Science Hut, the player meets Jin Park, a geographer, who offers the student two quests to help identify landforms located around the island. In the first landform quest, Jin asks the student to place signs near the landforms she has drawn on her blackboard. The second landform quest involves the student taking photos of landforms based on the definitions Jin provides the student and returning the photos to Jin for her album. Other quests are offered when the student speaks with the village's map maker inside the Cartographer's Hut, who works with the student to develop her modeling skills.

The first modeling quest asks the student to match an actual photo of the island with a model that represents the corresponding part of the island. The second modeling quest has the student create a model of the village using a modeling app provided by the cartographer on the virtual tablet, which allows the student to drag and drop 2D icons of the various huts in the village to construct their model. In addition to these quests, the student's problem-solving activities are scaffolded through several mechanisms. Her virtual tablet includes a reference app that provides multimedia presentations on topics about landforms, maps, and models.

Throughout the game, non-player characters communicate with the student through dialogue and text messages to offer context-sensitive advice. She can take notes in her journal to record details about her adventure, and the mayor provides her with a Problem-Solving app, which uses the Polya framework to dynamically guide her problem-solving activities throughout her quests. Once she has successfully completed the six quests in the village, she is granted access to a new area of the island where she must solve a complex puzzle that requires all the skills she has developed completing her earlier quests: problem solving, map reading, and navigation. Upon completing her final quest, the student constructs a communication device, which she uses to contact the outside world for rescue, and wins the game.

To provide problem-solving scaffolding and create engaging learning experiences, a virtual tablet computer was introduced. The virtual tablet is a multi-functional device that provides a set of tools for students to use throughout their quests: the *IslandPedia* app, the *Problem-Solving* app, the *Camera* app, the *Photo Journal* app, the *Text Message* app, the *Map* app, and the *Quest* app. Each of these tools is discussed below.

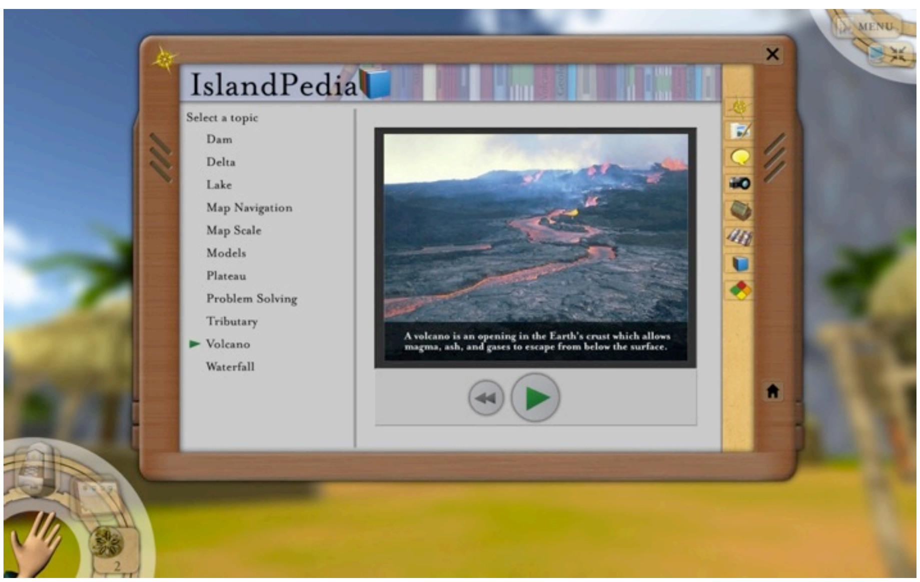

Figure 3. IslandPedia app on the Virtual Tablet

IslandPedia app. To address the need for students to access learning resources throughout their problem-solving episodes, the virtual tablet includes the *IslandPedia* app (Figure 3). *IslandPedia* provides students multimedia presentations of key content. They are available on demand as students solve problems to successfully complete quests in the game, and characters opportunistically recommend that students consult *IslandPedia* when needed. Accompanied by voiceover narration with close captioning, *IslandPedia*'s presentations dynamically highlight salient visual elements. Presentations draw connections between virtual objects and real-world phenomena. Authored in Flash and imported into CRYSTAL ISLAND through the Unity game engine, some presentations are diagrammatic, while others are photographic.

