Topobo in the Wild

Longitudinal Evaluations of Educators Appropriating a Tangible Interface

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ABSTRACT
What issues arise when designing and deploying tangibles for learning in long term evaluation? This paper reports on a series of studies in which the Topobo system, a 3D tangible construction kit with the ability to record and playback motion, was provided to educators and designers to use over extended periods of time in the context of their day-to-day work. Tangibles for learning - like all educational materials - must be evaluated in relation both to the student and the teacher, but most studies of tangibles for learning focus on the student as user. Here, we focus on the conception of the educator, and their use of the tangible interface in the absence of an inventor or HCI researcher. The results of this study identify design and pedagogical issues that arise in response to distribution of a tangible for learning in different educational environments.

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Tangible User Interface, Learning, Digital Manipulative, Education, Case Studies

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K.3.1: Computers and Education: Computer Uses in Education H.5.2 User Interfaces: Evaluation/Methodology

INTRODUCTION
Tangibles for learning [7] have sought to build on the success of educational manipulatives and constructivist learning while engaging learners in new ideas about dynamic systems through the use of hands-on experimentation with embedded computer technologies. The design principles behind Tangible User Interfaces [5] include leveraging natural metaphors of object usage and taking advantage of people's inherent skills and assumptions about the physical world. This research has yielded numerous projects which have sought to create tools and environments which make accessible to children many of the complex and temporal processes that computers can model and demonstrate well.


Figure 1. Children play with Topobo at a festival in Denmark

Because of the physical nature of tangibles, large scale deployment (which could be much more easily accomplished in a software system) is challenging; it is difficult and expensive to produce and maintain the extensive hardware necessary. Research projects are generally evaluated in small scale user studies run by the researchers who created them, and who are looking to qualitatively examine a planned hypothesis and evaluate the children's experiences and/or use of the interface. Such studies often employ observation and interview with the users, and follow an ethnographic model of qualitative evaluation. However, ethnographic methodology has shown that in real world situations, the issues and results that people confront with products or systems are often divergent of the designer's assumptions, and often arise when the designer is removed from the scenario [15]. While there has been one prominent tangible programming system that was evaluated at length in an educational context with students [14], our research focuses design evaluation on teachers as users rather than on children as users. The precedent of this approach was established by Rode in the technique of Curriculum-Focused design [12]. The results of this study seek to further the understanding and implications of the appropriation of technology in educational settings by educators, as originally discussed by Salomon [13], among others.

MOTIVATION AND RESEARCH GOALS

This paper reports on a series of studies in which the Topobo system [10] (fig. 2), a 3D constructive assembly with kinetic memory, was provided to educators and designers to use in the context of their day-to-day work, over extended periods of time. Over the past three years, tens of thousands of people in Europe, Asia and North America have experienced Topobo in settings ranging from classrooms, museums, festivals, workshops, community centers, and homes. While numerous, many of the interactions were very short in exposure and confirmed the initial findings of the original Topobo studies. As part of a deeper question concerning the potential educational impact of a tangible interface, we sought to turn sets of Topobo over to educators to address issues related to large-scale use of a tangible for learning:

- In what contexts and environments can Topobo succeed?
- Over what time period will children use Topobo, and how will their use and interpretations of the system evolve?
- What age children will benefit from Topobo, and how will their experiences differ?
- What uses will other educators invent with Topobo?

The Topobo system

Topobo is a 3D constructive assembly system with the ability to record and playback physical motion. Topobo uses a programming by demonstration model (fig. 3). By snapping together a combination of Passive (static) and Active (motorized) components, people can quickly assemble dynamic biomorphic forms like animals with Topobo, animate those forms by pushing, pulling, and twisting them, and observe the system repeatedly play back those motions. For instance, a child can build a dog and teach it how to walk by twisting the dog's body. The dog will then walk on its own. Normally, in a structure with many Actives, all of the actives will synchronously record or playback their own local motions. However, if a special active called a Queen is used, all of the other actives will mimic the Queen's motion.

The original evaluation of Topobo, conducted in classrooms with children ages 5-13 suggested that children develop syntonic relationships with Topobo creations and that their experimentation with Topobo allows them to learn about movement and animal locomotion through comparisons of their creations to their own bodies. Children explored physics concepts like dynamic balance, center of gravity, torque/leverage and system behavior in their experiments with the system [10].

