Tangible Programming and Informal Science Learning: Making TUIs Work for Museums

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ABSTRACT

In this paper we describe the design and initial evaluation of a tangible computer programming exhibit for children on display at the Boston Museum of Science. We also discuss five design considerations for tangible interfaces in science museums that guided our development and evaluation. In doing so, we propose the notion of *passive tangible interfaces*. Passive tangibles serve as a way to address practical issues involving tangible interaction in public settings and as a design strategy to promote reflective thinking. Results from our evaluation indicate that passive tangibles can preserve many of the benefits of tangible interaction for informal science learning while remaining cost-effective and reliable.

Author Keywords

Tangible User Interfaces, museums, informal science learning, children, education, programming languages

ACM Classification Keywords

H5.2. Information interfaces and presentation (e.g., HCI): User Interfaces

INTRODUCTION

In their mission to engage, inspire, and open minds, science museums have been at the forefront of innovative interaction design for children. They seek to provide memorable learning experiences that cannot be duplicated in schools, libraries, or the home. In an effort to engage diverse populations, science museums have adopted a constructivist approach, offering self-guided, authentic experiences that allow visitors to construct their own knowledge by exploring scientific or technological concepts in a hands-on way [2,9,16]. For these types of interactions, visitors are encouraged to form their own opinions and hypotheses, discuss them with friends and family, and test them in real time.

Not surprisingly, computer technology plays a role in many interactive exhibits, empowering designers to enrich the visitor experience. Yet, with this power, there is also a temptation to program not just the computer, but also the learning experience itself. Rather than facilitating self-guided, authentic experiences, computer-based exhibits often lead visitors through scripted presentations with pre-determined outcomes. Physical manipulation is replaced by pressing buttons or rolling trackballs. As Ansel [3] points out, most computer-based exhibits could just as easily be experienced from home over the Internet. And, despite the fact that people tend to visit museums in social groups (families or class visits), computer-based exhibits tend to encourage single user interaction, sometimes to the detriment of the social group as a whole [4,7,13].

Figure 1: A tangible computer programming and robotics exhibit on display at the Boston Museum of Science. Visitors use wooden blocks to create programs to control a robot on display.

By combining the capabilities of computer technology with the richness of physical interaction, Tangible User Interfaces (TUIs) have been cited as an appealing alternative to traditional screen-based computer interaction for informal science learning [8]. Unfortunately, however,

TUI technology can be expensive and unreliable, often making it impractical for use outside of laboratory settings. Of course, this is not always the case, and there are many examples of thoughtfully designed TUIs in informal science learning settings (e.g. [8,12]).

In this paper we describe the design and initial evaluation of a tangible computer programming and robotics exhibit that we are developing for the Boston Museum of Science. A prototype of the exhibit has been on display for several months. We also discuss five design considerations for TUIs in museum settings that guided both the development and the evaluation of this exhibit. In doing so, we propose the notion of *passive tangible interfaces*. For the exhibit, the use of a passive tangible interface served both as a way to address practical issues involving tangible interaction in public settings and as a design to promote reflective thinking. Results from our evaluation indicate that passive tangibles can preserve many of the benefits of tangible interaction for informal science learning while remaining cost-effective and reliable.

DESIGN CONSIDERATIONS FOR TUIS IN MUSEUMS
Recent literature on science museums includes many practical design considerations for exhibit developers [2,9,13]. Some of these design considerations seem especially applicable to educational tangible interfaces. The unrestricted nature of science museums is an appealing aspects for visitors and one of the biggest challenges facing exhibit developers [2]. Because visitors are free to choose when and where to spend their time (unlike classroom settings), effective exhibits must be both inviting and easy to understand. Furthermore, they must hold the visitors' attention and motivation throughout the interaction process. All of these issues must be addressed while keeping development and maintenance costs reasonable. Thus, we highlight five design considerations for tangible user interfaces for children in a museum setting.

- Inviting – Exhibits need to catch the attention of visitors and invite them to interact.

- Apprehendable – Visitors with no prior experience should be able to easily learn how to use an exhibit. Allen suggests the term *immediate apprehendability* as the quality that "people introduced to [an exhibit] for the first time will understand its purpose, scope, and properties almost immediately and without conscious effort" [2].

- Engaging – An interactive exhibit strives to hold the attention of diverse visitors throughout the exploration process.

- Supportive of Group Interaction – Science museums are usually visited by family and school groups [2,13] rather than by individuals. As such, exhibits should support social learning and group interaction with both active participants and passive observers [13].