The *IslandPedia* app includes presentations on the following topics:

- *Dams:* Provides students with a basic definition of a dam and describes what dams are used for in today's society; includes examples of famous dams, such as the Hoover Dam and the Grand Coulee Dam, the largest dam in the United States.
- *Deltas:* Provides a definition of deltas and how to identify them; includes examples of the largest deltas, such as the Nile Delta.
- *Lakes:* Provides a definition of lakes; includes examples of lakes throughout the United States.
- *Plateaus:* Provides a definition of a plateau with images and examples of large and small plateaus.
- *Tributaries:* Provides a definition of a tributary with images.
- *Waterfalls:* Provides a definition of a waterfall; includes examples of some of the largest waterfalls from around the world, such as Victoria Falls in Africa.
- *Volcanoes:* Provides a definition and categorization of volcanoes with images; includes examples of volcanoes that have been active in recent years, such as Mount St. Helens in Washington State.
- *Map Navigation:* Introduces students to a compass, the directions on a compass, how to remember the order and location of North, South, East and West on the compass, and what it is used for on a map; provides examples of how to use a compass when comparing the relative location of landforms to each other.
- *Map Scale:* Introduces students to the concept of a map scale and why one is needed when trying to accurately read a map; includes an example of how to use the scale when reading a map to tell how far objects are from each other in real life.
- *Models:* Provides a definition of models and provides examples of both large models representing small objects, small models (such as a map) representing large objects, as well as models that represent processes; examples illustrate models that students might encounter in everyday life and how scientists use models; model presentation also briefly discusses how perspective affects the viewing of an image and provides an example of a photo taken of a set of objects from three different locations: front, top, and side.
- *Problem-Solving Process:* Teaches students about how to approach problem solving; introduces students to Polya's [56] problem-solving strategy (understand the problem, make a plan, carry out the plan, and look back and reflect); describes each step of the problem-solving process and explains why the step is important.

Problem-Solving app. Because problem solving is central to the scientific enterprise, the virtual tablet includes a *Problem-Solving* app, which uses the Polya framework to dynamically guide students' problem-solving activities throughout their quests in CRYSTAL ISLAND. With the dual goals of improving students' problem-solving effectiveness and their problem-solving efficiency, the *Problem-Solving* app scaffolds problem-solving activities on a per-quest basis by helping students work through the multi-phase process of (1) Understanding the problem, (2) Devising a plan, (3) Carrying out a plan, and (4) Looking back (reflecting). Students are dynamically presented support through the *Problem-Solving* app as they work through quests.

Camera app. The *Camera* app (Figure 4) enables students to take photos in the environment. They can aim the camera and zoom as necessary to take pictures of landforms and animals. Quests frequently utilize photo taking as a key gameplay mechanic by requiring students, for example, to take photos of landforms or animals at particular locations or map coordinates, as well as photographing new discoveries.

Figure 4. Virtual Tablet's Camera app

Photo Journal app. The *Photo Journal* supports quests in which students take photos of landforms at particular locations or map coordinates, as well as photograph new discoveries. It also provides integrated note-taking and journal management functionalities to promote reflection.

Text Message app. The *Text Message* app provides students with timely advice in an unobtrusive fashion. It enables virtual characters in the game to send messages to students to (1) alert them to learning resources they might want to consult to successfully complete their quest, and (2) to provide recommendations if they appear to be progressing too slowly, or are off-task. For example, a student might be contacted with a text message suggesting that they contact the mayor to learn about village-level quests (Figure 5). When students receive a message, their heads-up display provides a visual indication and an audio cue indicating the arrival of a new message.