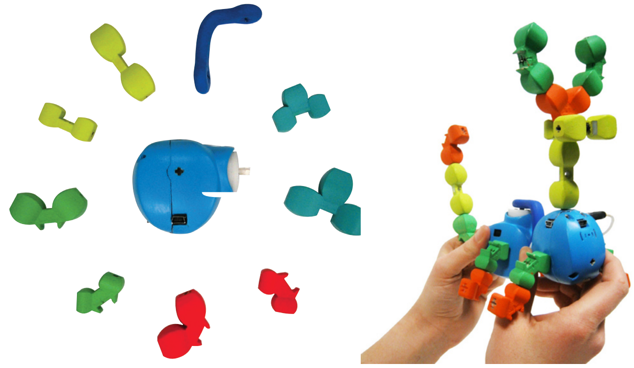

Figure 2. a) The Topobo System: an Active surrounded by Passives b) a Topobo 'moose' designed by 2 eighth grade girls in the original Topobo evaluation

METHODOLOGY

As part of a research initiative pursuing outreach for educational technologies [4], Topobo was reengineered and mass produced with the specific purpose of providing educators with a new means to explore motion construction and kinematics principles. This manufacturing effort was funded by a modest educational outreach grant and required two years of extensive collaboration with an Asian toy manufacturer. Sets of manufactured Topobo were then distributed to educators (teachers, museum developers, educational researchers, graduate students) in the United States and Europe. The sets included Actives, Passives, basic Queens, power supplies and cables, and simple booklets. The booklets described the project concept, design and technical details, instructions for programming, and three sample creations with basic assembly instructions. The educators were also directed to the Topobo website which contains additional videos, published papers and visual materials.

Extensive data has been collected over the past year and a half, mostly in the form of interviews with educators and educational researchers working with Topobo. We are seeking to examine the perspective of the educators, and their reactions and plans when presented with Topobo as a new educational toy or kinetic material. We report how Topobo was used by various educators and what kind of initiatives, programming, or curricula they developed in these different environments when the researcher was removed entirely from designing a study or guiding the technology. In this

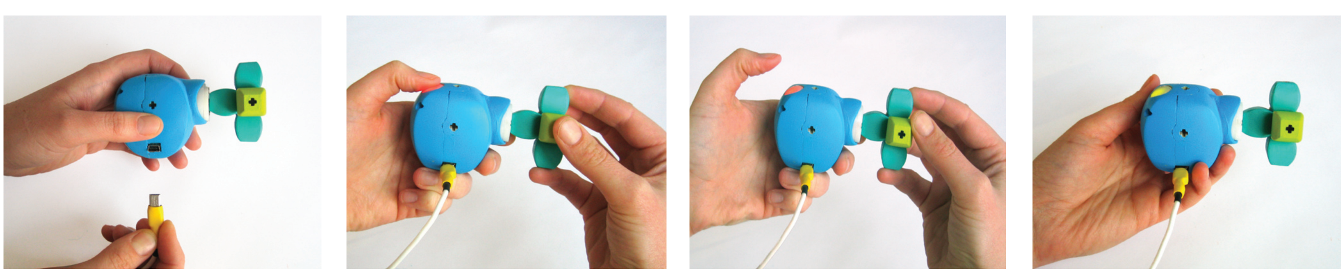

Figure 3. Programming Topobo a) plug in Active b) press button to record c) turn the axis with a motion d) press button for playback

Educator	Context	Student Age	No. students	Time Span	Interaction
teachers	after-school enrichment program	13-15	18	3 months	themed sessions, free play
science teacher	4th & 7th grade science classrooms	9-10, 12-13	36	8 months	goal-oriented lessons, free play
educational researcher	after-school robotics center	4-6, 8-14	32	5 months	guided sessions
exhibit developers & programmers	science museum	4-adult (target 9-15)	200+	4 months	on-the-floor museum activities, demos, internal conversation
graduate architecture students	archtecture course/ studio	24-29	12 (focus on 1 specifically)	8 months	self-directed thesis design work

Figure 4. Breakdown of the five selected case studies

respect, the teachers (not their pupils) are the "users" we address.

FIVE SELECTED CASE STUDIES

The five following case studies (fig. 4) represent a sampling of our research findings in diverse educational contexts with varying aged populations. They represent a cross section of usage environments, target age user and target user scenario. They were chosen because they are representative of common findings while at the same time offer significant depth and layered complexity from which to draw analysis. We aim to highlight the specific issues associated with using a tangible technology in different environments, and to identify the common issues that arise for educators in all environments.

We will present case studies interjected with discussion, rather than a more extensive concluding analysis, because of the results of the study. The analysis of our data from the varied environments revealed that the most interesting ideas to draw upon came from individual scenarios. Beyond baseline usability issues, different populations will try to solve different problems with the same tool. The value of the case studies is their ability to highlight the specific questions that arise for various populations who use a single tool. We will address commonalities among populations of users after presenting the individual case studies.

AFTER-SCHOOL ENRICHMENT PROGRAM

Over the summer, sets of Topobo were loaned to an after-school enrichment program for middle and high school students. The director, Lori first saw Topobo in use in a local classroom and inspired by its potential, sought out to procure sets for her summer program. She intended to provide the system as an inspiration material for her program teachers with the hope of incorporating it in a more structured way the following summer. We provided a basic explanation of the system but did not set expectations of what we thought it should be used for or how we saw it fitting into her program. As curriculum director, Lori became the liaison to the teachers, explaining the system. Her enthusiasm for Topobo was shared by Dale, a middle and high school technology teacher in the program who used Topobo in his class.

