Smart Blocks: A Tangible Mathematical Manipulative

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ABSTRACT
We created Smart Blocks, an augmented mathematical manipulative that allows users to explore the concepts of volume and surface area of 3-dimensional (3D) objects. This interface supports physical manipulation for exploring spatial relationships and it provides continuous feedback for reinforcing learning. By leveraging the benefits of physicality with the advantages of digital information, this tangible interface provides an engaging environment for learning about surface area and volume of 3D objects.

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Tangible User Interface, Education, Mathematics, Manipulatives

ACM Classification Keywords
H.5.2 [Information Interfaces and Presentation]: User Interfaces

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INTRODUCTION
Physical manipulatives are often used in classrooms to help children understand abstract concepts. For example, children work with base 10 blocks to learn about counting, adding, and subtracting numbers (Figure 1). When students learn about the volume and surface area of 3-dimensional (3D) shapes, teachers often use physical manipulatives. This teaching method enables students to ask questions and visualize the volume and surface area of each manipulative. These math manipulatives have proven effective at aiding students in learning high-level, spatial concepts [4]. However, with one teacher in each classroom, students often work with manipulatives in an unsupervised environment where they may develop misconceptions about the educational content.

Figure 1: Base 10 blocks, used to help children develop counting, addition, and subtraction skills.

Proponents of educational software believe that one way to improve learning is to provide students with personalized tutors through the use of educational software [2]. However, while educational software can curb misconceptions by providing students with real time, accurate feedback and guidance, it lacks the physical manipulations needed for learning abstract concepts [8]. Tangible computing [3, 6] combines the best of the digital and physical worlds: real time feedback for each student and physical manipulatives to promote abstract learning [4, 9].

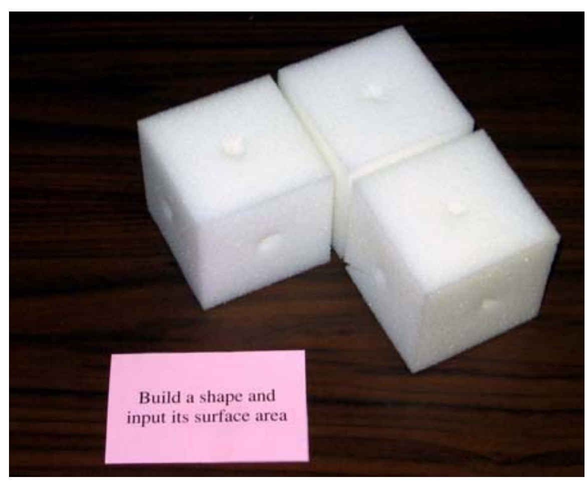

Figure 2: Smart Blocks: blocks with holes on each face, connected by dowels (not visible) and a question card.

We introduce Smart Blocks (Figure 2), an augmented manipulative that combines the benefits of physical manipulation with real-time feedback. In addition to physicality and pedagogic guidance, a major design consideration for Smart Blocks was cost, since keeping educational technology inexpensive is a priority when working with educational tools [5]. Smart Blocks are aimed at inexpensively facilitating hands-on learning of the volume and surface area of 3D shapes. It supports more than one user at a time and allows trial and error exploration [13].

DESIGN CONCEPT

The underlying principle behind Smart Blocks is that when cubes are connected together, they create a shape that is recognized by the system. More precisely, the system is able to calculate the volume and the surface area of that shape, and it can provide feedback about these characteristics to the user.

RELATED WORK

We developed Smart Blocks by building on previous work in the areas of mathematics education, educational software, and tangible user interfaces (TUI). Anderson et al. [1] used tangible interaction to enhance 3D modeling by creating building blocks that capture the geometry of the block structure. Watanabe et al. [12] used ActiveCubes to enhance entertainment applications. These cubes support the construction of 3D environments out of the workspace. However, while each active cube is implemented using two microprocessors, this approach may be too costly to implement in educational environments. Yonemoto et al. [15] developed pattern blocks for hands-on math learning. Marshall et al. studied tangible systems to support learning and concluded that they must present the learner with exploratory or expressive activities [7].