Figure 5. Virtual Tablet's Text Message app

Map app: The *Map* app (Figure 6) provides students with situated map skill experience. It includes a grid showing the student's current location, a map key, and a compass that automatically updates. Students frequently use the Map app to successfully complete their quests. The *Map* app also supports the "valley" level of the game where a multi-skill quest unfolds.

Figure 6. Virtual Tablet's Map app

Quests provide a strong sense of adventure. To enable students to cope with the problem-solving complexity introduced by the quests, in addition to the apps above, CRYSTAL ISLAND also provides a *Quest* app. The *Quest* app indicates to students which quests they have accepted, which ones are active, and which ones they have successfully completed. It also indicates which characters they should consult for assistance with particular quests, and it displays the trophies they receive upon completing each of the quests to encourage content mastery.

Students use the apps in an integrated fashion to successfully complete their quests. Throughout their quests, they consult characters, such as the resident geographer, answer questions to open treasure chests scattered throughout the island to obtain sand dollars (CRYSTAL ISLAND's currency), use maps and coordinate systems to navigate the island (Figure 7a), taking photos along the way (Figure 7b). Students can use the sand dollars they earn to purchase items and buy a ticket to ride to the top of the lookout tower (Figure 7c). Students also construct virtual models of their village using a modeling app on their virtual tablet (Figure 7d). When they have completed all six quests in the village level, the mayor informs them that they have located a secret passage to a new area of the island, which they can then proceed to explore and work on solving the multi-skill quest. Upon successful completion of the multi-skill quest, students are rescued from the island.

Figure 7. CRYSTAL ISLAND quests

To support large-scale deployments, the CRYSTAL ISLAND: UNCHARTED DISCOVERY learning environment was designed as a cloud-based application (Figure 8). Its functionalities are decomposed into those running on its *Browser-based Client Runtime Environment* (running on the Unity 3D Game Engine) and those running on its *Cloud-based Server Runtime Environment* (running on the Google App Engine). The Browser-based Runtime Environment consists of the following components: the *Narrative Director*, which structures narrative episodes; the *Quest Manager*, which oversees a student's quest progress; the *NPC Manager*, which directs the behavior and dialog of the virtual characters; the *Inventory Manager*, which tracks each student's inventory; the *Quiz Manager*, which determines which quizzes to issue and in which contexts; the *Virtual Tablet Manager* and *Level Manager*, which track students' tablet and level activities; the *Camera Controller*, which manages the virtual camera that "films" all of the actions in the virtual world; the *Photo Journal Manager*, which manages students' notes and photos; the *User Game Settings*, which manages graphics and audio settings; and the *Trace Data Connector* and *Game Save Connector*, which collectively log and store trace data and game states and supervise all data management and client-server communication.

CRYSTAL ISLAND's Cloud-based Server Runtime Environment manages and stores all trace data and game states. A notable design feature is that it provides teachers with a pedagogical dashboard, which serves three key roles. First, it allows teachers to configure the learning environment for each of their classes. This includes adding courses, adding students along with their sign in credentials, and configuring game settings to control which features were active during the implementation. Second, it acts as an entry point for students to sign into the learning environment while providing cloud-based storage for their game progress. Because the dashboard was developed using Google's App Engine framework, CRYSTAL ISLAND is able to leverage Google's scalable infrastructure to minimize system downtime. Third, the dashboard allows members of the project team to monitor the rollout of the learning environment. During studies, project team members can review teachers' dashboard activity to ensure the fidelity of the implementation (e.g., verifying that the correct quests are enabled). The pedagogical dashboard is a critical step towards integrated classroom deployments because it enables teachers to assume ownership of the learning environment implementation within their classroom.