Putting Topobo to Use

Dale conducted two sessions, two hours long, each of 7-9 students aged 13-15. Students elected to join both sessions and the second session contained many repeat students from the first session, which Dale interpreted as a sign that the students had made progress with Topobo and wanted to learn more. After some quick initial experimentation on his own, Dale began by giving the students a challenge of which he participated, "I'm having trouble getting something to walk [in reality, he was], can you make it walk?" Three boys in the session ended up making a walking robot but did a lot of purely structural experimentation until they began to use the Actives to actually connect, control and locomote the structure.

In the second session, Dale decided to present a series of scientific concepts to enrich the experience of Topobo, but by his own admission, he got carried away with what he wanted to achieve, frustrating himself as well as the students. In the first half hour he used only the passives, looking to explore the systems' geometry and angles, wanting to instill an overall sense of 'engineering platonic solids.' Then he brought in the Actives and shifted to how the system could mimic molecular reactions, like breaking and creating chemical bonds. He described that upon first seeing Topobo, it immediately reminded him of a PBS special he had seen that showed DNA being spliced. In this vein, he wanted to teach chemical bonding with it, explore crystalline structure, and on a different scale, tensegrity. Dale figured out midway though the session that the material was too dense and presented too quickly for the students.

Dale's Conception of Topobo

Dale's sessions ignited both excitement at the possibilities of what Topobo could demonstrate and frustration at his own inability to immediately put them into action. At multiple times during our interview, he suggested the need for a teacher's guide which would provide advice on building creations that walked successfully. He was careful to stipulate that the guide should not didactically provide exact instructions, but rather that it should provide general design guidelines and examples on how to obtain a particular kinetic behavior, combining structure and programming. He described the guide as scaffolding for the teachers to gain a deeper understand of Topobo's possibilities, as opposed to a series of lessons plans to implement in the class. The guide should also feature common mistakes students make when working with Topobo, to keep teachers preemptively informed. Dale and Lori also suggested running a workshop for teachers, possibly at an education conference, combining teachers of all disciplines.

Pedagogical Ideas

Even after limited initial exposure to Topobo, Dale, Lori and other teachers at the program were overflowing with curriculum ideas of what Topobo could be used for in the classroom. A language arts teacher suggested using Topobo to find the rhythm of poetry, almost like a metronome, programming a creature to move in a particular rhythm and asking the students to write a poem about this creature matching the rhythm of the poem to Topobo's. In addition to his ideas about chemical reactions, Dale mentioned that his 8th grade technology class made Rube Goldberg devices in which Topobo could be easily incorporated. "We could connect it to a ramp or some kind switch then we could set a whole bunch of other events in play." He discussed several scenarios for creating real world models for math and science concepts, such as parabolas, using a Topobo construction to knock a ball into the air, like an automated golf club, observing a parabola created in a real world situation. He also envisioned Topobo to be of use in discussing elementary circuit design: he wanted to figure out a way to create a logic relationship, like an and/or gate, between a Queen and the Actives. He struggled with how he would design it but had a sense that by mimicking a programming structure in a physical behavior, it could become more intuitive and easier to comprehend for the students.

Discussion

Dale begins by using Topobo as a holistic system, creating walking creatures with his students, but soon transitions into a mind set envisioning Topobo as a tool for simulations ranging in scale and time: it becomes an enabling technology for kinetic behavior. This shift shows how Dale has come to recognize Topobo as a flexible and open-ended modeling tool. However, he recognizes the limitations in time and effort of putting those models to work in a classroom, "In general, education is something where you want the fastest and easiest solution, and if it's something you have to stretch your imagination to make something work for a specific situation, that's not something people usually do in a classroom."

Lori offered a more theoretical perspective on Topobo's suitability for a classroom situation, "What Topobo offers is that surprise element...It's intriguing just in its design and its newness, it has that cool factor... maybe I've been taught parabolas before but maybe now that I can make one happen with Topobo, it may sink in. Teachers have to teach and reteach and do it in different modalities and do it in different intelligences in hopes that you hit the one of every kid." She cites its novelty as a factor which can help draw students in, resonating with students of alternative learning styles, and references a multi-modality that is often a specific design principle of tangible technologies.

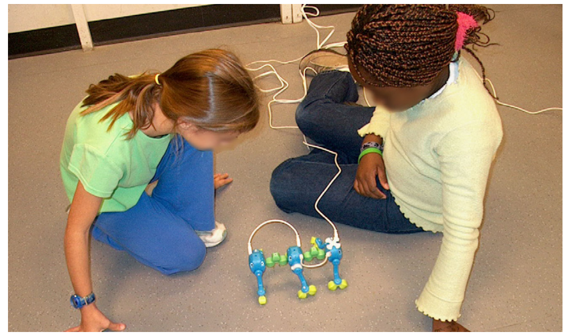

Figure 5. Girls work with Topobo during a lesson on locomotion in a 4th grade science class

ELEMENTARY/MIDDLESCHOOL SCIENCE CLASSROOM

Jane, an elementary and middle school science teacher at a Montessori-inspired school, borrowed sets of Topobo to use in her 4th and 7th grade science classes for 8 months. The school had a hands-on approach to learning and she was accustomed to using manipulative materials in her classes. Our goal with Jane was to learn if Topobo could succeed as a formal educational tool: could it fit within a lesson plan, state educational guidelines and other constraints that teachers juggle daily in designing their class material.

