Architales: physical/digital co-design of an interactive story table

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ABSTRACT
Many research efforts today explore how digitally augmented tables enable face-to-face interaction with digital content and applications. Yet the design of digital tables is still largely driven by the constraints and requirements of the underlying sensing technologies. In order to move digital tables into our real-world physical spaces, researchers need to work closely with architects and industrial designers in order to engage the knowledge and skills from a long history of physical design and fabrication in the creation of tabletop systems. This paper presents Architales, an interactive story table for gallery exhibition, developed as an experiment in physical/digital co-design. We describe the creation of the interactive table, tangible storytelling system, and story content, which evolved together in a closely unified design process, drawing on the skills from computing, media, design and architecture. We also describe lessons learned about the interdisciplinary design process and the creation of physical/digital artworks.

Author Keywords
Physical/digital co-design, tangible interaction, digital tabletop, design, media art, architecture, interactive stories.

ACM Classification Keywords
H.5.1. [Information Interfaces and Presentation]: Multimedia Information Systems---*Video*; H.5.2. [Information Interfaces and Presentation]: User Interfaces---*Input devices and strategies, Interaction styles, Screen design*; H.5.3. [Information Interfaces and Presentation]: Group and Organization Interfaces---*Collaborative computing*; J.5 [Arts and Humanities]: *Architecture*.

INTRODUCTION
Tables are historically artifacts around which people gather and around which space is organized. They become spaces of exchange and consumption. Kitchens and dining rooms can be organized around the dining table, while meeting rooms are often organized around the conference table, and many living spaces are organized around the coffee table. The space of the table performs two complimentary tasks simultaneously: bringing people together to promote intimacy, and holding them just enough apart to ensure security and personal space. At the same time, physical spaces have long been inscribed with virtualities. The stained glass depictions of gothic cathedrals and the figural statues of Greek gods around temples were constructed to remind us that the physical realm of matter has always been explicitly intertwined with the virtuality of the Meta world. Yet in our increasingly digitally connected world, the physical materiality of the built environment recedes when we dive into digital spaces through the limited set of interaction portals available today (desktop PCs, mobile devices). While an increasing number of research areas seek to better bridge the physical and digital spaces (e.g. tangible user interfaces, ubiquitous computing, interactive surfaces), the efforts remain largely driven by the need to find better methods for accessing and interacting with digital information (i.e. by the technological constructs).

The work described in this paper addresses the separation between the physical/digital realms from a different perspective, by engaging the skills and knowledge from fields of design that are related to the human and social use of media and architectural spaces. Instead of foregrounding the creation of interfaces and devices that map onto and access digital information, we equally explore when and how digital and computational media can be drawn back into the physical environment and built architectures. This can in parallel inform the design of the digital systems that underlie these physical and social spaces. We refer to this approach as physical/digital co-design.

As our first experiment in physical/digital co-design, we have selected an area of focus: narrative experiences around tables. Digital storytelling tabletops are a starting point for two reasons. First, they build on a long history of tables as physical and social constructs that can engage people in shared informal storytelling in both work and play. Second, they relate to our shared expertise in designing and constructing tabletop storytelling systems. Architales is an interactive table for shared story engagement that draws on

a specific social situation and setting: conversational public/transitional spaces. The piece was designed for gallery exhibition through a process of physical/digital co-design in which the design of the table, environment, tangible storytelling system, and story content evolved together. This experimental work has served as a means to better understand the process of physical/digital co-design and resulting user experience. In this paper, we begin with a brief look at related and inspirational work in storied physical design, and tabletop and tangible storytelling. Next, we provide an overview of the Architales piece and a description of the design process across the physical, digital and thematic aspects of the project. Finally, we discuss our observations from a gallery exhibition of the piece, and conclude with lessons learned about the design process and physical/digital artworks.

RELATED WORK

Recent years have seen a growing interest in tabletop computing. Researchers are developing novel sensing approaches, interaction techniques and applications for multi-user tabletop systems. Interaction methods include both multi-touch and tangible object tracking, and make use of different technologies such as computer vision, acoustic ranging or electromagnetic sensing. Applications range across media browsing, gaming, information visualization, children's learning, musical performance and many more. We provide a brief overview of research and design in two areas: the design of physical tables that evoke, inspire or support various forms of narrative experiences, and tabletop and tangible media systems for storytelling.