- Inexpensive and Reliable – Museums are non-profit institutions that rely heavily on support from individuals, corporations, foundations, and government agencies. Thus, keeping development and maintenance costs low is a priority.

TANGIBLE PROGRAMMING EXHIBIT
To help make these ideas more concrete, this section describes an exhibit on robotics and computer programming that we are developing for the Boston Museum of Science.
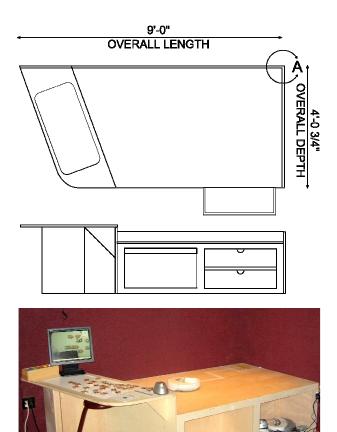

Figure 2: Diagram and prototype of the Tangible Programming exhibit at the Boston Museum of Science.

Guiding Theme and Learning Objectives
In developing the exhibit we used this guiding theme to focus our design:

> *Even though a robot can act like it has a mind of its own, at the heart of every robot is a computer program, written by a person, that makes the robot seem alive.*

To illustrate this in a compelling, hands-on way, the exhibit allows visitors to create and run their own programs to control a robot on display. At the Boston Museum of Science, exhibits are designed with the belief that "it may

be more important for visitors to acquire experience, observation, perception, experimentation, imagination, discovery, thinking like a scientist than to learn any specific facts in any specific fields of science" [1]. Similarly, we are less concerned with teaching complicated robotics and computer programming concepts than with giving visitors a positive, hands-on experience that might inspire them to learn more about computer programming and robotics on their own. Our goal is for visitors to walk away thinking: *I programmed a robot today, and it was easy and fun!* Secondary learning objectives include conveying basic vocabulary ideas for concepts such as robots, sensors, actuators, and computer programs.

Audience

We designed the exhibit with elementary and middle school children in mind, although we hope to engage older children and adults as well. Our goal is to engage girls as well as boys and be inviting to visitors of diverse backgrounds. The programming blocks themselves are labeled in both English and Spanish, and the exhibit will eventually be completely bilingual.

Setting

The exhibit is on display in Cahners ComputerPlace, one of the Museum's three Discovery Spaces. Unlike other areas of the Museum, the Discovery Spaces are staffed full-time by volunteers who guide visitors through activities and interpret exhibits. One advantage of this setting is that it allows for incremental, live prototyping of exhibits with visitors. Furthermore, staff members provide us with invaluable feedback, identifying both positive and negative aspects of visitor interactions. Although installed in a staffed area, we designed the exhibit to be successful in unstaffed environments. And, in practice, visitors regularly interact with the exhibit without any assistance from staff members.

Exhibit Overview

The exhibit consists of an iRobot Create™ robot, a programming console, and a platform on which the robot can move around (Figure 2). The programming console contains a collection of wooden blocks shaped like jigsaw puzzle pieces that represent actions for the robot to perform. Rather than writing programs with a computer keyboard or mouse, visitors instead construct programs by connecting chains of the wooden blocks (Figure 1). The blocks themselves are relatively inexpensive toy wooden train tracks with printed paper faceplates glued on top. The system uses a web camera and computer vision to convert physical programs into digital robot instructions. At the press of a button, a visitor's program is wirelessly transmitted to the robot, which immediately begins to act out the program instructions. A computer monitor displays a picture of the visitor's program, and an arrow on the screen highlights the instruction that the robot is currently executing.

The exhibit also features a *Block Tester*, which is a block-shaped indentation on the upper-right side of the programming console. When a visitor places a block in the indentation, the robot immediately performs that action, and the system displays a help message about the block on the computer monitor. The Block Tester uses a Phidget RFID reader (http://www.phidgetsusa.com), and we attached an RFID tag to each block underneath its faceplate.

Installation

Following the Museum's guidelines for universal access, the installation was designed according to the Americans with Disabilities Act standards for accessibility. We considered the height and reach of children in designing the programming console and we provided enough room for two or three active participants. We also provided ample surrounding space for passive observers and were careful to design the installation so that both the robot and the programming console were easy to observe.
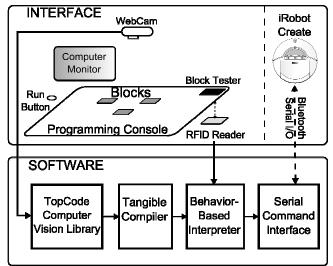

Figure 3: System diagram showing implementation details of the tangible programming exhibit.