Putting Topobo to Use

Jane incorporated Topobo in her classroom in two ways, first as part of a lesson plan with a curricular goal with her 4th grade class, and second, as a free play activity (for recesses on rainy days) for both her 4th and 7th graders. Jane initially experimented with Topobo in her home and watched her own elementary-age children, nieces, and nephews play informally with Topobo. She tested some of her pedagogical ideas on them, and based on these observations Jane designed a formal lesson plan for her 4th graders about locomotion.

Jane's students worked with Topobo as part of a unit on structures. Lessons took place in two sessions. First, Jane isolated the activity of programming, and set up a specific task all the students could accomplish: children were given identical pre-built creatures and challenged to get the creation to walk 30cm, timing for speed. Jane focused on measurement and data collection as part of this exercise, as well as concepts such as friction, gravity and balance. The children expressed desires for free play and experimentation, and it was difficult to keep them focused on a structured task.

In their second session, students were shown video clips of Muybridge's horse [6] and walking robots as background material on natural and mechanical locomotion. They were asked to build their own four legged creature and make it walk a meter as quickly as possible, and describe the order of the leg movements. In building their own creations, a lot of children started with a creature very similar to what they had used in the previous session. Jane explained, "its always easier to take a model and tweak it." Overall, she was satisfied with the children's success in the activity and Topobo had engaged the attention of her students the entire time, particularly notable with a student who usually displayed attentional disorder issues in extended exercises.

Jane also provided Topobo as a material for free play, during rainy or bad weather days. Deep engagement characterized students in her 4th and 7th grades. "They really, really, really wanted to play with it. It was unbelievably attractive as a play toy – whoever saw it, whatever the age range, from 19 or 20 to 8, people loved to play with it, but they had a hard time unless they had a model to follow." Topobo was more popular as a play toy than as an educational material for Jane, and this evidence suggests that attractive tools can reach students in school outside the context of formal lessons.

Discussion

Jane represents a teacher who has put in considerable time and effort to understanding Topobo's potential and being able to communicate it to her students successfully in the classroom. She described the time put in as essential for her own understanding. Knowing that she could make basic things gave her the confidence to teach it to the children. However, she still did not feel she had a deep enough understanding of how to start working with Topobo in more complex ways, nor as a teacher did she have time. "It would be really cool if I could make it do that, but I don't have time to figure that out." Jane was enthusiastic about her results using Topobo in her structures lesson, but did not use it for formal teaching again. She felt that one of the most important issues with using Topobo in the classroom was educating the teacher on how to think about Topobo and the opportunities it provides.

When asked if Topobo has a place in the classroom, Jane described her philosophy toward activities. "I go back to simplicity. It's the efficiency question, like the efficiency of straws and paperclips" to explore structures. Simple materials that are easy to work with can get a salient message across in a very direct way. While Topobo provides a certain ease of entry to use, the newness and novelty of the technology is actually a hurdle to identifying and focusing on underlying science concepts.

Like her students who found it easier to tweak the Topobo model she had built, Jane would have found it easier to tweak lesson plans we had provided her. Supplementary materials such as a booklet of basic constructions, and principles behind why and how they work (not just examples of full activities), would be very helpful to give teachers confidence to push forward with making their own activities for Topobo. This finding echoes Dale's comments from his experience in the after-school center. One challenge will be to teach sufficiently interesting and new ideas (or old ideas in new ways) so that the cost of learning the technology is outweighed by the benefits of the students using it. From Jane's perspective, it's hard to compete with the simplicity and economy of straws and paperclips.

AFTER-SCHOOL ROBOTICS CENTER

Several sets of Topobo were sent to Mary, an educational researcher studying the advantages and disadvantages of educational robotics for learning with normal and special needs children. Mary conducted her research in an after-school robotics center where children could participate in semester-long courses in which they could engage in somewhat unstructured play with technological tools. She requested Topobo as part of a study investigating how a robotics kit - and a tangible interface in particular - could benefit children in special needs education.

Putting Topobo to Use

Mary worked with two groups of children, one group aged 8-14 with mixed attentional disabilities including ADHD and Asperger's syndrome, the second, a group of kindergarten school children (non-special needs) ages 4-6. The study looked at 32 children in 13 sessions over a period of 5 months. Each child participated repeatedly in at least 6 sessions, and Mary focused on collecting longitudinal data of children's uses of Topobo.

