The Digital Dream Lab: Tabletop Puzzle Blocks for Exploring Programmatic Concepts

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ABSTRACT

Tangible interaction links digital data with physical forms to support embodied use. Puzzle pieces, which their inherent physical syntax of connectable elements, provide a powerful and expressive metaphor on which to construct such tangible systems. Prior work has explored this potential in the domain of edutainment systems for children aimed at tasks such as learning logic, programming or organizational skills. Although this work is promising, it has largely focused on relatively advanced concepts and children of ages 7-12 years. The work presented in this paper adopts the same perspective but focuses on young children (5 and under) and a simpler range of concepts relating to the clustering and manipulation of data. To achieve this it presents the design (including results from a series of six formative field studies) and implementation of the Digital Dream Lab tabletop puzzle block system. This system, intended for installation in a museum, engages young children (aged 4-5) to explore simple programmatic concepts and the link between the physical and virtual world. The paper closes with design recommendations of future work targeting this goal, setting and age group.

Author Keywords

Tangible programming, museum, tabletop, design, children.

ACM Classification Keywords

H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION

Tangible systems meaningfully pair digital contents with the form and manipulation of physical objects - bits are rendered directly accessible through partnership with graspable, physical atoms [12]. This idea is compelling and tangible interaction is now an established field of research and design practice focused on the implementations, implications and possibilities of interacting with computationally enhanced objects in the physical world [9].

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One area in which tangible interaction has shown considerable promise is in facilitating problem solving, planning, and simulation tasks. Such activities are well matched to educational scenarios and, indeed, many tangible systems are designed to support learning [21]. Particularly in young children, a key motivation has been to take advantage of central role of physicality in cognitive development [17]. It has also been argued that tangible systems are more inviting, understandable and supportive of active participation than purely graphical interfaces [7].

Despite these advantages, many questions about the value of this interface paradigm remain. Specifically, although the benefits of tangible interaction for very young children (five and below) are conceptually clear, the details of how to design for this demographic have received less attention [15]. For instance, young children are reported to experience fundamental difficulties performing physical interactions (such as fine object manipulations) [14] and also confusion regarding what actions can be meaningfully sensed by tangible systems (e.g. object movements on a tabletop surface, but not above it). Reflecting these problems, existing interface metaphors for this age group are highly simplistic – for example tying the presence or absence of physical objects to the presence or absence of digital counterparts [e.g. 15]. It is not currently clear how these metaphors can be meaningfully extended to express more sophisticated or abstract concepts to young children.

This paper argues that one candidate solution, already a recurring theme in tangible systems aimed at older users, is to develop systems based on digitally tracked jigsaw puzzles pieces [1, 7, 22]. This metaphor has proven popular for a number of reasons. Firstly, physical puzzles represent powerful tools for developing logic and organization skills - while completing puzzles, children manipulate physical objects to build spatial relations but also develop cognitive skills for interpreting and planning these prospective configurations [22]. Furthermore, the constrained forms of puzzle pieces express the rules by which items can be combined and reduce the need for explicit instructions. Finally, the act of manipulating puzzle blocks on a tabletop surface allows and invites children to collaborate playfully while keeping the underlying technology firmly in the background [4, 8].

Inspired by these observations, this paper presents the Digital Dream Lab tabletop puzzle block system, a prototype that exposes young children to simple programming concepts in order to develop basic logic and computational thinking skills. In contrast to prior work [e.g. 7, 20], the DDL focuses on conveying concepts relating to how information can be clustered and manipulated rather than on creating sequences of commands or behaviors. The project was developed for the MakeShop space within Children's Museum of Pittsburgh, a hands-on workshop environment that provides raw materials for children to learn making skills through small hands-on projects. The target demographic for the project was four to five year old children with limited reading and writing skills. The initial brief was to allow children to engage in a creative activity that would expose them to programming concepts and highlight links between the physical and the virtual world.

This paper is a design case study that reflects these constraints. Its core contribution is in exploring the design of an educational tangible system for very young children. Specific foci that compliment and extend prior work are: on tailoring the system to be engaging and understandable for four to five year olds; on maintaining a focus on hands-on creative activity and; on expressing abstract programmatic concepts. An intensive iterative design process involving six field studies conducted with children in the museum space and involving systems prototypes of various fidelities was conducted in order to support these objectives. The remainder of this paper is structured as follows: relevant literature is reviewed; the DDL is introduced; the design process and system are described; design recommendations and directions for future work are presented.