Storied Physical Design

Tables are physical products, more specifically pieces of furniture with smooth flat tops usually supported by one or more vertical legs. Although there are different types of tables, e.g. picnic tables, dining tables, coffee tables, working tables, bar tables, etc., they all share one common physical component: a surface. Yet, tables are also artifacts where people perform activities. To think about a typology of tables is to think about a typology of activities performed around them. Tables facilitate connections: physical connections through forms and materials, and social connections through interactions of people around them. Tables are a symbiosis of form, function and experience where people connect visually, functionally and socially.

Tables tell us stories through their physical characteristics: height, shape, legs, size, location, arrangement and materials. For example, tables from ancient Rome were low enough to serve as couches, while more recent types are higher to accommodate chairs. Four-legged tables have predominated ever since ancient Egypt, although Greek and roman tables were often slab-sided, in the manner of altars [2]. The history of table design has been closely linked to architecture, for example, avant-garde architects formulated new concepts of space that shaped how furniture was conceived. Art Nouveau tables, such as the furniture of Louis Majorelle, were designed to reference the natural world but geometrically idealized, as a type of domestic nature. Table legs were shaped as dynamic elastic forms. In the Arts and Crafts work of Frank Lloyd Wright, tables echo the story of built structures from natural materials (stone, brick and wood) designed to accentuate the natural beauty of the surroundings, forming a voice for “organic architecture”. This can be seen in Wright’s Robie House (1908), which features a cantilever design that extends from the table. Charles Mackintosh designed objects around a table (a chair) that was tall enough to create a private space within a space around the table; he worked on symbolism and balancing opposites. In modernism, George Nelson's focus was to treat furniture as sculpture, attending to the part-to-whole process to do much more with much less. His table designs create space within spaces, especially in his desk designs with organized storage. Currently, Gateano Pesce, Zaha Hadid and Frank Gehry propose furniture designs that reflect the deconstructionism movement, where furniture is conceived as a liberation of expression, exploring the idea of “performance design” with new production materials and techniques.

Many tables designed in the past tell us stories about art movements and industrial progress. Today, with the impact of technologies, the way tables and objects around tables are conceived has changed: information physically and functionally shapes the way we interact with product(s). For example, Hyun-Yeul Lee proposes an approach to design thinking that extends the praxis of form and function to include the expression of time [9]. Her bench is instrumented with sensors to continuously capture the passage of time in an audio stream, adding aesthetic and cultural value – a "storiedness" – to the object. Pieces such as the Drift Table and History Tablecloth challenge the traditional design view that electronic domestic products should be purely utilitarian, instead encouraging ludic activities such as reflection, daydreaming, curiosity and play [3, 5]. In interactive arts, recent books such as *4DSpace* explore how emerging practices in interactive architecture transform the built environment by blurring the boundaries between work, play, and digital information [4].

As such, to design a table is to design behaviors. Beyond matters of function and structure, the fundamental worth of tables in the present lies in their rhetorical properties, the communication of meanings, attitudes and values, the experience they embody and facilitate. Using this interpretive lens, tables can be designed as the product of ourselves, with a purpose that shapes us physically and emotionally. As our ideas change, so does the design of tables – in expressing individuality, community, and, especially as technology becomes a vehicle for tangible interactions, in establishing frames for social interaction.

Tabletop and Tangible Storytelling

A number of digital storytelling applications make use of emerging tangible and tabletop interaction technologies to

enable interactive story experiences for multiple co-located users. Some examples include Tangible Viewpoints and Tangible Spatial Narratives, which made use of tagged pawns and other physical objects (e.g. selection device, time tool) to navigate multi-viewpoint and spatially structured stories on a tabletop display [11]. These systems demonstrated that digital tables can serve not only to display stories, but also to incite informal storytelling, since users weave their own improvised stories as they interact with the digital content that is visually represented on the table's surface. Another example of this is StoryMat, a children's play mat that acts as a storytelling partner by recording and later re-playing the stories that children tell as they play on its surface [14]. When later children hear and see past stories revive on the mat, they incorporate them into their own storytelling play. Improvisational storytelling is also common in traditional role-playing games, which are often played around a table, on which physical artifacts (e.g. pen, paper, figurines, dice) are used to progress the story. Some researchers have also combined traditional role-playing games with newer digital forms using digital tabletops with tangible interaction [10, 12].