Both groups of children expressed immediate attraction to Topobo and they engaged continuously with it for long time periods (up to an hour), something very unusual for both populations. With special needs children, Mary found that Topobo kept them very focused but that they needed directed and guided tasks, such as small specific problems to solve or

Figure 6. Creations and play by special needs children at an after-school robotics center

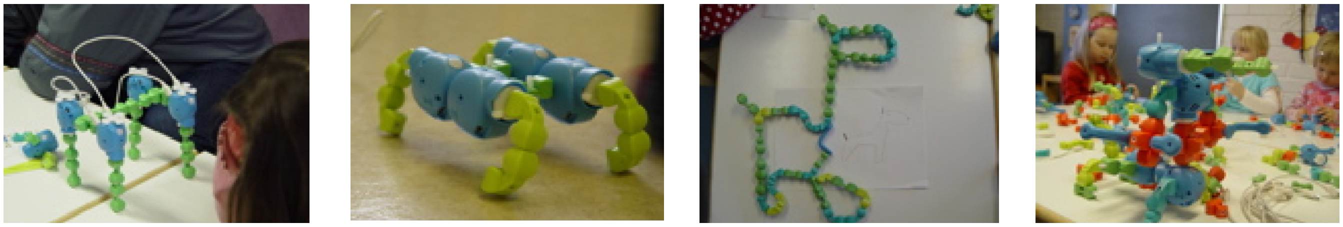

Figure 7. Creations by kindergartners in an after-school robotics center after many weeks of play

very detailed instructions to follow. With kindergarten children, all children engaged with Topobo over long time periods (typ. 30-60 minutes) but some children needed initial scaffolding to understand the programming model.

For both groups, Topobo had a very easy point of entry, different from other robotic systems, and children could quickly and easily build what they desired because the system did not use a on-screen programming environment. Younger children and children who had difficulty with programming could still easily be successful at programming motions for their creations. Over the course of the study, however, Mary observed that Topobo was more suited to the kindergarten. It kept these younger children continuously engaged throughout the sessions, while the older children began to request added functionality such as sensors to build more difficult or complicated programs and scenarios.

Mary's conception of Topobo

As a classroom tool, Mary believed Topobo touches on a number of pedagogical themes including information and communication technology, mechanics, modeling of environments (interdependencies) and procedural thinking. Mary cited that her country's national curricula states that information and communications technology (ICT) should be integrated into all subject matters, but doesn't specify the tools. In this respect, she saw Topobo as a tool that could be integrated into many subjects with younger children. However, children didn't experience these pedagogical ideas directly from Topobo: core technology concepts would need to be introduced in other ways by teachers first, and Topobo could then becomes a concrete [9] example of the concept.

One area in which Topobo excelled was in promoting collaboration and cooperation between students in both groups. She described that children would first build and program their own creations but then would share and try to program each other's work. They could then use the knowledge gained from each other's experiences to figure out how to make their own creations work better. Why did children collaborate more with Topobo than with other tools? She believed it was because Topobo was easy for everyone to use and understand: not only could a student easily create and program their own model, but they could also easily look around and understand what everyone else is doing. This transparency facilitated group learning and unstructured collaborative design processes.

Discussion

Mary had success with much younger children than in previous Topobo studies. Although she didn't believe that Topobo was necessarily more attractive to kindergartners than static manipulatives, all young children in her study engaged deeply with it. Where technology-related concepts are sought as part of a young child's experience, she noted that Topobo, with a tangible programming model, allowed for extended play and engagement with technology at a much younger age than systems which required screen-based (GUI) programming models.

Mary's conception, as well as her specific uses, of Topobo stress the importance of establishing in teachers a deep understanding of the system, in order for teachers to be able to present salient concepts to their students. She conceived of Topobo as a "computer" or "technology" system with which children could play with computer-related concepts. Mary sees Topobo as a technology to play with ideas similar to educational-technology work like Logo [8] or LEGO Mindstorms [11].

This indicates that tangibles may make certain common technology concepts accessible to children at younger ages than non-tangible technologies, as argued by Frei [3]. However, in failing to identify concepts from biology which her students pursued in building creatures and investigating walking motions, Mary illustrates that preexisting conceptions of technology education can limit an educator's perspective on what technology is actually capable of teaching. If this is true, researchers in educational technology should focus on broadening the scope of themes that technology is "supposed" to teach.

URBAN SCIENCE MUSEUM

Sets of Topobo were loaned to a large urban science museum for four months. Topobo had been displayed at many exhibitions in the past but the interactions with visitors were generally very short and while the exhibitions may have been themed in areas such as innovation in play or robotics, no framework had been built around Topobo to guide its pedagogical context. Thus, sets of Topobo were turned over to teams of exhibit developers and programmers to find out how, or if, Topobo could be incorporated into their development process or inspire new experiences in informal education. Use of Topobo would be voluntary, based on interest in the system. Much internal discussion and two different scenarios incorporating Topobo on the museum floor emerged over a period of five months.