RELEVANT WORK

Using modular tangible tokens that sit, click or snap together to express programmatic concepts is an established idea. For example, Siftables [16] are small programmable blocks featuring a screen and capable of determining when they are placed next to one another. Applications include music tools that enable users to compose songs by arranging the blocks in specific spatial configurations. Similarly, Topobo [18] explores programming robotic movement by demonstration - multiple pivoting pieces are connected, movements are entered by twisting the pieces and then endlessly replayed by the system. Combinations of recorded movements can result in rich and sophisticated behaviors. Also in the domain of robotics, roBlocks (or "cubelets") [20] allow their users to snap together a sequence of physical cubes, each with a different ability or behavior. By connecting these components complex, dynamically reacting robots can be simply constructed. Jigsaw and puzzle pieces have been employed to achieve similar results - basically the construction of sequential algorithms through the configuration of physical tokens. Tern [6, 7] is a prominent example that has been shown to increase children's engagement with programming tasks compared to analogous visual alternatives. It employs tangible user interface technology to allow teachers to conduct in-class programming activities away from the complexity of desktop computers and environments. Much of this work has been inspired by Scratch [19] a fully virtual system that provides a playful graphical interface to support programming tasks by dragging, connecting and positioning blocks. Inspired by this prior work, this paper seeks to explore how a puzzle piece metaphor can be used to represent concepts underlying information, and the storage and manipulation of that information, in programming tasks. To the best of our knowledge this approach and perspective are novel.

THE DIGITAL DREAM LAB

The DDL hardware platform is an interactive tabletop (42" wide by 32" long by 25" high) on which multiple physical blocks can be placed. The bases of these blocks are tagged with ReacTIVision [13] fiducial markers and a camera situated under the table is able to detect these in order to infer piece identity, position and orientation. The tabletop is located in front of a wall and all graphical content relating to the system is projected on to this vertical surface (58" by 44" display size). The Unity 3D game engine is used to render the graphics. Design considerations that impacted the selection of this system configuration were its cost-effectiveness, robustness and reliability, its immunity to occlusions (either of the fiducials by the users or of the digital content by the physical tokens) and its scope for supporting collaboration and the multiple blocks necessary for a puzzle-inspired interface.

The central concept underpinning the DDL is the use of physical puzzle pieces to instantiate and manipulate virtual characters shown on the projected display. This extends prior work (e.g. Marco et al. [15]) that associates the presence and position of virtual characters with that of tangible tokens. Specifically, it moves beyond these past efforts in its consideration of how a puzzle piece metaphor can be leveraged to create richer and more sophisticated mappings and relationships between and among the virtual contents and physical tokens.

Iterative Design and Formative User Studies

In order to define, inform and refine the DDL, six user tests were conducted at the Makeshop space of the Children's Museum of Pittsburgh. This reflects recent research highlighting the importance of on-site testing for museum installations [10]. The goal was to understand how physical puzzle pieces could be designed to easily afford use by young children and to explore how such objects could be created to engagingly convey programmatic concepts. Each of the tests closely followed the target user demographic and involved between 20 and 50 children of between 3 and 12 years of age. Considering that young children primarily visit the museum with family or kindergarten and school groups, the studies also engaged parents, museum staff and older children (6-12 years). All sessions took place during regular museum visits and focused on direct observation of users and (if they agreed to sign a consent form) documentation using photographs and videos (see Figure 1 for examples). Each session lasted approximately three hours. During all the studies, the children were actively considered as co-inventors and design partners [3]. This perspective was intended to allow them to express their opinions freely and confidently.