In museums and galleries, digital tabletops have been used to provide engaging, informative and "storied" experiences for visitors. For example, the Un-Private House exhibition at the Museum of Modern Art in New York included an interactive table that presented information associated with the different houses featured in the exhibition [13]. The table used both tangible artifacts (tagged coasters) and touch interaction for navigating through a series of floor plans, photos and other media related to the featured houses. The Dialog table, commissioned by the Walker Art Center, provided similar social learning experiences through digital media storytelling, by creating links between disciplines, ideas and art works in the museum's collections [16]. In this case, the table used gesture-based interactions for content navigation. Another kind of tabletop story experience was showcased at the Experiments in the Future of Reading exhibition, in the form a tilting table covered with nonsense fairy tales. As users tilted the tabletop, they moved through the space of words, creating trails through a seemingly infinite plane of stories [6].

An increasing number of researchers have also been developing applications for media asset management on shared tabletop displays, e.g. browsing and visualization of photo, video and audio collections. Tabletop navigation of personal media affords informal storytelling, since we browse photos primarily to recall and share our experiences with others. Examples include the Personal Digital Historian on the DiamondTouch [15] and the SharePic photo sharing application for the elderly [1]. Both use mutli-touch interaction. An example that uses tangible interaction is Photohelix, which displays digital images on a helix-shaped timeline around a rotating physical handle [7].

The Architales project builds on past work on tabletop storytelling and media browsing, extending it to explore how stories can be expressed and experienced not only through digital media content on (and user interactions around) a tabletop display, but also through the design of the physical table, its environment and the interactive tangible artifacts that are manipulated on its surface.

Figure 1. Architales at a public gallery exhibition.

ARCHITALES PHYSICAL/DIGITAL CO-DESIGN

Architales is an interactive story table that encompasses shared engagement with cinematically-inspired narrative expressions that unfold on its surface and throughout its space. The piece is designed for public transient spaces, so the physical structure is designed to evoke the interest of the passing user, and the digital applications are designed for short interactive experiences around the tabletop. Users first experience the broad story themes and concepts as they approach the piece, through the physical form of the table and surrounding space. The physical structure invites users to its center, where they can dive into the digital story material through tangible and touch interactions on the surface of the rear-projected tabletop display (see Figure 1).

The piece was designed in an interdisciplinary research and studio class across the architecture, industrial design and digital media departments at Georgia Tech in spring 2008. The goal of the class was to create a compelling tabletop story experience by combining design and engineering techniques and technologies from architecture (tables and spaces) with digital and tangible media forms (computation, content and visual arts). Students were challenged to re-mediate content from the documentary film *Fast, Cheap and Out of Control* (Errol Morris, 1997). The film investigates the lives and philosophies of four characters: a mole rat expert, a robotics engineer, a lion tamer and a topiary gardener. It was selected for its thematic and visually evocative nature, and for its multi-threaded and layered story structure that weaves together the stories of the four characters and their shared themes. Through the process of physical/digital co-design, our goal was to explore how this threaded and layered story with different characters and shared themes could be evoked both in the physical structure of the table and environment, and in the design of the digital applications and content.

Students in the class worked together in teams of nine, each comprised of students from the different disciplines: digital media and human-computer interaction, industrial design, and architecture. Each team was asked to develop a unified

concept for the piece, including both the physical table and environment and the tangible story application design. The process of physical/digital co-design was iterative, and the design of physical, digital and storied components informed each other from concept generation to production. This involved exploring the film's themes, structure, and visual content, and reshaping it for tabletop and tangible delivery, in a form that could be simultaneously reflected through the physical design of the table and environment.

A midterm design competition with an external jury panel selected the best designs, and the second half of the semester was devoted to production of a final concept that merged the best designs. The two selected design concepts were based on the threaded and layered structure of the story respectively. At this stage, the architecture and industrial design students from each team came together to produce the final (physical) concept, while the digital media and human-computer interaction students finalized the development of the two (threaded and layered) tangible story applications. The final piece with both threaded and layered story applications was showcased at an art gallery exhibition at the end of the semester.

The following section provides an overview of the hardware and software technology. Next we describe how the design process evolved the form of the tangible story, table and environment in two concepts: threads and layers. We then describe how these concepts came together in the realization of the final piece.