USE SCENARIOS – EXPLORATION AND QUESTIONING

The following use scenarios drove the design of Smart Blocks. The users of Smart Blocks are mainly young students, ages 5-12. They use this system in a classroom with other students or at home after school. While using Smart Blocks to estimate and calculate the volume and surface area of 3D figures, users can apply the rules they have learned in class as well as rediscover rules by manipulating the 3D blocks.

The Smart Blocks system has two modes: *exploration mode* and *question mode* [7]. While in the exploration mode, the system interactively updates the surface area and volume as the student assembles the blocks and places them on the surface. This mode allows users to observe the impact of changing a shape on its volume and surface area in real time. It also reinforces the relationships of the number of blocks to volume and the number of visible sides to surface area.

In the question mode, students select, read, and place a question on the WorkSpace. Question cards disable the online display of information. There are two types of questions; the first asks a user to create a shape with a specified surface area and/or volume; the second asks a user to create a shape and input its surface area and/or volume. When the user informs the system that he/she is done, the system provides feedback, indicating whether the answer is correct or incorrect [14].

SYSTEM ARCHITECTURE

The Smart Blocks system consists of 3” lightweight cubes, 3” dowel connectors, a WorkSpace, and question cards. Figure 3 illustrates these components. Each cube has six holes, one in the center of each side. The connectors fit into the cubes’ holes. Each block, connector and question contains a unique RFID tag. When a shape is assembled, the user puts it on the WorkSpace, which contains an RFID reader. The reader recognizes any RFID tags placed on the WorkSpace and the underlying Java program is responsible for determining which identifiers are blocks, connectors, or questions.

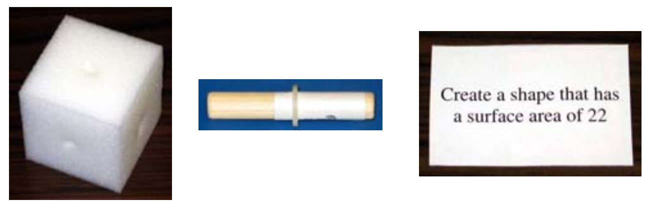

Figure 3: Cube, Connector, Question

DESIGN CONSIDERATIONS AND IMPLEMENTATION

The Smart Blocks system is a product of an iterative process that included developing a series of prototypes and using rapid modeling to iteratively refine interaction design. To rapidly model the structure and behavior of Smart Blocks, we used TUIML, Tangible User Interface Modeling Language [10]. TUIML views the structure of a TUI as a collection of token (physical objects that represent digital information) and constraint (physical objects that constrain the behavior of tokens) relationships [11]. In the Smart Blocks system, blocks serve as tokens while physical connectors serve as constraints, constraining the ways blocks can be assembled together. As outlined in the previous usage scenarios, the Smart Blocks system can be in one of two modes: *exploration mode* or *question mode*. We used TUIML to refine the transitions between these modes and to define the tasks users could complete while the system is in a certain mode.

Some of the primary design challenges were determining the communication technology between the tangible manipulatives and the system, and determining techniques for the system to compute the surface area of the shape. Other design decisions were concerned with the presentation and content of the tangible questions and the feedback provided by the graphical interface. These design considerations are discussed below.

Communication

Communication between the shape and the program is done with RFID technology, because it allows the use of a large number of connectors, blocks and questions in a short amount of time and at a very low cost.

The volume of a shape is computed by multiplying the number of blocks in the shape by the individual volume of each block (side length^3). By default, each block is considered one unit cubed. Therefore, if a shape is one unit wide, the volume and the number of blocks are equal.

Calculating the surface area of the structure is less straightforward using the RFID tags. The RFID reader can only determine whether an object is present or not. The surface area depends on the presence of each block *and* the way the shape is configured. Connectors were chosen as a feasible, inexpensive, solution to this problem. The physical design of the blocks and connectors constrains the possible assemblies that can be made.