Implementation

We started work on the exhibit in May 2007 beginning with *Tern*, an existing tangible programming language designed for classroom use [6]. To the language we added parameters, sensors, structured loops, and other flow control blocks. We then developed a custom runtime interpreter and an assembly language for controlling robots in real time over a wireless Bluetooth connection. We also made substantial changes to the computer vision system, improving both speed and accuracy, while at the same time switching from a point-and-shoot digital camera with a shutter and optical zoom to a 2 megapixel consumer web camera. The camera is mounted three feet above the programming surface and captures still images of visitor programs. Each of the programming blocks is imprinted with a circular barcode symbol called a TopCode [5]. These

codes allow the system to determine the position, orientation, and type of each programming block.

We deployed an initial prototype on the museum floor and have gone through many iterative revisions since, fixing technical problems and making improvements based on feedback from the museum staff and visitors. The current prototype has been on display for six months and will remain up until we complete the design and construction of the finished, permanent exhibit. According to the exhibit logs, visitors compile around 5,000 programs a month, representing between 700-800 visitor interaction sessions.

Programming Language

We designed the programming language itself to be as simple as possible while still allowing for interesting interactions. The goal is for a child with no prior programming experience to be able to learn how to use the exhibit in a minute or two. The language syntax is conveyed entirely through a physical jigsaw puzzle metaphor (see Figure 1), and, following the lead of systems like PicoBlocks or Scratch [11] it is impossible to produce a syntax error. In all, there are eight types of blocks, with some examples shown in Figure 4.
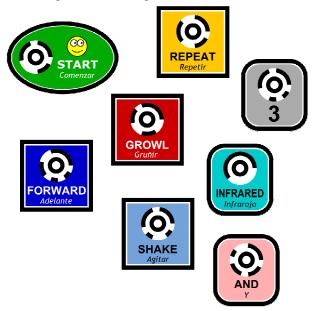

Figure 4: A selection of faceplates for the tangible programming blocks. The round black-and-white symbol is used by the computer vision algorithm to determine the position, orientation, and type of each block.

- **Start Block (green)** There is only one START block, and the robot will only act out the chain of blocks connected to the START block. Any other blocks on the table are ignored.

- **Motion Blocks (blue)** These blocks move the robot forward or backward or turn the robot in place left or right 90 degrees.

- **Dance Moves (light blue)** These blocks tell the robot to perform one of its *dance moves*—wiggle, shake, or spin.

- **Sound Blocks (red)** These blocks tell the robot to make different sounds—growl, whistle, sing, or beep.

- **Control Blocks (yellow)** These blocks allow for simple program control flow structures including a while loop, a repeat loop, and a conditional wait.

- **Sensor Blocks (cyan)** These blocks are used in conjunction with the control blocks to allow for simple sensor input. The sensors that we expose are a bump sensor, an infrared light detector, and a cliff sensor.

- **Number Parameters (gray)** These blocks are used with the repeat loop to specify the number of loop iterations.

- **Logic Blocks (pink)** These blocks allow for visitors to combine sensor input into logical statements. There are AND, OR, and NOT blocks.

PASSIVE TANGIBLE INTERFACES

Tangible interfaces have been cited as being well-suited for use in museums [8], but there are potential problems involving cost and reliability as well. This is not to say that tangible interfaces cannot be reliable and inexpensive; however, designers must make carefully reasoned tradeoffs between the type of interaction desired and the reliability and expense of the technology needed to support that interaction. One such tradeoff is in the closeness of the coupling between digital and physical aspects of a tangible system. In the framework for tangible interaction advanced by Hornecker and Buur [7], this is called *Isomorph Effect*—how closely coupled in space and time physical actions are to digital responses.

Some examples of systems with close coupling are FlowBlocks [17], Tangible Programming Bricks [10], and Electronic Blocks [15]. In these systems, electronic components are embedded in the physical elements of the interface. As blocks are assembled physically, the digital response is immediate, both in time and space—lights blink and motors move. Ideally, this supports playful and exploratory interaction, well-suited for informal science learning. The downside is that each element of the system requires embedded electronics and a connection to a power supply, potentially adding cost and decreasing reliability.