A long-term goal of the project team is to support the integration of narrative-centered learning environments into classroom activities over the course of an academic year. To begin exploring the kinds of interactions that will need to be provided, the project team designed CRYSTAL ISLAND to satisfy three additional requirements. First, all quests support repeated play to promote content mastery. Students receive trophies upon completing quests, and they can strive to achieve higher levels of awards based on accuracy and efficiency. Second, quests are integrated into the CRYSTAL ISLAND Pedagogical Dashboard to allow teachers to enable quests as their students work through the CRYSTAL ISLAND lessons. Finally, students can pursue a multi-skill quest to support continued mastery as they prepare for an in-class map creation activity.

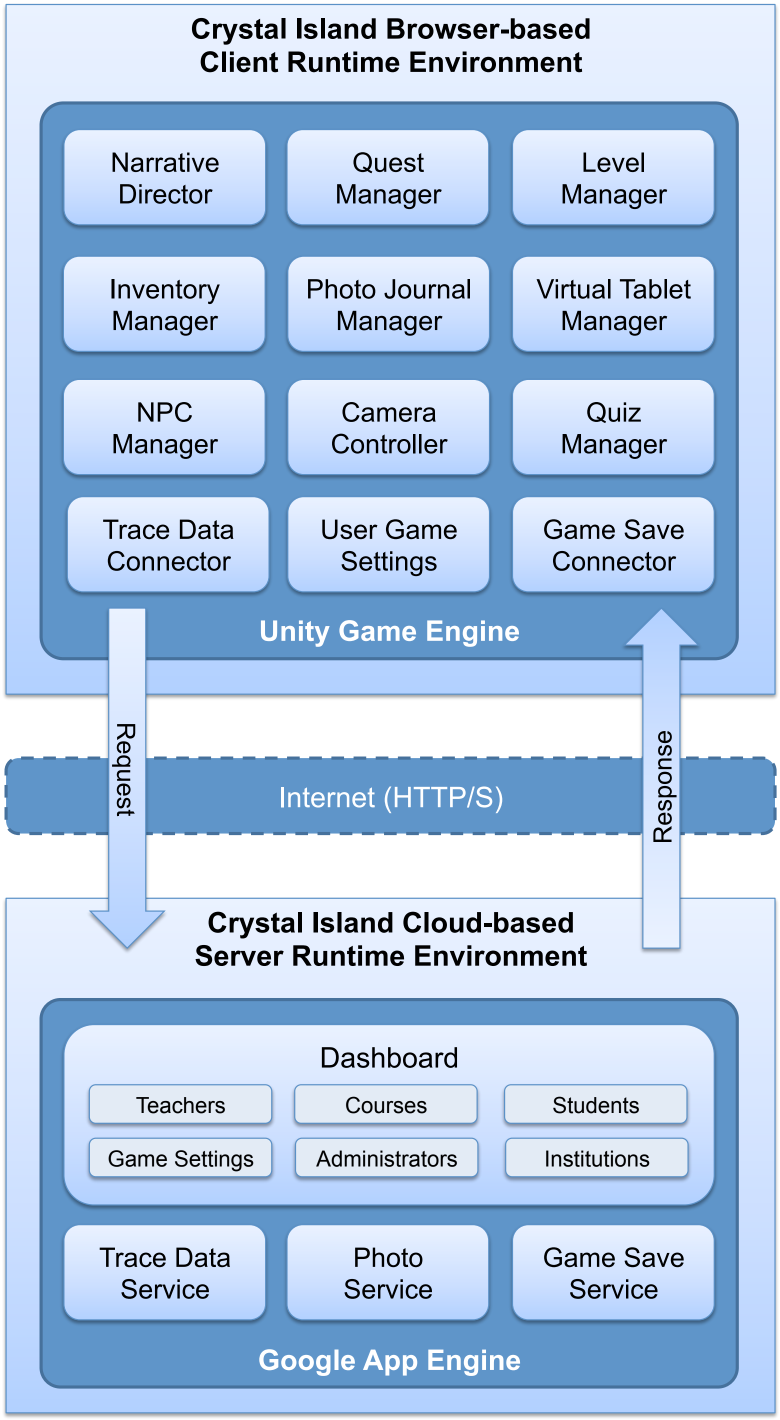

Figure 8. CRYSTAL ISLAND's cloud-based deployment architecture

5. CRYSTAL ISLAND studies

Critical to the success of creating a high-quality game-based learning environment is the process of iterative refinement that begins with design, proceeds to development, continues with implementation, and then repeats the cycle with lessons learned from each successive deployment. The CRYSTAL ISLAND: UNCHARTED DISCOVERY learning environment has undergone a series of iterations, each stage of which has incorporated feedback obtained from student and teacher interactions with the system. It is important to note that although this article is limited to research conducted in the United States, CRYSTAL ISLAND has also been implemented with students and teachers in classrooms in China and New Zealand. Over the course of four years, the project included three phases: (a) pilot study, (b) experimental field tests, and (c) an integrated classroom deployment to initiate a shift towards ecological validity.

5.1 Pilot study

The primary objective of the pilot study was to introduce a preliminary version of the CRYSTAL ISLAND: UNCHARTED DISCOVERY learning environment to a representative set of fifth grade students in order to obtain early feedback on its design. A specific focus of the study was evaluating the software's support for students' ability to navigate in the environment and control their characters. In addition, the study provided an opportunity to test the software on school computers to ensure that the game could be downloaded from the server and that it functioned properly with reasonable performance. To achieve these objectives, the study centered on collecting information regarding the students' game experiences and behaviors, providing an overview of the storyworld, and having students interact with the game while collecting items around the village.