Technology and Design Constraints

A key design requirement for the Architales interactive table was to enable the tracking of multiple objects and fingertips, since we anticipated up to six users interacting with content at a time through touch or tangible interaction. The working area of the tabletop thus needed to be around 50 inches in size. We chose computer vision to realize this goal within our budget, making use of reacTIVision for image processing and data interpretation [8]. reacTIVision uses the TUIO protocol, based on Open Sound Control (OSC), allowing for easy communication with application-level software. It also provides a library of unique fiducial markers that can be affixed to the base of tangible objects, in addition to fingertip detection routines. On our table, the fiducial markers are 3 inches in size. Students needed to take this size constraint into account in the design of their tangible story interaction objects. The constraint suited the goal of the piece, since the tangible objects could be designed to fit comfortably in an adult hand.

Each tangible story application required an underlying computational story engine to communicate both with the sensing technology in the table, and with a database of audiovisual story content and meta-data. The story engine is coupled with a graphical interface on the tabletop display. Together, the story engine and interface serve to organize the unfolding story through the display of video, audio and imagery based on real-time user interactions. The two story applications both picked up on common thematic elements across the four character stories, yet chose to express them using two different organizational and navigational principles: threads and layers. The first application was developed in Flash/Actionscript, and the second in XNA.

Threaded Concept

The first concept is based on the multi-threaded structure of the film. As the film progresses, the stories of the four characters become increasingly intertwined, evoking the idea of weaving threads. The concept extends the notion of threads across both the physical design of the table and environment, and the interactive and visual design of the tangible story application.

Working as an interdisciplinary team, students generated a series of variations on both the physical and digital designs that explored different ways to unite the two components. The variations played with the idea that the four threads weaving through the physical space would be visually continued in the digital interface design on the tabletop. The four story threads were thus envisioned as four separate pieces of material that weaved around the table and formed a roof overhead. These physical threads were continued in the digital interface as ribbons that connect different story fragments that participants bring up on the table through tangible interactions (see Figure 2).

Figure 2. In this concept, threads representing the story structure weave through the physical space (left) and are picked up as digital ribbons on the tabletop (right).

Four tangible story objects represent the four characters, and their forms evoke their different professions and passions, e.g. the lion tamer's object is reminiscent of the circus tents where many of his scenes take place. These objects are used like physical stamps, with which users leave digital marks of the different characters on the tabletop (e.g. a lion's head for the lion tamer). As more and more marks are left on the table, the colored ribbon-like threads spread from these digital marks, visually connecting the different story pieces. At the same time, the digital threads and tabletop user interactions are mirrored in the surfaces that form threads in the physical space, as these were envisioned to be constructed from reflective materials.

The story material is segmented into short video clips for each character, and the stamping action controls video play-out in a circular window at the table's center, which can be re-oriented using finger touches. Together, multiple users can mix and match the stamping of different objects in

order to see how the stories of the four characters interact. A fifth tangible object is a large global modifier wheel, which can be rolled onto the table at any time. Each side destabilizes the story in some way, so a user holding the lion tamer's stamp might suddenly find they are stamping flowers for the topiary gardener. The users' experience thus mirrors the experience of the story characters, who at times experience not only intense love, but also frustration as they struggle to master their respective passions.

Layered Concept

The second concept is based on movement between the four character layers in the story. The layers reflect and mirror each other, and users must explore each one separately, but also find ways to move fluidly between them in order to draw thematic connections and gain a complete experience.

As with the threaded design, students worked as an interdisciplinary team to generate variations on the concept that would unite the physical and digital components of the piece. In this case, the central idea was to create layers in the physical space represented by surfaces of different heights, and users could sit or stand on these different surfaces to gain different perspectives on the digital experience on the tabletop. This layered physical design is reflected in a digital design in which tangible objects are used to move between layers representing the four characters in the story (see Figure 3).

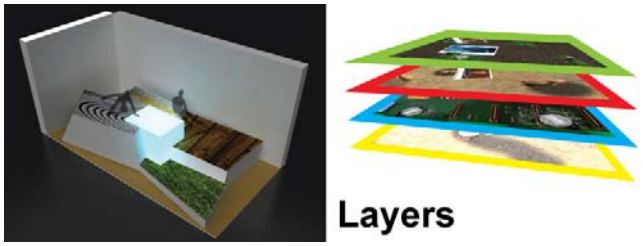

Figure 3. In this concept, the story layers form different surfaces in the physical space (left) and different digital levels that users must move between on the table (right).

