Play in the Museum: Designing Game-Based Learning Environments for Informal Education Settings

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ABSTRACT
Interest in digital games for education has grown significantly over the past decade. Much of the work on game-based learning has focused on formal education settings, such as K-12 classrooms. However, recent advances in game technologies have enabled deployments in a broader range of settings, including informal learning contexts such as museums and science centers. In this paper, we describe the design of FUTURE WORLDS, a game-based learning environment for sustainability education in museums. FUTURE WORLDS leverages strategy game designs, interactive narratives, and surface computing to create story-centric collaborative investigations of environmental sustainability. FUTURE WORLDS' face-to-face collaborative gameplay unfolds in rich 3D virtual environments rendered on a multi-display surface-computing-based exhibit. In this paper, we discuss design criteria and interaction patterns for game-based learning in museums. In addition, we describe the iterative development process used to create FUTURE WORLDS, including successive prototyping and museum deployments. We report lessons learned, as well as empirical findings, from a pilot study in the project's partner museum. Results suggest that FUTURE WORLDS has positive impacts on students' conceptualizations of sustainability and fosters key learning processes targeted in informal science education, such as sparking interest and engagement, as well as fostering scientific reasoning.

Categories and Subject Descriptors
K.8.0 [**Personal Computing**]: General – *Games*; K.3.1 [**Computers and Education**]: Computer Uses in Education – *Collaborative learning*

General Terms
Design, Human Factors

Keywords
Serious games, informal science education, surface computing, learning in games.

1. INTRODUCTION
Over the past decade, growing evidence has emerged that games are effective learning tools for a broad range of subjects and student populations [4, 5, 18]. Much of the research literature has focused on two categories of game-based learning: 1) games for formal education settings such as schools [8, 18], and 2) serious games, which typically investigate game technologies for training [19] or increasing awareness of social, geopolitical, or economic issues [14]. While important, these research directions do not address a notable class of educational contexts that stands to benefit as much, or perhaps even more, from the introduction of well-designed educational games: informal education settings, such as science museums. From a game development perspective, museums introduce novel opportunities and design challenges that are under-examined in the research literature. From an education perspective, the goals and priorities of informal education are naturally aligned with the strengths of digital games, creating fertile ground for cross-pollination between the two fields.

Formal education settings, such as schools, differ from informal education settings in several important ways. Formal education settings often emphasize cognitive outcomes, such as learning gains, retention, and knowledge transfer. Informal science educators emphasize distinct learning goals, including sparking interest and excitement, enabling learners to observe and engage in authentic science practices, and exploring opportunities for science-related careers [15]. In general, learning in museums, quite literally, "looks" different from classroom learning. There is typically no teacher guiding learning at a museum exhibit. In classrooms, learners often must stay at their desk for a fixed amount of time; in a museum, learners come and go as they please, their engagement often voluntary and leisure-based. Museum exhibits may be designed to accommodate either a single learner or groups of learners, including participants spanning a broad range of ages. And museums emphasize active learning and exploration, as opposed to direct instruction or practice-and-drill activities. These distinctions have significant implications for game-based learning design—including aesthetic, gameplay, and instructional designs—and require careful consideration to ensure effective and engaging deployments in museums.

In this paper, we explore the design of game-based learning environments for informal science education by presenting a case study of FUTURE WORLDS, a game-based learning environment for collaborative explorations of environmental sustainability in museums. FUTURE WORLDS integrates turn-based strategy games, interactive narratives, and surface computing tables to create engaging interactive story experiences where learners explore the impacts of alternate environmental decisions in simulated 3D environments. We discuss the key design criteria and interaction patterns that drove the development of FUTURE WORLDS, and summarize the iterative development process used to build the game. Results from a museum pilot study with FUTURE WORLDS

FDG'14, April 3–7, 2014, Ft Lauderdale, FL, USA.

suggest that learners achieve significant gains in sustainability concept knowledge, and they demonstrate conversational behaviors aligned with key informal science learning processes.

2. RELATED WORK

The affordances of digital games align naturally with the goals of informal education, such as sparking interest in environmental science, and enabling students to manipulate, test, and explore hypotheses about environments [15]. We describe two areas of related work that have informed our efforts to design game-based learning environments for informal science education: educational game design and advanced learning technologies in museums.