On the opposite end of this tradeoff are systems with weak isomorph effects. For such systems, the digital response to physical manipulation is remote in time and/or space, but there are substantial potential advantages in terms of robustness, durability, and cost. We propose the term *passive tangible interface* to describe these types of systems. Passive tangible interfaces consist of a collection of unpowered physical components with a non-continuous link to a digital system. The physical components can be

inexpensive to produce and make use of passive sensor technology like computer vision fiducials or RFID tags. For this reason, passive tangible systems may give interaction designers greater freedom to choose materials and forms that make sense for an application rather than the technology used to implement it.

Some examples of passive tangible interfaces include Smith's GameBlocks programming language [14] and the exhibit interface described in this paper. With these interfaces, a user's physical actions (i.e. moving, connecting, and disconnecting blocks) are not tracked in real time. It is only when a user *compiles* her program that a connection between the physical and digital is made. The choice of a passive tangible interface has two advantages for us. First, it allows us to use inexpensive and durable interaction objects like wooden blocks. Second, by decoupling physical actions and digital responses, we hoped to introduce an opportunity for visitors to reflect on and discuss the outcome of their program design, ideally reinforcing the learning process. In other words, we hoped to implicitly enforce a workflow that involves design, testing, reflection, and revision.

EVALUATION

We have conducted an initial evaluation of the exhibit to determine its effectiveness in terms of being:

- Inviting – Do visitors who notice the exhibit decide to interact with it?
- Apprehendable – Can visitors quickly learn how the exhibit works? That is, do they understand how to create a program and send it to the robot?
- Engaging – How long does the exhibit hold visitors' attention?
- Supportive of group interactions – Are visitors able to interact with the exhibit in groups? Does the exhibit support simultaneous active participants? Does the exhibit support both active participants and passive observers?
- Inexpensive and Reliable – Was the exhibit relatively inexpensive to develop? What kinds of and how much maintenance does the exhibit require?

Method

During the evaluation, visitors used the exhibit without help from the researcher or the museum staff. Quantitative data involving visitor behavior was logged automatically by the exhibit computer as well as manually by the evaluators. During periods of observation, an evaluator sat ten feet away from the exhibit and watched visitors' interactions with the exhibit.

To measure the *inviting* quality of the exhibit, the evaluators kept a tally of the number of people who noticed (looked or glanced at) the exhibit while within a five foot radius of the installation. Of the people who noticed the exhibit, the evaluators recorded the number of people who

touched or interacted with the exhibit in some way. The time that the visitor first touched the exhibit was recorded as the start of a session.

To measure *apprehendability*, the evaluators noted whether or not each visitor was able to develop an understanding of how the exhibit worked. In other words, could a visitor understand that pressing the run button caused the robot to execute a program? For our purposes, programming the robot one time was not sufficient evidence of understanding as visitors often accidentally programmed the robot by randomly pressing the run button. Instead, we required evidence that a visitor was purposefully putting pieces together to create more than one program. Typically, if a visitor successfully learned how to use the exhibit, he or she did so within the first minute or two of a session and often made some verbal remark like, "Oh, I get it."

To measure *engagement*, the evaluators recorded the duration of each interaction session. For group interactions, evaluators measured this as the time the first group member started interacting with the exhibit to the time that the last group member left the exhibit. This method is based on prior studies of engagement with interactives in museums [9]. We recognize that session length is a narrow definition of engagement, a phenomenon that has intellectual, physical, emotional, and social aspects; however, museum research has shown that session length correlates well with physical, intellectual, and social aspects of engagement [9].

To determine the extent to which the exhibit is *supportive of group interaction*, evaluators noted the numbers of active and passive participants for each interaction session. Qualitatively, they observed the types of interactions taking place both between group members and the exhibit and among different group members.

Participants and Evaluation Sessions

In our first evaluation session, we observed 55 museum visitors, 35 male and 20 female. Of these, 23 were children (seven girls and sixteen boys). Seven visitors used the exhibit alone. The remainder of visitors interacted with the exhibit in groups from two to six people. In all we observed 19 interaction sessions.

During this session, we noticed some usability problems. First, the RFID Block Tester was not functional at the time of our observations, leaving visitors with no way to quickly test the functionality of a block. Second, there was a device on the programming console that is used to activate the robot's infrared sensor. Visitors commonly confused the infrared device for some sort of robot remote control. Finally, when the robot moved towards the edge of the platform a safety system would terminate the visitors program to prevent the robot from falling over the edge. At this point visitors had to physically pick up the robot and place it back on the platform, although not all visitors

realized that their program had been stopped. Also, not all visitors realized they were allowed to touch the robot.