The surface of the table provides a different visual backdrop (or ground) for each character's story, e.g. the light sandy ground of a mole rat tunnel, the dark earth of a topiary garden. These four digital grounds are mirrored in the different materials used to compose the physical surfaces in the space. Hidden within the ground of each layer are different media pieces from the corresponding character's story. Users must discover these media pieces using a set of identical clear plastic tangible objects. Drawing inspiration from the themes of passion for and control of different creatures, the tangible objects are all shaped like collars with grips on the sides.

When placed on a layer, the tangible collars grab and hold the digital creature corresponding to that character's story: mole rat, robot, lion or animal-shaped hedge. Through quick movements and rotations of the collar, users cause their animals to make actions that uncover media pieces in the ground. The mole rat and lion both dig in the sand, while the robot burns marks on the surface of a giant circuit board, and the hedge plants flowers in a garden. As users uncover the media pieces hidden on each layer, they see and hear segments from the story. Each layer also contains hidden portals that lead to other layers, allowing users to make connections between the four characters and their separate yet mirrored experiences.

Final Concept: Threads and Layers Merged

The final concept unites the core story structures of threads and layers. The piece is thus realized as a formal, functional and social response of intertwined cinematic narrative expressions. Users can connect visually, functionally and socially through the concept design. The story form is first experienced in the physical form of the environment and table, and then picked up again in the tangible story interactions that unfold on the table's surface.

For the final construction, the physical concept is broken down into separate modules. This modular concept emerged as an important design goal for two reasons. From the user experience perspective, it allows the user to navigate the space, experiencing different types of interactions (with the physical piece, the story, and other users), which come together to shape their overall experience of the work. From the product manufacturing and transportation perspective, modularity allows the table to be easily (re)produced, moved and set up in different venues. This modular design can also enable different configurations of the physical table and space. Architales was produced in GE Lexan Polycarbonate, a plastic material with a unique combination of high impact strength and flame retardancy, and China Birch plywood for structural support. It was prototyped at the Advanced Wood Products Laboratory at Georgia Tech.

The final physical piece is based on the formal geometry of a mobius strip, a normal surface with only one side and only one boundary component with a full twist that joins the ends, making a continuous loop. As such, the geometry represents the continuity of story creation based on user interactions, and reflects both the idea of threads (in the way it weaves through the space) and layers (in the way it gives the illusion of having different sides). Visually, Architales thus tells the story of four characters represented in formal bands traveling though the space with independent as well shared behaviors (see Figure 4). The bands continuously move as single bands to represent individual stories (point 1); they navigate side by side to represent the parallel perspective of the characters (point 2); they converge into unified stories reflected by the interactive table (point 3); they overlap in pairs, functionally creating seating devices, to represent how sound and visual creates the shared meanings (point 4); they converge into a single band to represented the shared narrative mirrored by the roof (point 5); the single band travels through the table creating another seating device for achieving a different perspective of the content (point 6);

and ends at the interactive table to represent two complementary behaviors: bringing stories together and promoting independence of input (point 7).

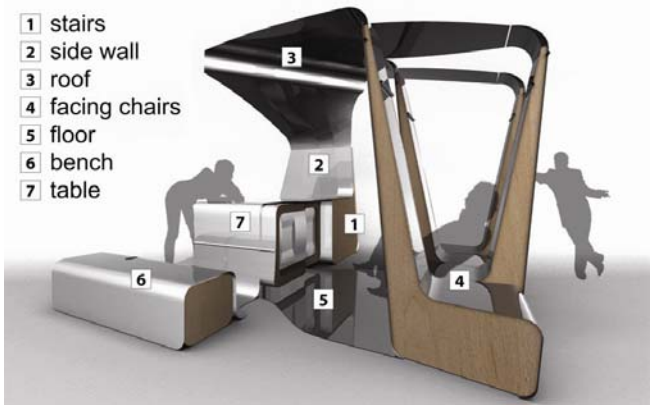

Figure 4. 3D rendering of the final layered and threaded concept for Architales which reflects a modular design.