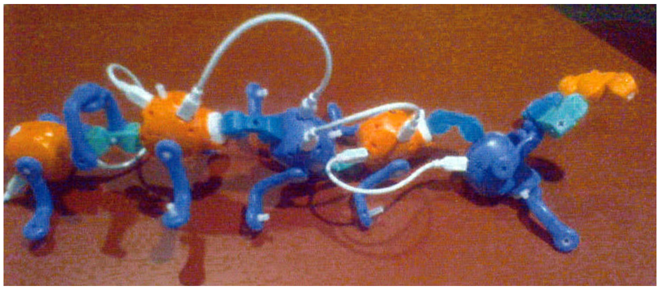

Figure 8. A 'space caterpillar' buit by a visitor and volunteer at the science museum's 'Computer Place' exhibit

Topobo in 'Design Challenges'

The first group to work with Topobo was the development team for 'Design Challenges,' a program which features drop-in activities on the museum floor, staffed for 2 hours everyday, looking to provide "gender neutral non traditional engineering experiences." During the activities, children would build with provided materials to accomplish an engineering goal. The museum staff were present as guides but the focus was on allowing the children to engineers the projects on their own. The activities were planned for children aged 9-15. However, with the varying nature of museum visitors, a much wider range of children and adults participated. The team, led by Leah, took Topobo out on the museum floor for four sessions over a period of 2 months. The activity around Topobo was relatively unstructured but focused on making creatures walk, or if that was too difficult in the time frame, making them wave. She noted that visitors played with it for an average of 20 minutes, considered a very long time for a museum floor experience.

Leah's conception of Topobo

When discussing the concept of the Topobo design challenge, Leah described what they had been investigating as biomimicry, attempting to make a connection to how animals walked. But she stated 'I don't think we went into it thinking that there was a science concept that we wanted to get across." She described their initial aim as showing people a new technology that they wouldn't get to experience somewhere else, citing Topobo's novelty as a big draw for museum visitors. The process of designing a 'design challenge' involved brainstorming a concept, prototyping solutions and narrowing the appropriate materials to make available, leaving the experience open enough to make four or five things that are totally different but can still accomplish the same goal.

If she were to design a deeper experience for a Topobo Design Challenge, she found the nature of Topobo as a well designed 'kit' to be a limitation, because the limited range of pieces could make it hard for students to arrive at diverse solutions. It had not occurred to her to mix Topobo with various other materials (cloth, LEGO®, etc.) as it seemed to go against the nature of the how the system 'should' be used. When asked if providing Topobo Actives that had the appearance of a raw motor, she thought 'it would feel like a material, a raw craft experience as opposed to a kit.' While the 'construction kit' might be seen here as a limitation, the attractiveness and completeness of Topobo's design also drew in a wider age group than their usual audience, especially younger children. They were not accustomed to running a design challenge that spanned such a wide age range.

Topobo in 'Computer Place'

Topobo was also incorporated into a staffed exhibit entitled 'Computer Place' whose goal was to introduce visitors to new computer technologies and present emerging computational concepts. Recently they had been moving into demonstrating robotics technologies, as this was seen as an emerging area in computation. Sonia, one of the program coordinators, brought Topobo into Computer Place for a week of continuously use. She and other staff would demonstrate Topobo and then allow visitors to build creations of their own. To visitors, she described the activity with Topobo as biomimicry, with the goal of "making a computer act more like an animal." In referencing Topobo, she also discussed concepts in computing such as programming (Topobo programming occurred with the body instead of code), networking, and swarm behavior, based on visitors' varying interest and engagement.

Sonia's Conception of Topobo

Sonia's relationship with Topobo focused on its identity as an emerging technology. Based on her area within the museum, the concept of teaching people about creating locomotion and biomimicry was an engaging experience which functioned as a stepping stone to draw people into a second and perhaps more fundamental goal of demystifying and teaching people about technology. Sonia thought it would be good to take Topobo apart, to show people what the sensors and motors look like, citing that they had a Robosapien® that was deconstructed and was very popular and engaging for visitors. As others had indirectly done, Sonia was directly tapping into the novelty of the system as one of its educational values. While this was clearly unintended in Topobo's design, it an interesting paradigm for researchers to consider how Topobo's identity will change as it (and perhaps robotics in general) transition into more commonplace technologies.

Discussion

In these two scenarios, and throughout conversations with other developers in the museum, it was evident that Topobo's novelty and 'cool' design was a big attraction in a busy space with many experiences vying for attention. But to make a system like Topobo successful in the context of the museum floor, it becomes necessary to constrain it. For tangibles to contribute to the museum experience, one guideline is to create an experience that is constrained enough so people can absorb an idea in under two minutes, and open-ended enough so that people can make the discovery for themselves. One approach may be to appropriate the Exploratorium [2] model of exhibit design in which an idea is made accessible by providing many different exhibits that all isolate and provide a different way to "discover" an idea.

GRADUATE ARCHITECTURE SCHOOL

Topobo was introduced to the teacher of a kinetic architecture course at a leading graduate architecture program. Similarly to the other scenarios, the system was presented as a way that students could explore motion concepts and provided to the professor for a long time period. Unlike the other scenarios, this professor did not try to specifically "teach" anything with Topobo, but rather provided it as a "material" prototyping motion concepts in designs of transformable and deployable structures. Because the teacher's role was minimal, this study focuses on the one student's experiences (Ray) as self-taught with the system, and how it was reappropriated for applications that diverge from Topobo's usual purpose.