The study consisted of two sessions, which lasted approximately one hour each. Subjects were chosen to include only students who did not participate in the earlier focus group study. The subjects consisted of three girls and five boys. In addition to the gameplay elements investigated in the focus group study, students first used the software's character selection controls, then they used navigation controls to explore parts of the island: keyboard controls were used for navigation, and the mouse was used for positioning the virtual camera. Playtests were conducted by having pairs of students work collaboratively at one computer with one "driving" while the other offered suggestions. Students switched places mid-way through the sessions. It was found that the Unity web player downloaded and installed correctly on school computers, and CRYSTAL ISLAND downloaded correctly and ran at a reasonable frame rate. Videos from the study provided detailed feedback on many environmental and control features, which was then directly incorporated into the subsequent design and implementation.

5.2 Experimental field tests

Over the course of the project, the team conducted experimental field tests to investigate the usability of the software and examine two variations on instructional conditions that included collaboration and scaffolding.

5.2.1 Collaboration study

Two forms of collaborative game-based learning were investigated: face-to-face two-student collaborative game-based learning and virtual two-student collaborative game-based learning. In both forms of collaboration, a planner-driver team framework was employed. In the planner-driver framework, one student was assigned the role of the planner, who was charged with guiding the team's decision-making activities; the other student was assigned the role of the driver, who was responsible for enacting the team's decisions and taking action in the world. The planner and driver were encouraged to engage in ongoing discussion throughout problem-solving sessions. In order for both participants to have the opportunity to play the role of both the planner and the driver, half-way through each session, the planner and driver changed roles. The study had three conditions: the *Solo* (single-student) condition, to which the collaborative conditions were compared; the *Face-to-Face Collaboration* condition, in which students were physically located at the same computer; and the *Virtual Collaboration* condition, in which students were located at different computers that display dynamically updated views of the game state, and the students communicated via headsets. More than two hundred students were randomly assigned to one of the three conditions. It was found that students in both the *Solo* and the *Face-to-Face Collaboration* conditions, but not the *Virtual Collaboration* condition, achieved significant learning gains (as indicated by pre-test and post-test scores). Across the three conditions no gender differences were observed, even though girls reported less experience with gaming environments as they entered the study.