2.1 Educational Game Design

Recent reviews of the game-based learning literature have broadly concluded that games can yield positive learning outcomes across a range of educational subjects [5]. Two recent meta-analyses independently concluded that, in general, digital game technologies are often more effective than traditional instructional methods in fostering learning and retention [4, 18]. Expanding on this conclusion, Wouters et al. advise, "the next step is more value-added research on specific game features that determine ... effectiveness" [18, p. 262].

However, the research literature on effective educational game design is relatively sparse. In one of the few exceptions, Isbister, Flanagan, and Hash conducted interviews with experienced game developers to identify key design practices used by professional game developers [11]. The interviewees described themes such as emphasizing fun as a central design value, requiring high levels of polish and well-tuned end-user experiences, emphasizing deep learning content rather than 'bolted on' learning materials, supporting collaboration and specialization, designing for role-playing and emotional engagement, and including affordances for exploring complex systems. While the identified themes are high-level and abstract, they do describe characteristics often lacking in game-based learning environments, and they apply equally well to games for formal and informal settings.

In other work, Linehan and colleagues describe methods for educational game design rooted in applied behavior analysis [13]. Their framework emphasizes personalized instruction and mastery learning, describing a four-step design pattern that involves 1) defining and measuring learners' behavior, 2) recording and analyzing changes in learners' behavior, 3) providing immediate corrective feedback, and 4) tailoring game events based on learners' performance. It is notable that Linehan and colleagues' guidelines are theoretically grounded, but unfortunately they are not examined in the context of an actual educational game.

A handful of empirical studies have been conducted to investigate the learning impacts of specific game design decisions. Habgood and Ainsworth found that tight integration of subject matter and game mechanics in a game for elementary mathematics yielded enhanced learning outcomes compared to versions that separated content and gameplay [8]. Other work has investigated the impacts of narratives in games [1, 16]. Results from this work suggest that narratives may be effective in fostering student motivation, but narrative designs should be crafted sparingly in order to avoid seductive details or extraneous cognitive load.

2.2 Advanced Learning Technologies in Museums

Recent years have witnessed growing interest in the application of advanced learning technologies in museums, such as multi-user interactive tabletops [10] and animated pedagogical agents [12, 17]. Leveraging these capabilities, advanced learning technologies for museums have been developed for a range of subjects, including evolution [10], sustainability [2], and history [7]. There have also been efforts to couple novel hardware platforms, such as interactive tabletops, with digital games to promote *active prolonged engagement* [10]. Utilizing the rendering capabilities of game engines, virtual humans have been devised that serve as simulated docents, offering personalized guidance and feedback to visitors through natural language and affective expressions [12]. While a handful of game-based learning environments for museums have been developed [2, 7, 10], few projects have examined the distinct design challenges introduced by game-based learning in museums.

3. DESIGNING GAME-BASED LEARNING FOR MUSEUMS

Just as the educational priorities of formal education settings, such as K-12 classrooms, differ from informal education settings, the design requirements for game-based learning in classrooms differ from games in museums. In this section, we present design criteria and usage patterns for game-based learning environments that specifically arise in museums. These recommendations were identified through several discussions with museum partners, as well as visits to prominent science museums, while gathering requirements to guide the development of game-based learning environments for informal science education.

3.1 Museum-Centric Design Criteria

In formal education settings, experts have traditionally emphasized cognitive outcomes—such as learning, retention, and knowledge transfer—as paramount. In contrast, the informal science education community has identified six interrelated strands of informal science learning: sparking interest and excitement in science; enabling students to understand, remember, generate, and use science concepts; encouraging students to test, explore, question, and observe the natural and physical world; fostering reflection on the scientific process; creating opportunities for learners to participate in scientific activities; and encouraging students to think of themselves as scientists [15]. These six strands point toward an emphasis on active learning, exploration, and interaction in museum-based learning, as opposed to lecturing and other forms of passive instruction common in schools. Furthermore, learning processes and affective outcomes are prioritized even more highly than cognitive outcomes in informal science education, unlike in many school settings. Discerning the extent to which a game-based learning environment embodies the six strands of informal science learning constitutes a framework for evaluating game-based learning environments' designs, as well as identifying directions for iterative refinement.