Putting Topobo to Use

During a studio session, student designers experimented with Topobo in an open-ended fashion. As part of the course, students were using the Arduino [1] programming environment to control sensors and actuators, so they were accustomed to the idea of embedding kinetic behavior physically into their models. However, these students were more comfortable working with physical materials like foam core or paper than with embedded technology. Topobo thus became part of their hands-on modelling and design processes to quickly and easily experiment with movement in their models.

Ray incorporated Topobo as part of his own learning and creative process. Following his experiences during the class session, Ray continued working with Topobo over the following six months, utilizing it in the design stages of his Master's thesis project. Ray's thesis work involved the design of a conceptual transformable opera house (fig 10a) set on Potsdamerplatz in Berlin. The building morphs between two physical states, representing two alternate realities: one represents its form in the 1980's before the Berlin wall fell, and the second fictional state represents the building as imagined if the Germans had won WWII.

Ray's Conception of Topobo

Ray used Topobo as a kinetic prototyping tool as part of the initial design phases for the project. He describes his process: "The most important part for Topobo for me architecturally has been toward the use of diagrams. This model is a representation of some of the kinetic movements in the final project…I used it very early on in the project but as my building started becoming more spatial [modeled in detail & scale] the use for Topobo was eliminated. In the very first stage of a project,...Topobo was instantly these modular parts which I could bring into a kinetic state for discussion."

Ray used Topobo as one medium among many in which

Figure 9. Ray explains his 'kinetic diagram' made with Topobo next to the final model of his thesis project

he communicated his design, with the most useful part for Topobo being early on in the research, "getting my kinetic idea across." When discussing the limitations of Topobo and why he had not continued to use it further along in his design process, Ray cited that he felt constrained by form factor, specifically the joints being a single degree of freedom which made his kinetic model bulky and spatially more complex as he had to offset each joint. As he continued with his design, however, he cited one wing of the building's mechanical design being directly inspired by this constraint, "[this area of joints] came about when I had to keep offsetting the Topobo and I noticed that the axis of rotation could be elongated." (fig 10b). What began as a limitation became part of his design language.

Discussion

Topobo did not become part of Ray's more detailed design phases. While we had given him permission to modify the parts and embed them into his model, Ray preferred to begin 3D modeling in a GUI as the next phase of his design process, "Physically I could take it apart and try to build a chip board model around it but that isn't the method I usually work in, I usually go straight to the computer, draw it in 3D, send the file to the 3D printer. It's just faster."

The advantages of the physicality and immediate access to kinetic behavior had now been outweighed with a more detailed oriented and familiar tool, 3D modeling. However, the Topobo models Ray had made directly influenced many joineries in the final model. He found it useful to think about

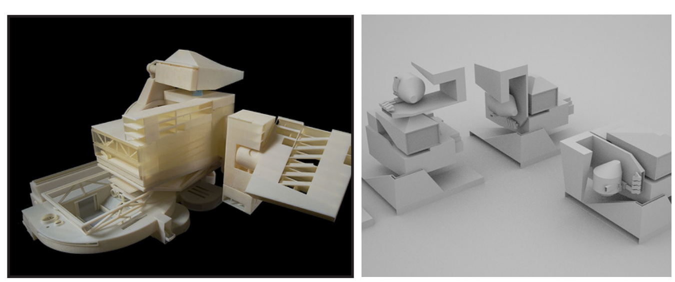

Figure 10. a) Ray's final thesis model b) iterative joint models inspired by Topobo

the design modularly, like Topobo, designing in segments and then connecting them with Lego-like attachments. It helped to work with a physical kinetic material first, when thinking about what would work mechanically in space before attempting to draw it on screen. The building took on a very toylike playful aspect to it, rare in architecture, which he felt may have come from his interactions with Topobo. Ray also used Topobo in one unexpected way, mapping the colors of the passives in different areas of his model to denote their spatial functionality, he described it as his 'legend.' The color mapping that began with Topobo continued into his 3D onscreen model to become part of the design language in communicating the project.

OVERALL FINDINGS

In addressing our original goals, we found it was not possible to analyze them separately; in every study, usage revealed interdependencies between context, age ranges and amount to time spent with the system. Together, these variables affected ways in which people worked with and conceived of the system.

Context of use

In all contexts - museum, classroom, after-school center, robotics center, graduate school - Topobo was regarded as a useful or provocative tool by the educators who worked with it. However, as a construction kit it seemed to excel in contexts that allowed for longer periods of engagement. Jane used it more as a play toy than a curriculum material. The museum asked to use it again, but in the context of a day-long activity. (They would like to use it in computer place, but in a more limited context, e.g. pre-built or somehow constrained in use.) Students and teachers in the after-school robotics center, who have more time to play with the technology, continue to work with it with success.