5.2.2 Scaffolding study

A second experimental field test investigated scaffolded game conditions. The field test took place across three days at four different elementary schools with approximately four hundred fifth grade students, who completed the pre-test assessment in class one week prior to the beginning of the intervention. On the first of the three days, students watched a video backstory providing a narrative context for the game. Then they completed the tutorial, which offered practice navigating the environment. Following the successful completion of the tutorial level of CRYSTAL ISLAND, students were allowed to login to the first level of CRYSTAL ISLAND and begin playing the game with the remaining class time. The following day, students were allowed to spend the full class period (60 min) playing CRYSTAL ISLAND. On the third and final day, students were allotted 20 min of gameplay time and 30 min to complete the post-test assessments.

The field test had a 2x2 design with approximately four hundred students, each of whom was assigned to one of four engagement and problem-solving conditions: (1) *Problem-Solving Scaffolding*, (2) *Engagement Scaffolding*, (3) *Problem-Solving/Engagement Scaffolding*, and (4) *No Scaffolding*. Problem-solving scaffolding was implemented in the game using an app on the virtual tablet based on Polya's four-step process. Engagement scaffolding was implemented through character dialogue as well as fanfare and animations that played upon successful quest completion. It was found that while the engagement and problem-solving scaffolding had neither a positive nor a negative effect on learning, the overall CRYSTAL ISLAND experience again yielded learning gains. Students' content test scores increased significantly from pre (M = 12.29, SD = 3.79) to post (M = 13.01, SD = 3.97). There were also significant gains from pre (M = 1.83, SD = 1.47) to post (2.03, SD = 1.49) on a 4-part Polya process ordering question designed to probe at problem-solving skill acquisition.

5.3 Integrated classroom deployment

In an attempt to increase ecological validity within the classroom research process, the project team conducted, a 4-week classroom integration study. The study coincided with the long-term goal of integrating game-based learning into classrooms with teacher-driven implementation (i.e., teachers in their natural classroom setting without the constant presence of the project team). The study focused on two research questions: (1) How does the integration of a narrative-centered learning environment into classroom instruction impact STEM content knowledge, problem-solving skills, and engagement? and (2) What are the effects of game-based learning environments on diverse populations?

5.3.1 Participants and procedures

Approximately eight hundred students participated in the study, which was conducted over a 4-week period. Across the eight participating schools, 49% percent of participants were male; 62% Caucasian, 14% African American, 8% Asian and other. The schools represented urban (40%), suburban (20%), and rural settings (40%). A schedule was developed that took place over four weeks with twelve 50-min class periods of activities prescribed. Half of these class periods were spent playing the CRYSTAL ISLAND game and half were spent engaging in supplemental lessons developed by teachers to enhance the learning experience. Additionally, teachers were asked to encourage students to use the software outside of class, either at home or in the schools' available laboratories. The optimal CRYSTAL ISLAND experience could take place over approximately 800 min.

The project team conducted at least one spontaneous fidelity check at each school participating in the study, on random days, to confirm that the intervention was being implemented in a uniform and quality manner across classrooms. According to the data collected, the teachers used the resources provided with a high degree of fidelity. There was some variation noted, which is to be expected in this type of intervention. For example, some teachers allowed students to cluster in groups to play the game and others "constantly reminded students to play by themselves and not to talk." A few classrooms had to deviate from the suggested schedule due to challenges reserving computer laboratories and school holidays and events. The results also suggest that the supplemental lessons are highly detailed and need to be covered over multiple, rather than single, class periods. Overall, the quality of the implementation was high across schools.

Teachers were given access to the CRYSTAL ISLAND wiki, a website that provided them with access to all the resources they needed to execute the study. For example, step-by-step instructions provided detail about what they were supposed to do each day of the week, contact information for help, suggested schedule and timeline information, the supplemental lessons, and a video tutorial about how to use the CRYSTAL ISLAND Pedagogical Dashboard. The dashboard provided a mechanism by which teachers could control student access to various quests and levels within the game. Teachers registered their classes and provided sign-in information for each student.