Learning in museums also carries its own set of implications for game-based learning design [15]. Museums often have broader ranges of capabilities—such as facilities, resources, and staff—than what are available in schools. Museum-based learning is often voluntary or leisure-based, in contrast with compulsory attendance in schools. Museums also host broad ranges of visitors, including non K-12 students, emphasizing engagement and outreach with the public. Based on these observations, we sought to devise a game-based learning exhibit for explorations of sustainability that would specifically target the opportunities, requirements, and constraints of museum-based learning. To address this objective, we held a series of discussions with the project's science museum partners, and conducted our own review of interactive exhibits in prominent science museums across the eastern United States, to gather requirements for the game's design. From this review, we identified five overarching design criteria for the project.

1. **Low barrier to entry.** Since interactions with museum exhibits can be either short or long in duration, embedding game mechanics that are accessible and quick-to-learn is critical. For this reason, we adopted natural user interfaces—in our case multi-touch interaction—and highly streamlined heads-up displays (HUD) to guide learner interactions, an approach that more so resembles casual games than PC games and serious games. Similarly, we sought to leverage learners' prior knowledge whenever possible, adopting multi-touch controls that are widely adopted in modern computing (e.g., tap, swipe, pinch-to-zoom, two-finger rotation), as well as game paradigms that are widely recognized by the public (e.g., SimCity-style visual appearance).
2. **Exploration and curiosity.** Effective interactive exhibits often avoid didactic instructional methods, such as lengthy text presentations and non-interactive animations. We sought to minimize passive learning, and especially the amount of text in the game. Instead, interactions with the exhibit emphasized direct manipulation of virtual environments, as well as explorations of cause-and-effect and interrelations between disparate environmental factors, rather than direct instruction about environmental science concepts.
3. **Immediate and dramatic feedback.** Immediate feedback is important for any educational setting, but discussions with museum partners yielded recommendations for incorporating melodramatic feedback (in their words, "use fireworks") to convey the effects of learners' decisions. This advice was specifically targeted at young learners, with the implication that subtle effects are often missed or ignored in museum-based learning. Museum spaces often house many competing exhibits, and learner attention is easily diverted. Therefore, we sought to integrate rich combinations of animation, color, and sound to make the effects of young learners' actions clear.
4. **Inviting visual aesthetics with broad appeal.** Although the project targeted young learners, parents and guardians often accompany these visitors. Given the broad range of potential participants found in science museums, we sought to devise a visual style that was inviting and had broad family appeal; we chose not to adopt a visual style that was edgy or dystopian in conveying the impacts of environmental decisions. While labor-intensive, we also sought to emphasize visual "polish," consistent with recommendations from the educational game design literature [11]. The importance of visual polish was particularly salient in our review of exhibits in prominent science museums. High-quality visual presentations are the standard, not the exception, in museum-based learning. This emphasis on visual quality is a notable differentiator from many game-based learning environments for schools.
5. **Novel hardware platforms.** Given the leisure-based nature of many museum visits, and relatively high bar for learners' attention[1], we determined that using a novel hardware platform was an important opportunity for fostering learner interest and engagement. We decided to leverage surface computing hardware to create interactive learning experiences that were not feasible in most school or home settings. This criterion is contrasted with formal education settings, where even rudimentary games are often viewed as being more engaging than conventional instructional methods, such as lectures. Surface computing tables simultaneously integrate multi-touch interfaces, which are immediately familiar to many learners, with novel multi-user collaboration possibilities. We then extended the platform by integrating the surface computing table with a second, vertically mounted high-definition digital display, doubling the available screen real estate for the exhibit (Figure 1). One collaborator described the platform as akin to a "giant Nintendo DS."

Figure 1. Early artist rendering of FUTURE WORLDS multi-display exhibit

These design criteria, along with the six strands of informal science learning, provided a set of heuristics for guiding the development of the game-based learning environment for museum-centric explorations of sustainability. To complement these principles, we also identified a set of common interaction patterns that learners employ in museums. We discuss these interaction patterns in the next section.