In our next session, we made changes that we thought would improve these factors. First, the Block Tester was implemented, allowing visitors to learn about the blocks with immediate feedback. Second, the infrared device was moved to the side of the workstation, so that it did not distract visitors from learning the basics before moving to the advanced functionality of the infrared sensor. To prevent the confusion with the robot moving near the edge of the platform, we simply placed the robot in the center of the platform between sessions so that users would be less likely to confront this problem before having a chance to learn how the exhibit worked. The goal was to measure improvements in the user experience after making these changes.

In our second round of evaluation, we observed 100 museum visitors, 56 male and 44 female. Of these, 43 were children (14 girls and 29 boys). Fourteen visitors used the exhibit alone. The remainder of visitors interacted with the exhibit in groups from two to seven people. In all we observed 35 interaction sessions.

Results

Here we analyze the results in terms of the five design considerations for TUIs in museums.

Inviting

As a tangible interface, we expected the exhibit to be highly inviting. The idea is that familiar objects (such as wooden train tracks) can transform an abstract and potentially intimidating activity like computer programming into a concrete and playful experience. Data from both evaluation sessions supported this assumption. 78.2% of visitors in the first session (S1) and 79% of visitors in the second session (S2) who noticed the exhibit stopped to interact with it. Among children, 85.7% (S1) and 92.9% (S2) of girls and 87.5% (S1) and 93.1% (S2) of boys who noticed the exhibit stopped to try it. Given that museum visitors have complete freedom to decide whether or not to stop at an exhibit, these results seemed surprisingly high. Evaluators only recorded people who looked at the exhibit within a five foot radius of the installation, so it is possible that other people noticed the exhibit from farther away and decided not to approach. Furthermore, this data includes both active and passive participants. For the purposes of our evaluation, active group members included visitors who manipulated blocks, pressed buttons, or touched other exhibit elements. Passive group members included visitors who watched the active members work without touching the exhibit. If we consider only active participants, then 60% (S1) of visitors who saw

the exhibit actively interacted with it. For children the numbers were 71.4% (S1) of girls and 75% (S1) of boys[1].

Supportive of Group Interaction

As a tangible interface, we expected the exhibit to have good support of group interaction. This is both because the interface is made up of many physical manipulatives for active participants to share, and because passive participants can easily observe the actions of active participants. Hornecker and Buur refer to these properties as *multiple access points* and *non-fragmented visibility* [7]. In addition, we were careful to design the exhibit installation so that it would be easy for people standing around the platform to observe both the robot and the programming console.
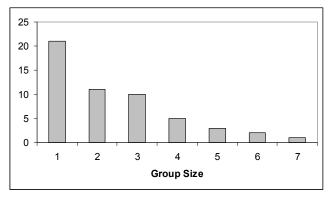

Figure 5: Frequency of group size observed in session 1 and session 2 combined.

The average group size was 2.47 people in the first session and 2.35 people in the second session. Groups were as large as six people in S1 and seven people in S2. Figure 5 shows the frequency of group size for both sessions. Overall, 76.7% (33 out of 43) of participants in the first session were active rather than passive[1]. Qualitatively, groups tended to include both passive and active participants, and group members often transitioned between active and passive roles. Passive group members seemed to be able to easily watch active participants working and frequently contributed suggestions.

Apprehendability

With passive tangible interfaces such as the tangible programming exhibit, there is a non-continuous link between physical actions and digital responses. As such there is a danger that users will have a difficult time understanding how a system is supposed to work. For the tangible programming exhibit, visitors must *discover* that they have to press a button to trigger the camera to take a picture of their program to send to the robot. One of our primary concerns was that visitors would give up and walk away before figuring out how the exhibit worked. Data

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[1] We only recorded information on active vs. passive participation for individuals in the first session.

from our first evaluation showed that these fears were not unfounded. Of the nineteen groups who used the exhibit only ten (52.6%) successfully learned how to use the exhibit. Of those ten groups almost all figured out the exhibit in a minute or less. Of the remaining nine groups, four gave up in the first minute. The other five groups spent between two and five minutes trying to figure out how the exhibit worked before giving up. These results were discouraging, but we also noticed three specific reasons why visitors were struggling (absence of block tester, confusion by infrared beam, and robot getting stuck near the platform edge) as described above.