The user tests were iterative; the output and observations from one session were integrated into refined system designs before the next based on subjective assessments of validity and effectiveness for our target audience. A number of core themes emerged and are discussed below:

Conveying Concepts: The DDL experience was designed to convey a range of concepts to young children. Most fundamentally, it needed to express the link between manipulations of the puzzle pieces and the on-screen content. Unsurprisingly, the studies showed that this was best achieved via a tight coupling of the physical and virtual contents (as noted in [15]). However, the studies also stressed the value of visibility of the underlying working principles of the system. Throughout the studies, children frequently flipped, turned and tossed the tokens to investigate their function. By including prominent fiducial markers on the tokens and using a tabletop with transparent windows, we were able to provide opportunities for the children to infer the system's operating principles without engaging in these extra exploratory behaviors. For instance, the windows enabled children to peer into the table to understand that there was a camera underneath. By combining this openness with a small displaying showing the raw images captured by the camera (see Figure 2), we were able to increase children's comprehension of the system's operating principles: sensing particular types of image (fiducials) only when they are resting on its surface. Based on these experiences, we suggest that this kind of explicit exposure of mechanisms can improve the walk-up usability of tangible systems for young children. In the DDL, this process was possibly facilitated by the widespread deployment of optical tracking technology in other situations (e.g. barcodes, QR codes) - children may have prior exposure to similar types of system.

At a higher level, the DDL was designed to express programmatic concepts via the metaphor of a puzzle. Prior work has shown the value of this mapping in terms of constructing or connecting sequences of commands, inputs, processes or behaviors [e.g. 7, 20]. DDL, on the other hand, focused on concepts relating to the manipulation and grouping of information – fundamental ideas that underlie variables and classes in computer programming. Puzzle pieces, with large highly distinctive joints capable of either physically locking together or enclosing one another, proved a powerful mechanism to convey grouping concepts. Children readily adopted the idea that making (or breaking) physical connections led to similar ties between associated virtual data. The permanence of connection

Figure 1. Children play with DDL puzzle blocks and tabletop at the Children's Museum of Pittsburgh.

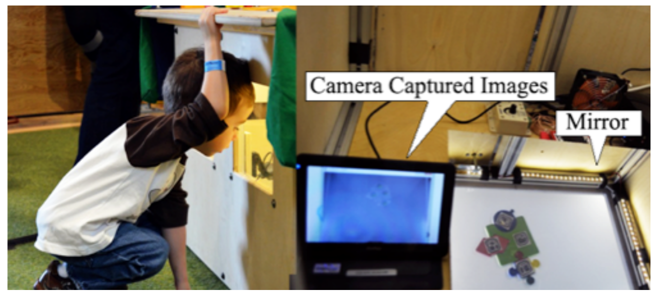

Figure 2. A boy looks into the DDL table (left). Interior of the DDL table with computer showing raw camera image, as seen through table window (right).

points that naturally and persistently snapped together clearly helped to reinforce this. Indeed, accidental connection or separation of non-physically linked pieces placed casually next to one another was highly confusing for the children. Essentially, in a system based solely on token proximity, children struggled to understand the relationships and links between the different pieces. Reflecting these observations, we suggest that using pieces that create a strong visual affordance for connection (and then subsequently physically maintain it) will be important in designing tangible token sets that young children can easily understand.

In terms of data manipulation, DDL initially explored two highly related mechanisms. These were: swapping out different puzzle pieces and altering the attachment of pieces with multiple connection points. Both of these categorical manipulations were simple and effective and children rapidly understood that, for example, attaching a differently colored piece to another would apply that attribute to the associated digital content. However, such simple representations are a poor fit for many types of data; they are discrete and support a limited set of fixed options. Consequently, in order to expand the expressivity of the system, we explored how continuous information could be integrated into a puzzle metaphor. This was achieved through the design of a circular puzzle piece featuring a single rounded protuberance. By placing this piece into a matching hemi-circular socket, the position could be maintained while the orientation of the protruding part was adjusted smoothly through 180 degrees. When used to control analogue attributes such as size, children readily understood this piece, possibly due to its resemblance to common visualizations of magnitude such as clocks and gauges. In sum, these experiences suggest that jigsaw pieces are a powerful way of conveying relationships and types of data. Theoretical constructs such as image schemas [11], which express metaphorical understandings, may be useful tools to support the future design of such mappings.

Commands and Modes: Several forms of explicit mode and command block were deployed throughout the tests. Some elicited confusion in the children. For instance, early versions of the system featured a "show me" block. This was used to separate the act of manipulating the character blocks from viewing the results of these configurations – a programmatic analogy inspired by the distinct acts of writing and compiling or executing code. Children struggled to understand this abstract relationship and manipulating puzzle blocks without immediate on-screen interactive feedback caused many children to lose interest in the system. We resolved this issue by removing the compile block entirely, so that all changes to the character blocks were immediately reflected in the projected contents. This ensured rapid graphical responses to all movements and manipulations of the tokens.