3.2 Museum-Centric Interaction Patterns

In addition to distinctive design criteria for game-based learning in museums, there are several interaction patterns that distinguish museum-based learning from other settings, particularly classroom learning. These interaction patterns are conceptually similar to "use cases," a concept often used in requirements analysis and software engineering. However, the interaction patterns we describe here are more general than use cases, derived from the learning affordances of museums rather than the concrete designs of actual software systems. We focus on three categories of interaction patterns that arise in science museums and discuss their implications for game-based learning design.

1. **Solo vs. collaborative interactions.** Learners approach museum exhibits in many different types of configurations. Learners may explore museums individually, engaging in solo learning experiences involving limited conversation and social interaction. Young learners may explore exhibits while accompanied by siblings, parents or guardians. Adults, who may or may not directly interact with the exhibit themselves, will often scaffold young learner's interactions by asking questions or giving advice. In another interaction pattern, learners may approach exhibits that are already partially occupied, engaging in collaborative or cooperative learning with "strangers" with whom they share no prior relationship. Alternatively, learners may approach exhibits as part of large field trip groups, exploring exhibits collaboratively with large

[1] In our partner museum, competing exhibits include panoramic theaters, dinosaur skeletons, live animals, and open labs where the public interacts with real scientists.

groups of peers with whom they have strong social bonds. Given these distinct types of configurations, game-based learning designs for museums should be compatible with a broad range of solo and multi-player interaction paradigms.

2. **Short vs. long durations.** Learner interactions may be shallow and brief—5 second interactions that are quickly abandoned—or they may be deep and extensive—30 minute explorations involving detailed conversations and reflection. Paradoxically, learner interactions may also be long in duration but shallow in terms of learning. In these cases, learners play with surface features of the exhibit but fail to engage with the content at a deep level. Gameplay and content in a museum-centric game-based learning environment should be devised to accommodate these different extremes of engagement, providing positive educational value in as many scenarios as possible.
3. **Active vs. passive engagement.** Active prolonged engagement is an oft-cited goal in museum exhibit design [9], but in practice learners may engage with an exhibit in many different ways. Some learners confidently approach an exhibit and begin physically interacting immediately. Others initially hold back, passively watching or deliberating whether to explore the exhibit more actively. Learners may also passingly engage with an exhibit while walking en route to another destination, judging whether to explore the exhibit at a later point in time. A salient indicator of these differences in engagement is physical proximity; active engagers are often physically close to the exhibit, while passive engagers are often farther away. Given these individual differences in engagement, game-based learning exhibits should be designed to support learning at different physical distances, gradually easing learners toward higher levels of active engagement as they are comfortable.

Having identified these museum-centric interaction patterns to guide our educational game design efforts, we next embarked on the development of a game-based learning environment for informal science education.

4. DESIGN AND DEVELOPMENT OF FUTURE WORLDS

In this section, we describe FUTURE WORLDS, a game-based learning environment for museum-centric explorations of sustainability. To create FUTURE WORLDS, we adopted an iterative design process that involved close interdisciplinary collaboration between developers (software engineers, digital artists), educators (informal science educators, elementary science educators), and subject matter experts (environmental engineers, environmental scientists). The game design model involved several iterations of designing, developing, deploying, evaluating, and refining prototypes of FUTURE WORLDS, including both paper and software-based prototypes. In addition, we identified and created several measures for learning and engagement during the iterations, administered the measures, analyzed outcome data, and refined the measures for subsequent iterations. We describe this process in detail in the remainder of this section.

4.1 FUTURE WORLDS

FUTURE WORLDS is a prototype game-based learning exhibit about environmental sustainability for children ages 9–12. The exhibit integrates turn-based strategy games, interactive narratives, and surface computing tables to support collaborative explorations of environmental sustainability. In the prototype FUTURE WORLDS exhibit, learners solve sustainability-centered problems by investigating the impacts of alternate environmental decisions in a 3D simulated environment. Learners explore environmental decisions—such as modifying a region's electricity portfolio or a farm's waste management practices—through collaborative, multi-touch interactions on the exhibit's interactive tabletop display. The effects of learners' environmental decisions are realized in real-time through rich 3D virtual environments, and they are accompanied by narrated explanations from a virtual docent who observes the learners' actions.

The prototype exhibit's physical design is comprised of two adjacent digital displays: a horizontally oriented Samsung SUR40 interactive tabletop, and a vertically oriented non-interactive 50" high definition television (Figure 1). The configuration provides an integrated two-screen setup; visitors congregate around the horizontal display to explore the science simulation through multi-touch interactions, and the vertical display provides additional screen real estate for explanations of sustainability concepts, which are also accessible to learners standing farther away from the exhibit.