Designing for multiple environments: Time and Age

The idea of constructive learning or self-discovery came through in every context. As an open ended system the level of success with different age groups was directly determined by (a) the amount of time children spent with the system and to some degree (b) age. The longer childen may play with it, the younger they can be. When Mary used Topobo as a completely open-ended system, kindergartners (previously considered too young for such a complex system) engaged with it meaningfully if given enough time. Conversely, in the science museum, Topobo was used as a simple demonstration or inspirational piece (not at all an open-ended interaction with Topobo) with all ages, but visitors had only one or two minutes to engage with an idea. Somewhere in between we find Jane's example of providing her students with pre-built models, so that they might constrain their efforts on programming motion. Universally, less time to interact with the system required it be more constrained in scope. We believe central issues in designing interfaces or toolkits for multiple audiences will be for the designers to provide means for users to adapt the interface to scenarios of varying time scales, and potentially to different levels of complexity for different aged users.

IMPLICATIONS

Support for Educators

Perhaps the most consistent and salient message from educators themselves is that educators need prior experience with the system, to gain confidence in their ability to teach with it. Jane is a teacher who put a lot of time and effort into learning the system and developing a lesson plan so that she could confidently communicate and teach new ideas to her students. In contrast, Dale jumped right into a lot of exciting, but difficult concepts and ended up frustrating himself and his students. Clearly all teachers needed support, and creating one's own lessons is too difficult for teachers to improvise.

Educators all requested similar kinds of support: to be taught examples they could use in their teaching, but they must learn the underlying principles of the examples. Here, the format of the examples was not prescribed, but printed materials in the form of an instruction / activity book may have met many educators' needs. Such a booklet might be similar between a teacher's standard activity guide, but the computational aspect of tangibles requires a level of systems-thinking that is not often specified in teaching with static materials. Certain challenges will arise, such as representing dynamic information (like movement) using a static printed page. Perhaps the booklet would have a companion on-line component of animated examples.

Inspiring the Use of Toolkits

Many researchers like to develop "toolkits" that can be appropriated by teachers or students in a variety of ways. This contrasts with an interface designed to make a specific idea or application salient. For toolkits like Topobo, it seems especially important to provide educators with an inspirational example of an application scenario. Nearly everyone in our study was interested in making small robotic animals walk, and this provided both an emotional and a pedagogical "hook" to get people started thinking about and working with the system.

The inspirational scenario did not confine the range of ideas people explored with Topobo. Sonia and Mary saw Topobo as an entry to more general computing concepts like networking and communications; Jane compared the system to materials like straws and paperclips (suggesting a general view of it as a material rather than an application); Ray actually used it as a prototyping material in a unique context; Dale envisioned learning conic sections and logic with the system. These digressions from the inspirational example of walking robots encourage us that toolkits can be reappropriated (which allows a user to get more out of their investment in the tools), but we believe the inspirational example application (walking robots) was critical to engage people's interest in the first place.

Tangible Interfaces for Learning

Dale's conceptions of investigating DNA, parabolas and logic principles suggest that educators are seeking the things that tangibles are already working toward: a more transparent programming and control structure, the ability to physically play with math and science ideas, and putting in people's hands the dynamic simulations that are increasingly an important part of scientific teaching. Mary's observation that transparency allowed collaborative work further supports teachers' goals in constructivist education. In terms of this transparency, accessibility and ability to model dynamic processes, the tangibles paradigm seems an obvious fit to education.

Some Comments on Design

Topobo's highly refined physical design helped it succeed with a broad range of educators in such a hands-off manner because the parts were robust, reliable and approachable. However, the novelty of the system has both pros and cons: on one hand, its uniqueness invited people to explore and play with Topobo, catching people's attention in competitive environments like the science museum. But on the other hand, it is equally valuable to make tangibles seem "familiar" by referencing existing products and interactions. Familiarity allows the researcher to more quickly test the reactions and interactions of a seasoned user.

CONCLUSION

Our original goals set out to identify contexts for success of Topobo, the time period and evolution of children's engagement, how age range predicts experiences with Topobo, and contexts and approaches other educators will bring to the system. In addressing the original goals of our study, we found it was not possible to analyze them separately; in every study, usage revealed interdependencies between context, age ranges and amount to time spent with the system.

In all contexts - science museum, classrooms, after-school center, robotics center, graduate architecture school - Topobo was regarded as a useful or provocative tool by the educators who worked with it, and the idea of constructive learning or self-discovery came through in every context. However, as a construction kit it seemed to excel in contexts that allowed for longer periods of engagement. In general, younger children want and need more time with the system than older ones, and short interactions (with any age user) demanded more constrained activities. Perhaps the most consistent and salient message from educators themselves is that educators need prior experience with the system to gain confidence in their ability to teach with it, and would have liked more complete teaching support materials.

Educators' comments and use of Topobo demonstrated that they are seeking the things that tangibles are already working toward: a more transparent programming and control structure, the ability to physically play with math and science ideas, and the ability to put into people's hands the dynamic behaviors and simulations that are an increasingly important part of scientific teaching.

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