From a user-centered perspective, people can navigate and experience different relationships with the table, environment and other users as they move through the different modules. As such, people can experience a variety of shared collaborations and conversations with the table and other users, mediated by objects in the environment. The central module of the Architales piece is the table itself (point 7), with its display and interaction surface. The table is standing height and can be approached from any side. However different sides support different experiences. For example, on one side the bands form steps that lead to a high seating platform at the table. By providing a place for users to seat themselves around the table, the short transitory interactions with the digital content that happen while standing can extend into longer seated interactions. Also, since only one user can be seated at a time, they often stay at the table longer than others, and are able to convey the story experience to newcomers who approach the table and draw them into an ongoing interaction. As they step back from the table, people can sit on the facing chairs (point 4) to talk about their experiences with the installation, and contemplate the reflections created by the plastic. Lastly, the bench (point 6) offers an opportunity for people to sit back and achieve an overview experience.

Overall, Architales is a poetic response with light dynamic spatial forms and reflective materials. It is a digital and physical co-design where people can engage holistically in an immersive relationship of time and space.

GALLERY EXHIBITION

Architales was shown at Listening Machines 2008 at the Eyedrum Gallery in Atlanta, GA. The show provided an opportunity to exhibit the piece as an artwork, while simultaneously testing our ideas about physical/digital co-design in a real-world public space. The show lasted for one full evening, with over 200 visitors. Architales was set up in the front gallery room, its physical features accentuated with colored lights in the darkened space. Since all visitors passed through this room to see other musical and installation pieces, it served as an ideal transitional space.

Our goal was to create a unified experience of the story through both the physical and digital aspects of the piece. We thus provide our observations of the gallery event as they relate to this goal. In particular, we discuss the interaction flow between the physical and digital spaces, and the way story exploration took place in the physical space and through tangible interactions on the tabletop.

Physical/Digital Interaction Flow

Visitors were clearly intrigued and attracted by the physical structure of Architales. They approached the piece to study its contours, typically circulating around the table and looking at the different areas of the environment. The flow of interest generally proceeded as follows: looking at the environment (sometimes making use of the seating areas for casual conversation), studying the interactions of others at the table, moving into a central position in order to interact at the table, and finally stepping back to let others approach the table. The flow thus transitioned seamlessly from the physical space, to the digital space, and back again to the physical space. Visitors typically spent 5-10 minutes interacting at the table, but we also observed people interact for less than 5 minutes, and a number of visitors remained engaged for over 30 minutes.

The different areas of the piece generally fulfilled their intended function and shaped the experience with the table and story material. For example, we observed people leave the table and seat themselves in the facing configuration to casually discuss their experience with the piece. People used the stairs to watch and interpret the action on the table. We observed that people seated on the top step would draw newcomers into an ongoing interaction, serving as narrators to explain the story to others, and thus extending the experience across smaller transitional groups. In this way, the steps leading to the table incited longer interactions at the table. We also noticed that people would rotate through this seated position. As one person left, someone standing would take their place and assume the role of narrator for the next group of people who approached the table. This suggests that fixed seating devices can be used to shape the experience and time spent around the table, as well as the roles of the people who make use of them.

Physical/Digital Story Exploration

Visitors who approached the piece actively engaged themselves in discovering the story in both physical and digital form. While the physical structure was evocative of the story structure, there were no clear references to specific story material in the physical space. As a result, we found that visitors tended to speculate about the story as they explored the physical space, but were only truly able to draw connections to characters and themes when they approached the digital table. Since we had two tangible

story applications, we featured them in shifts throughout the evening. No explicit instructions were given to visitors, but researchers involved in the design seeded the digital interactions by launching the applications and beginning to interact with the content. Visitors thus discovered the tangible interactions through a combination of observation (looking at others interacting) and exploration (improvising new interactions on their own). Figure 5 shows users interacting with the layered application on the table.

Figure 5. Participants dig for media objects using tangible collars on digital mole rats in the layered story.

Two things would have reinforced story exploration in the physical space: better visual feedback of the digital material into the physical space, and better use of lighting and audio throughout the space. The visual feedback was limited in part due to the fact that the roof was not completed in time for the exhibition. As a result, the reflections of the tabletop digital materials onto the physical surfaces were not as prominent as envisioned. Also, while the video clips in the tangible story applications had accompanying audio, it was difficult to hear due to the noise level in the crowded exhibition space. Four speakers located in the corners of the table were the only output for audio associated with the clips playing on the table's surface. Distributing additional speakers throughout the physical environment would have strengthened the connection between the story material and the physical space. Lighting was added to the physical environment to illuminate the physical structure in the dark gallery space. In the future, we would like to incorporate dynamic lighting that would reflect the colors and visuals shown on the surface of the table, in order to further connect the physical and digital spaces.