The curriculum for FUTURE WORLDS focuses on three integrated themes of sustainability: water, food, and energy. Visitors' objective during learning interactions with FUTURE WORLDS is to use the interactive tabletop display to collaboratively (or individually) reconfigure an unsustainable virtual environment into a sustainable environment. Learners can engage in deep, extended interactions with FUTURE WORLDS—solving sustainability problem scenarios and identifying complex relationships between alternate environmental decisions—or they can engage in shallow interactions with FUTURE WORLDS, tapping on the virtual environment and briefly listening to a narrated explanation before moving on. Furthermore, learners can actively engage with the exhibit by manipulating the 3D environment through the multi-touch interface, or they can engage passively by observing others or watching the vertical display from a distance. In this manner, FUTURE WORLDS explicitly addresses the museum-centric design criteria and interaction patterns identified during the pre-production phase of the project.

As an illustration of a typical learning interaction with FUTURE WORLDS, consider the following scenario. A small group of learners approaches the exhibit. Tapping on the start screen causes a 3D model of Earth to rotate into view. From the globe, a small environmental region from the United States' eastern coast emerges. The virtual environment represents the first problem-solving scenario: a portion of a simulated watershed that is in an unsustainable state. Players interact with the tabletop individually or in small groups in order to modify the virtual environment and improve its sustainability.

The virtual environment is divided into several discrete, hexagon-shaped locations (Figure 2). Each hexagon encompasses an atomic geographic region that can be acted upon by learners as part of solving the environmental sustainability problem scenario. The hexagon-shaped tiles contain various environmental factors, such as farms, forests, and rivers. The virtual environment's three-dimensional appearance is stylized, and at first appears to be brown and near lifeless. The environment's appearance is a melodramatic visualization illustrating that the virtual environment is "unhealthy", i.e. the environment is in an unsustainable state. Shortly afterward, a short description of the scenario's sustainability-centric objective is presented. The scenario focuses on issues related to farming, particularly waste management and electricity sources. Learners are instructed to

Figure 2. Successive stages of a virtual environment in FUTURE WORLDS

explore alternate choices for improving the sustainability of the farms. At this stage, learners are free to begin manipulating the virtual environment to explore the effects of alternate environmental decisions.

Learners can perform several different types of actions using multi-touch gestures. Learners can move the game world's virtual camera by performing gestures such as pinch-to-zoom and multi-touch rotations. Additionally, learners can tap on various hexagon-shaped locations in the virtual environment, request information about the different factors that bear on the environment's sustainability, and change the behavior of the farms. For example, one of the farms appears to be contaminating a nearby river through fertilizer runoff from a crop field. A learner taps on the farm, and a menu appears offering several options for changing the farm's hog waste management practices. Currently, the farm is considered "Poorly Managed." In order to learn more about the farm's current management practices, the learner taps an "Info" button on the menu. In response, the virtual docent appears on the second vertical display, providing a short narration about fertilizer runoff and waste management. The explanation is accompanied by a high-resolution photograph illustrating fertilizer runoff in the real world. This photograph is intended to help learners draw connections between sustainability issues in the virtual world and their counterparts in the real world.

After listening to the explanation, the learners swipe between alternate options for managing the farm. One visitor arrives at an option to add a *riparian buffer* to the hog farm. The learner taps on the "Info" button and receives an explanation from the virtual docent about riparian buffers. The docent explains that a riparian buffer consists of plants and tree roots that can absorb hazardous nitrogen levels, which leach from synthetic fertilizers used by many farms into nearby water bodies. The learner decides that installing a riparian buffer is worth exploring, and she taps on the menu to enact it. In response, the virtual environment immediately begins to change in appearance: the farm's 3D models transform as the brown-colored fertilizer runoff disappears and a stretch of small bushes, shrubs, and tall grass appears between the farm and adjacent riverbank (Figure 2). Nearby terrain grows greener, and portions of the environment begin to animate. The 3D virtual environment—replete with aesthetic lighting, detailed 3D models, high-resolution textures, and believable animations—provides a dynamic visualization of the learners' environmental actions through immediate feedback, in effect making learners' sustainability choices "come to life." Using this feedback, learners explore the sustainability simulation and solve the problem scenario by employing the scientific method: 1) learners test hypotheses by performing candidate changes to the environment, 2) learners observe the consequences of their decisions as realized in the 3D virtual environment, and 3) learners revise their mental models based on immediate visual feedback. Eventually, the learners arrive at a configuration that addresses each of the environment's main sustainability issues. The virtual environment is now a vibrant green color, and the trees, cities, farms, and river pulse with lively animations (Figure 2). Simulated fireworks erupt to indicate to young learners that they have succeeded in significantly improving the environment's sustainability, and they are ready to move on to the next scenario.