In the second session, we made the changes described above. Of the 35 groups who used the exhibit, 24 (68.6%) successfully learned how to use the exhibit. The 24 groups that understood the exhibit took between nine seconds and four minutes to figure out the exhibit, with most figuring it out in about a minute. Of the remaining seven groups, three left the exhibit within the first minute. The rest spent between 1.2 and 4 minutes trying to figure out how the exhibit worked before giving up. While the results of the second session were more encouraging, we believe that the exhibit could have better apprehendability with the addition of prominent and simple printed instructions.

Engagement

We measured engagement in terms of overall session length for each group. Of the ten groups from S1 and 34 groups from S2 that successfully learned how to use the exhibit, engagement was high. The average session length for these groups was 5.3 and 5.0 minutes (S1 and S2, respectively) and the maximum session length was 16 (S1) and 26 minutes (S2). However, for the remaining groups (nine in S1 and twelve in S2), the average session length was 1.9 and 1.3 minutes. This brought the overall average session length down to 3.7 minutes (S1) and 3.8 minutes (S2).
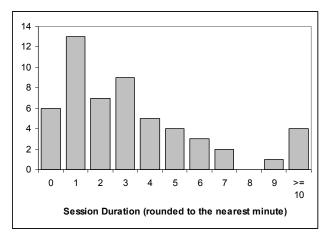

Figure 6: Frequency of session duration (rounded to the nearest minute) for S1 and S2 combined. The last column groups all sessions equal to or greater than 10 minutes. The actual session lengths were 10, 14, 16, and 26 minutes.

These results lead us to believe that if we could further improve the apprehendibility of the exhibit overall engagement would improve as well. Figure 6 shows the frequency of session lengths (rounded to the nearest minute) for the first and second sessions combined. The broad distribution indicates that the exhibit has the ability to draw visitors in to prolonged engagements. To put these results into perspective, recent research on engagement in science museums found average session lengths of 3.3 minutes for successful, *engaging,* exhibits [9].

Inexpensive and Reliable

As a passive tangible interface, we claim that the exhibit should have some advantages in terms of reliability and costs compared to other tangible systems. This is difficult to quantify without other interface examples to compare to. However, we can note that the exhibit has been running at the museum for over six months. In the first three months that the exhibit was on display, visitors compiled roughly 15,000 programs (roughly 170 programs per day, seven days a week).

In terms of the cost of technology and materials, the exhibit uses a consumer web camera that retails for about $100. The RFID reader and tags cost an additional $100. The exhibit computer is four years old and was donated by the Tufts Computer Science department. Each of the wooden blocks cost about $1-3 each. The iRobot Creates were donated by the iRobot Corporation, but they retail for around $130. The exhibit uses two robots; one is recharged while the other is in use. The exhibit does require occasional maintenance. So far this has included replacing the printed faceplates on the wooden blocks, replacing printed exhibit instructions, adjusting the position of the web camera, and repairing one of the arcade button connections.

Discussion

This evaluation has produced evidence that the tangible programming exhibit is inviting, engaging, and supportive of group interaction. As a passive tangible interface, we argued that the exhibit would be inexpensive and reliable. However, there was a danger that visitors would have a difficult time understanding how the exhibit works. The results of our evaluation suggest that when carefully designed, passive tangibles can, nonetheless, be reasonably easy for visitors to understand. Furthermore, we surmise that because the exhibit was highly inviting, visitors were more motivated to put in effort to figure out how it worked.

FUTURE WORK

Our work at the Museum of Science is ongoing. In the coming months we will implement a finished exhibit with a robot playground theme. We also plan to conduct additional evaluations to better understand the visitor learning process while at the exhibit and to compare the effectiveness of

onscreen versus tangible programming languages in informal science learning settings.

CONCLUSION

In this paper, we presented the design and implementation of a tangible computer programming and robotics exhibit for the Boston Museum of Science. The development of this exhibit was guided by five design considerations for tangible interfaces in museum settings. We also described an initial evaluation of the exhibit based on these five design considerations. In addition, we introduced the notion of passive tangible interfaces as a practical approach to tangible interaction for science museums. While passive tangible interfaces sacrifice some of the real-time interactivity of online (or active) tangible system, they also offer some appealing advantages. Foremost, passive tangible systems represent an affordable and robust alternative to active tangible systems. This makes them ideal for use in educational settings where cost is always a factor and technology that is not dependable tends to gather dust in the corner.

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