The importance of instant feedback was also noticeable in the design of a background block, a cube that could be rotated to alter the background image in the projected scene. As only one such scene could be shown at any given time, the orientation of this block (basically, which face was down) naturally mapped to this exclusive property. Furthermore, the simple dice-like affordance of the cube directly engaged the children - they visibly enjoyed tossing, rolling and throwing it around the table. The magnitude and immediacy of the changes (e.g. swapping a complete background image) contributed to this effect. From these experiences, we suggest that young children can understand modal changes in tangible systems, providing they are clearly illustrated with instant feedback and appropriately conveyed by the affordances of tokens. On the other hand, the use of more abstract commands is likely to result in confusion and disengagement. Furthermore, tokens that support playful manipulations (such as rolling or throwing) can also encourage and promote engagement.

Narrative Content: The studies also revealed that children's engagement and creativity was fostered by content that encouraged and supported them in developing their own narrative material. Recurring themes involved specific characters moving to specific locations to perform specific actions. Essentially this involved specifying whom (via tokens relating to the identity and appearance of characters), what (via tokens indicating activities), and where (via the background block). Content that supported these simple storytelling aids, basically providing an easily accessible range of characters, sites and activities that the children could explore, was enthusiastically received. It was also observed to support collaboration, with children adopting different characters and miming their virtual conversations. These observations helped finalize the media developed for the DDL.

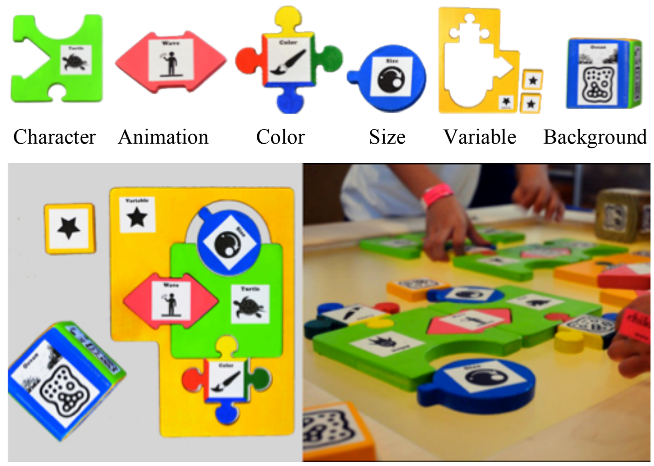

Figure 3. The six DDL puzzle elements individually (top), locked together (bottom left) and in play (bottom right).

Final System Design

The final set of puzzle elements reflected this process and these observations. It consisted of six types of piece. These are shown in Figure 3 and described as follows:

Character Block: The fundamental element of the system. There were seven different character blocks each representing a different creature (alien, chameleon, fish, frog, octopus, parrot and turtle) and iconic pictures situated on the top surface of the blocks were used to indicate this association. Placing a character block on the tabletop caused an animated version (showing a minimal "idle" movement pattern) to appear in an associated position on the projected display; moving or rotating the block caused the character to follow the movement and rotation in 3D graphic. The character blocks also featured prominent physical attachment points for the three different types of attribute block described below.

Animation Block: There were three forms of this categorical attribute block: walking, jumping and waving. The blocks were physically identical and the different actions indicated by graphical icons. Each of these blocks could be physically connected to any character block in order to have the associated graphical figure mime the depicted action. The block was also designed (as a bi-headed arrow) so that it could be simultaneously connected to a pair of adjacent character blocks in order to have them perform the same action together.

Color Block: All color attribute blocks took the same form, based on a classic jigsaw piece with four extruded tabs. Each tab was a different color and by connecting a specific tab to the relevant point on a character block, the associated virtual creature took on a texture of the same color. As with the animation block, the data represented by this block was categorical, but all values could be realized with every puzzle piece.

Size Block: All size attribute blocks were identical. Based on a circular shape with a single short handle (a form that resembles an analogue gauge) they could be placed in a hemispherical depression in each character block. Adjusting the orientation of the handle clockwise or anti-clockwise caused the size of the associated virtual creature to grow or shrink. The data represented by this puzzle piece was a single analogue attribute.