4.2 Paper Prototyping

After identifying design requirements to guide the development of FUTURE WORLDS, we undertook an iterative paper prototyping process that involved developing, testing, and refining several paper-based versions of the system (Figure 3). Paper prototypes emulate the visual appearance and interaction design of the final game environment while providing a low-cost method for rapidly creating, deploying, and refining alternate interaction designs. Paper prototypes resemble a "board game" version of the final system—they are typically made using paper and cardboard cutouts—and they source difficult-to-model aspects of the system's functionality to a human "game master." Pilot testing paper prototypes with young learners shares similarities with Wizard of Oz studies. In both cases a human emulates functionality that will eventually be provided by software, such as simulation systems or artificial intelligence functionalities. Examples of human-provided functionality in the FUTURE WORLDS paper prototype includes setting up virtual environments, moving environmental elements, presenting explanatory information, and updating a simplified environmental simulation.

During the project's first phase, the team conducted two studies to test early paper prototypes of FUTURE WORLDS. The first study was held during a teen-focused event at the North Carolina Museum of Art, and it focused on FUTURE WORLDS' interaction design and visual style. The second study was held at the North Carolina Museum of Natural Sciences, and it focused on a refined version of the FUTURE WORLDS paper prototype, investigating the complexity of the environmental problem-solving tasks.

During the first study, 11 learners ranging in age from 13-17 interacted with the paper prototype. The prototype focused almost entirely on tradeoffs between energy generation and pollution. Its main purpose was to support investigations of FUTURE WORLDS' core gameplay dynamics. In addition to testing basic interaction design, the study provided an opportunity to investigate methods for presenting scientific information, and compare alternate visual styles for the virtual agents. Learners worked individually and collaboratively to solve two problem scenarios with assistance from a project team member. All learners solved the scenarios, and several learners discovered alternate solutions to the scenarios. However, the research team observed that learners did not appear to engage deeply with the descriptions of alternate energy sources or consider a broad range of environmental factors in their decision making. The project team reviewed the paper prototype following this first focus group in order to generate feedback about the science content and presentation. The paper prototype was modified in order to enhance the science content, refine the task descriptions, introduce an additional problem scenario, and modify the input mechanics. More specifically, the following changes were made:

- Problem-solving task descriptions were rewritten to improve clarity and brevity;
- An additional problem scenario was created with an emphasis on water-centric issues;
- The simplified environmental simulation—specifically designed for the early paper prototypes—was expanded to incorporate water tradeoffs;
- Presentations of environmental science concepts were modified to encourage learners to read the content.

The second study was held in coordination with a science summer camp program hosted by the North Carolina Museum of Natural Sciences. The study was designed to examine the revised implementation of the FUTURE WORLDS paper prototype. The focus group involved 17 learners in total. The learners were divided into groups so that learners could work on the paper prototypes in pairs while a designated researcher oversaw each paper prototype. Each group interacted with the paper prototypes for approximately 15-20 minutes.

During the focus group's pre and post assessments, learners completed a drawing task that involved creating a picture of what is an environment based on their understanding. Participants were asked to label parts of the drawing and write an explanation of what makes their drawing a representation of an environment. Learners produced images of forests, towns, water bodies, animals, and the sky. As part of the post assessment that was administered after the FUTURE WORLDS experience, learners were given the opportunity revise their original drawings. Of those learners, 16 elected to make changes and improve their representation of the environment. All of these learners chose to make additions and not remove aspects of their original drawings. The most common new inclusions were representations of energy sources such as wind (wind mills), solar (the sun), petroleum (oil power plants), hydroelectric power (water sources) and human beings, providing preliminary evidence of positive gains in sustainability understanding.