5.3.2 Results

The results suggest that the CRYSTAL ISLAND experience produced significant learning gains ($p < .05$) in a diverse student population under teacher-led conditions. Content test scores increased significantly from pre ($M = 11.84$, $SD = 4.05$) to post ($M = 13.63$, $SD = 3.65$).

Problem-solving skills were also evaluated on the pre- and post-test using a near transfer question requiring use of Polya's Problem-solving Model on a four-part map application question. Students were required to order their steps to approaching the following scenario: "Imagine that you were asked to create a map of your school for a new student. In what order would you go about creating your map?" The results indicated that students' scores on this skill-based assessment increased significantly after using the software for four weeks ($t(713) = 3.72$, $p < .01$). This finding suggests that students develop their abilities to approach problems in an organized manner through their engagement in CRYSTAL ISLAND. Additionally, there were no significant differences in learning based on gender, despite the fact that boys reported more gaming experience before playing CRYSTAL ISLAND.

6. Discussion and conclusion

Game-based learning environments offer significant potential for STEM education. A key challenge posed by game-based learning in general, and by narrative-centered learning environments in particular, is designing them to be effective learning tools in the real-world settings of classrooms. One of the most promising approaches to creating such complex systems is adopting an iterative approach in which designs are created, implemented, and refined in an ongoing cycle of rapid development and extensive testing. The end result of this design approach has led to a number of theoretical and practical implications for CRYSTAL ISLAND with regard to creating environments that combine science content learning with interactive gameplay.

Based on the findings, the CRYSTAL ISLAND studies corroborate existing results that have illustrated the potential of game-based environments for learning in classroom settings [51,68]. Specifically, the discussion focuses on implications for theory (i.e., narrative-centered learning, problem solving, and engagement) and classroom practice. First, it appeared that the additional cognitive load presented by the narrative-centered learning aspect of the game supported the science content learning rather than distracting from the learning. Additionally, the game supported the approach of situating key disciplinary content (i.e., science) within the context of narrative [4]. Second, with respect to problem solving, the design was successful at taking a long-standing model of problem solving [56] and integrating it into the game in the form of a tablet application that fit into students' contemporary use of technology. Results demonstrated that students learned problem-solving steps through the game interactions. The research did not, however, illustrate how students can more readily understand problem-solving steps in relation to non-game environments. Third, design features (e.g., virtual reminders, trophies based on performance, and character dialogue) were included in the game with the intention of increasing engagement. Further studies are needed to isolate specific game design features so as to understand which ones are specifically relevant to student engagement. Another avenue for increased engagement is collaboration, which may, if designed appropriately, assist students in co-regulating their learning [31].

Over the past four years, the authors have been creating a narrative-centered learning environment for upper elementary science education, CRYSTAL ISLAND: UNCHARTED DISCOVERY. This article has illustrated the iterative design approach with CRYSTAL ISLAND as a case study. After determining the curricular focus, gathering the narrative interaction requirements from student focus group studies and teacher focus group studies, and selecting a game software development platform, the project team designed, developed, and iteratively refined CRYSTAL ISLAND through a series of pilot studies and experimental field tests.

A classroom integration study was conducted to explore the possibility of integrating game-based learning into classrooms over extended periods of time with a teacher-led (rather than a researcher-led) implementation. The results of the trial suggest that game-based learning holds much promise for classroom-based science education. The findings support the notion that game-based learning environments not only increase student engagement, but also positively impact content knowledge on science topics and problem-solving skills. A key finding was that both genders consistently showed significant gains across studies, despite initial gaming experience on the part of boys prior to interaction with CRYSTAL ISLAND. This result supports emerging trends in gameplay as reported by Papstergiou [54], in which high school students (both boys and girls) performed better on a computer application that emphasized a gaming versus a non-gaming approach. In order for game-based learning technologies to scale to national adoption, they must be easily integrated into the classroom with accessible teacher training and minimal hands-on support. We believe that CRYSTAL ISLAND represents a promising first step toward this objective, which could play an important role in creating more effective and engaging science education for all learners.

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