LESSONS LEARNED

We summarize the outcomes of our experiment in physical/digital co-design from two perspectives: lessons learned from the interdisciplinary co-design process, and lessons learned from the exhibition of the resulting physical/digital artwork.

Co-Design Process

Successful physical/digital co-design necessitates a balanced interdisciplinary design process across disciplines, in which skills are shared rather than distributed and the end-to-end design process across the different parts is connected rather than merely concurrent.

• ***Balance*****:** We found that an important basis for co-design is to form teams that are balanced across all the disciplines involved. Additionally, teams need to have strong voices (managers and decision makers) across each discipline, otherwise one component risks overshadowing the others. In our case, the teams with the strongest concepts by the midterm were those that worked most closely across disciplines in the early stages of the project.

• ***Sharing*****:** We found that it is important to encourage skill sharing across disciplines. One way to do this is through a series of start-up exercises in which physical designers work with digital designs and technologies, while digital designers and technologists work with physical forms and materials. This ensures fluidity at later stages, since iterative design variations can more easily shift the physical and digital components in synchrony. Although this probably requires a longer timeline (i.e. more than one semester) for a project, in our future co-design experiments we would like to emphasize this sharing of skills particularly in the early stages of the project.

• ***Connectedness*****:** To achieve an end product that is balanced across both its physical and digital components, it is crucial to maintain a closely coupled design process from beginning to end. Our project was least successful in this respect. In the second phase of project, the architecture and industrial design students separated from the digital media and human-computer interaction students. The former worked on the construction of the table and environment in the wood products laboratory, while the latter worked on the tangible application development in the computer laboratory. It was partly due to this separation that the story exploration was not as effectively mirrored across both the physical and digital spaces as it could have been.

Physical/Digital Artwork

Artworks that seek to provide a transitory experience that immerses visitors in both physical and digital constructs need to weigh the balance of these components, and create appropriate flow and pacing of content expressions and interactions across the physical and digital spaces.

• ***Balance*****:** Our experience highlighted the importance of balancing the physical, digital and thematic constructs to create a seamless experience. In our case, the two tangible applications were featured in shifts, which created an imbalance in the physical and digital experience of threads and layers. While both structures were ever-present in the physical environment, each application privileged one concept over the other. In future versions, we thus hope to merge the two concepts in a single digital application. With respect to balance, it is also important to note that the physical and digital do not necessarily need to mirror each

other exactly, but can serve complementary roles in the way the underlying themes of the piece are evoked.

• ***Flow*:** We found that in order to convey a unified vision, the flow of both content and interactions between the physical and digital needs to be bi-directional. In our piece, the physical form and experience were reflected into the digital designs on the tabletop. Participants observed the threads and layers in the space, and saw these themes picked up in their interactions with the digital story materials at the tabletop. However we did not fully succeed in reflecting the story and digital interactions into the physical space, e.g. through reflections, sound and lighting as described above. As a result, participants were not as easily able to draw a connection with the story themes from the physical experience. Architales also demonstrated how fixed structures in the space can provide cues on how visitors should approach and experience the piece.

• ***Pace*:** We found that the pacing of story expressions and interactions across physical and digital space is crucial to engaging participants in public and transient spaces. Although stories with thematic depth and complexity are often difficult to convey in short timeframes, the structure of the physical space and digital content can help to both guide participants through the experience and define the interactions that take place. The design of architecture and furniture has long been used to structure human interactions in social spaces, and these concepts can be further extended into the digital realm. Similarly, the digital content needs to be paced in a way to capture audience interest within short periods of time. In our case, the feature length film that provided a starting point for the piece needed to be remediated into short audiovisual fragments that could weave into an ongoing expression that was experienced by visitors in a primarily transitory manner.

CONCLUSION

Designers in many fields, including architecture, industrial design, and media arts, seek depth and richness of poetic expression and participant experience. We believe the physical/digital co-design approach can be extended and generalized to other application areas and contexts, for example to the design of educational systems for shared discovery, and to multimodal experiences where the surrounding environment can be used to shape and enhance the experience at the table. We have documented our experience with the hope that it will inspire others in the tangible interaction community to practice the co-design of physical and digital applications.

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