4.3 Iterative Development

Upon establishing a benchmark design through several iterations of paper prototyping and pilot tests, software production on the FUTURE WORLDS game-based learning environment commenced. An agile-based development process was employed, which involved identifying, prioritizing, and developing targeted sets of features for 2-4 week development "sprints." During each sprint, software development and art production activities focused only on the features identified for that sprint. At the conclusion of the sprint, an incremental build of the system was demoed internally to the project team, as well as outside collaborators, for constructive feedback. Software production proceeded in this manner for approximately six months. Although agile-based software development processes are common practice in the game industry, only in recent years have iterative development processes begun to gain attention in the research literature on educational game design [3, 9].

Figure 3. FUTURE WORLDS paper prototype

The FUTURE WORLDS game-based learning environment is built on the Unity game engine, a widely used game development platform for both commercial and academic game projects. Art assets for the project were custom-created by the project's digital art team. Two parallel builds of the software were maintained: one version ran on the Samsung SUR40 table and responded to touch input, and a parallel version ran on standard PCs and responded to mouse input. The latter version was maintained in order to facilitate sharing of incremental builds with project collaborators.

Due to incompatibilities between the Microsoft-provided libraries for touch input on the Samsung SUR40 table and the Unity game engine, an external touch input library called TouchScript[2] was employed to enable touch-based interactions in FUTURE WORLDS. A standalone wrapper application was developed to receive touch events on the surface-computing table, serialize them, and pipe them to the separate Unity game process. The FUTURE WORLDS process read, de-serialized, and interpreted the touch events, translating them into manipulations of the virtual environment. All other game functionalities were developed in C# with Unity.

5. MUSEUM PILOT TEST

In order to pilot test the implemented FUTURE WORLDS game-based learning environment, we conducted a study at the North Carolina Museum of Natural Sciences with 32 students from an urban middle school (Figure 4). The participants were visiting the museum on a field trip with their sixth grade class. The learners' average age was approximately 11 years old. The sample included 51% female participants. Learners completed both the pre- and post-visit measures and interacted with the implemented game-based learning environment.

During the study, in randomly assigned groups of 3-4 participants, students interacted with FUTURE WORLDS on one of two interactive tabletops. A project team member was positioned next to each interactive tabletop in order to answer learner questions and offer guidance to learners exploring the exhibit. Learners moved through a sequence of stations during the study, which included journaling with their teacher, drawing a Personal Meaning Map (described below), interacting with FUTURE WORLDS, and completing a post-exhibit knowledge assessment. Pre testing was conducted in the classroom setting prior to the field trip. For consistency, learners were allowed to dwell for 10 minutes at FUTURE WORLDS before moving to the next station.

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2 http://interactivelab.github.io/TouchScript/

Figure 4. Learners interact with the FUTURE WORLDS exhibit

The research design employed a mixed-methods evaluation approach, which included both quantitative and qualitative measures, to assess the prototype FUTURE WORLDS exhibit. A 9-item sustainability content knowledge questionnaire was developed and used to assess participants' learning gains. While this format of instrument would not be practical in a museum-centered summative evaluation study, it provided an informative assessment tool for evaluating the exhibit's capacity to promote content knowledge gains in a curated setting. A paired samples t-test revealed that learners exhibited statistically significant gains from pre (M = 4.4, SD = 1.9) to post (M = 5.3, SD = 2.0), $t(26) = 2.42$, $p <. 05$, an encouraging result given the prototype nature of the game-based learning environment.

In addition to completing the content knowledge questionnaire, learners created Personal Meaning Maps (PMMs) before and after interacting with FUTURE WORLDS. Similar to concept mapping, PMMs provide a tool for capturing an individual's understanding of a specific topic prior to and after engaging with an exhibit [6]. Participants were given a blank piece of paper with the prompt phrase "sustainability" at the top prior to using FUTURE WORLDS. Participants were asked to write/draw words, phrases, and/or pictures about what they thought and knew about "sustainability." Post-experience, participants were given the opportunity to revise their PMMs in a different color.