Variable Blocks: These blocks were designed to express the programmatic concepts of classes, instances and variables. There were two related piece types. Firstly, a *component* block that could physically surround and encapsulate a full set of character and attribute blocks. The system included two of these blocks, differentiated by abstract symbol (a star and a circle) on their upper surface. Each component block was associated with two small *instance* blocks marked with the same abstract symbols. If a component block was in play, placing an associated instance block on the tabletop caused an exact duplicate of the virtual character to appear at the location of the instance block. Multiple instances could be deployed simultaneously and independently, and changing the attributes in the component block caused all duplicate characters to mimic this change. This block set was designed to express the fact that information can be accumulated, collected and manipulated together and highlight the difference between data and depictions of that data.

Background Block: The background took the form of a simple cube with fiducial markers on each face. Depending on its orientation on the surface, the background image in the projection changed. Three scenes were included: park, forest and ocean. Each background included potentially interactive elements such as a moving swing seesaw, swaying flowers, waving corals or rising bubbles. These animations were activated by the proximity of the characters (e.g. placing a character next to the flowers caused them to start to sway). The background block was used to increase visual diversity and to stimulate opportunities for creativity and storytelling in the children.

Figure 4 shows the graphical content, the characters and backgrounds used in the DDL. A range of factors related to the edutainment context of this work influenced the selection and design of this material. These included the conceptual match between the characters and backgrounds (each character was selected to "be at home" in at least one background scene), whether the three possible activities were comprehensible (e.g. "jump" was visually distinct from "walk") and if the color choices appropriate and believable (e.g. no pink elephants).

DISCUSSION AND CONCLUSION

This paper presented the formative studies and design and development process that led to the Digital Dream Lab tabletop puzzle block system, a edutainment museum installation aimed at expressing programmatic concepts to children aged between four and five. The central metaphor

Figure 4. The seven characters and three backgrounds used in the DDL. Each background shows characters in context.

in the system is that of a jigsaw puzzle. This is linked conceptually to concepts such as grouping and manipulation of different types of abstract information. This design process was exploratory and a number of themes and findings emerged from this work that we believe will be valuable to future researchers and designers working in this general space. These are outlined below.

Engagement and enjoyment are pre-requisites and hallmarks of playful learning experiences [23]. This is certainly true for edutainment systems such as the DDL. In order to meet these requirements, the final DDL design incorporated a number of properties. Firstly, it emphasized continuous feedback for all sensed actions – any manipulation of the tokens was immediately reflected in the projected digital content. This responsiveness and high level of interactivity helped children both comprehend and engage with the system [2]. This approach also reflects the fact that the attention spans of young children (ages 4-6), particularly in collaborative settings, are short compared to those of older children (ages 7-11) [5]. Interactive installations need feature direct and responsive feedback if they are to engage a young audience. Secondly, the content in the DDL encouraged children to imagine stories [22]. The character based metaphor that drove the content allowed them to create scenarios and narrate activities related to the graphics while playing with the puzzle blocks. This helped engage them for protracted periods and increased their focus and concentration on the system. It also provided a framework that effectively motivated the children to explore all aspects of the DDL functionality.

The DDL also demonstrates that jigsaw puzzle pieces are a powerful medium for conveying sophisticated ideas. Beyond simple sequencing operations [e.g. 7], the DDL shows that careful construction of inter-connecting tokens can express a physical syntax [21] capable of representing concepts such as containment, grouping, association and types of data. These relationships create a sophisticated repertoire of meanings and manipulations that are comprehensible to young children. We believe that the explorations of this space in the DDL only scratches the surface of possibilities for leveraging puzzle pieces as structured tools to express concepts to young children.

Finally, explicitly exposing the structure of the installation and reacTIVision markers helped stimulate curiosity and convey system operation to its audience of very young children. This had a positive effect on dynamics of use, reducing confusion and inappropriate (or more correctly, un-sensable) manipulations of the tokens such as flipping them or moving them above the table surface. Based on this observation, we believe that visibility of system functioning is a desirable property for public tangible installations. We also believe this can be effectively achieved, in many cases, without sacrificing system robustness or integrity. The DDL achieved this through the simple use of windows into the underside of the tabletop.

In summary, the DDL is a puzzle based tangible interface intended for museum installation and designed to express a range of abstract concepts to young children. Extensive fieldwork informed and refined the design of this system and this process and outcome can serve as a case study that informs and guides future work on this topic.

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