During the study, 25 participants created PMMs. The PMMs were scored for number of relevant/accurate and irrelevant/inaccurate items included in the drawing. For both the pre- and post-experience PMMs, scores were calculated by subtracting the number of irrelevant/inaccurate items from the number of relevant/accurate items. Two raters scored each drawing, and inter-rater reliability was established using the Pearson product-moment correlation coefficient (r = .70). Results indicated there were significant improvements from pre (M = -.66, SD = 2.24) to post (M = 1.61, SD = 2.41), $t(21) = 2.27$, $p < .01$. On average, participants added 1.72 correct, relevant items (SD = 1.5) to their drawings after interacting with the prototype exhibit and removed 0.5 incorrect and/or irrelevant items (SD = 1.2) that were included on their original drawing. These findings suggest that learners' interpretations of "sustainability" improved in accuracy following their interactions with FUTURE WORLDS.

The project team also recorded real-time observations of learners' conversational behaviors during their interactions with FUTURE WORLDS. Among the recorded quotations, several were noted as providing evidence of learning processes aligned with the six strands of informal science learning [15]. A sample of these quotations is shown in Table 1. In particular, comments reflecting learners' engagement in the exhibit and reasoning about cause-and-effect were salient. These results provide preliminary evidence to support the promise of FUTURE WORLDS as an effective game-based learning environment for enabling explorations of sustainability in museums. In addition, the findings provide preliminary support for the design criteria and development processes identified for game-based learning environments in informal education settings.

Table 1. Learner quotations and six strands of informal science education

Strand of Informal Science Education	Representative Quotations
Strand 1: *Sparking Interest & Excitement*	"Tech and games are exciting – like the touch screen. It's not sitting and being directed – it's interactive." "I think this is really cool – this whole concept." "Can I buy this [FUTURE WORLDS game]?"
Strand 2: *Understanding Scientific Content & Knowledge*	"Sustainability is when the environment can take care of itself and if people just barge in and mess up stuff it won't be able to take care of itself."
Strand 3: *Engaging in Scientific Reasoning*	"Oh yeah, you can make everything green." "But what did we do to make it like that?" "Oh, they dance because they are good."
Strand 4: *Reflecting on Science*	"[The game] can show little kids how one little change can effect everything." "Science is getting more interesting day by day. This shows how we can solve problems for the future."
Strand 5: *Using the Tools & Language of Science*	Discussion and use of content terms: "farming" "pollution" "sustainability"
Strand 6: *Identifying with the Scientific Enterprise*	"I have it in mind to be a scientist and do something like this [environmental science] … how water gets to certain areas and gets polluted and how we can fix it."

6. CONCLUSIONS AND FUTURE WORK

Game-based learning environments show considerable promise for informal education settings. However, distinctions between formal and informal education settings have significant implications for game-based learning design. We have presented a case study of the design and development of FUTURE WORLDS, a game-based learning environment for collaborative explorations of environmental sustainability in museums. We identified a set of design criteria and interaction patterns that are specific to game-based learning in science museums. The design criteria include designing games with low barriers to entry, emphasizing exploration and curiosity, incorporating immediate and dramatic feedback, devising inviting visual aesthetics with broad appeal, and leveraging novel hardware platforms. Guided by these criteria, we presented the game development process used for creating FUTURE WORLDS, and presented findings from a museum pilot test that indicated learners achieved significant gains in sustainability concept understanding, and engaged in learning processes aligned with the strands of informal science learning.

Building upon this foundation, several promising directions remain for future work. First, we plan to further extend and refine the FUTURE WORLDS game-based learning environment to promote active prolonged engagement, as revealed by learners' dwell times, interaction patterns, and conversational behavior. Further, we intend to expand FUTURE WORLDS' sustainability curriculum to reflect the myriad complexities of environmental decision making, including multiple stakeholders, competing interpretations of scientific findings, and uncertainty in scientific models. In addition, we plan to conduct further studies that examine the cognitive and affective impacts of game-based learning environments in science museums during naturalistic deployments with the public, as well as compare to competing approaches for sustainability education in informal settings.

7. ACKNOWLEDGMENTS

The authors would like to thank colleagues from the North Carolina Museum of Natural Sciences, North Carolina State University, and Lafayette College for their contributions to FUTURE WORLDS. This research was supported by the National Science Foundation under Grant DRL-1114655. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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