Each block has 6 sides and connecting two blocks removes two sides from the surface area. Therefore, the surface area is (*number_of_blocks * 6) – (2 * number_of_connectors),* multiplied by the surface area of an individual side (side length^2). A pictorial representation of these equations is shown in Figure 4.

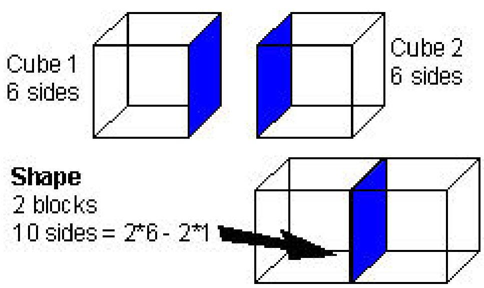

Figure 4: Calculation of the Surface Area

Connectors

To join blocks, we considered internal connectors and external connectors. Figure 5 (a) shows an internal connector. This connector is invisible when two blocks are joined together. This design is problematic because a connector could be attached to only one cube, sticking out of the shape, or could be omitted between two cubes. Both of these situations would result in a false surface area reading. Since it is imperative that Smart Blocks provide accurate feedback, the interior connector was not an option.

The second option, displayed in Figure 5 (b), uses connectors on the exterior of the cubes. These connectors are visible when the shape is completed. The disadvantages of the exterior connectors are that they slightly increase the surface area of the shape and they did not successfully join blocks together.

Our final connector design includes a mixture of both the interior and exterior connectors described above. A washer was added in the center of an internal connector, as displayed in Figure 5 (c). The resulting connector attaches the blocks while providing a visual cue of its presence.

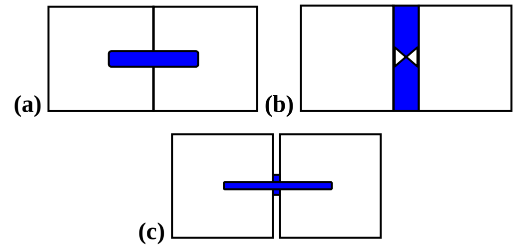

Figure 5: Interior Connector (a), Exterior Connectors (b) and Selected Connectors (c)

Question Cards

Each question card is equipped with an RFID tag, allowing the system to recognize the current question. There are currently two types of questions available to the user as described in the Use Scenarios section. Other questions can easily be added to the system.

Graphical Interface

While the student reads the question on the physical card, the graphical user interface (GUI) (Figure 6) displays textboxes for the student to enter surface area and volume information as needed. The GUI also displays a button for students to click when they feel that they have answered the question adequately. If no question is present, the volume and the surface area are provided as feedback through the graphical user interface, allowing the user to experiment with different shapes.

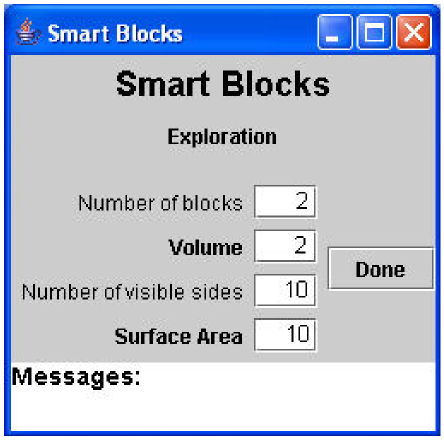

Figure 6: Screenshot of the Smart Blocks interface

FUTURE WORK

A. Evaluation Plan

We hypothesize that the physical manipulation supported by the Smart Blocks interface, combined with the real-time feedback it provides, makes the Smart Blocks interface an effective teaching tool. We intend to evaluate the usability and effectiveness of Smart Blocks with actual users and apply the results of this study in future prototypes. A comparative study that includes physical manipulatives, Smart Blocks and a GUI may provide additional information regarding the benefits provided by our Smart Blocks system.

In this study, the GUI and the physical blocks will mirror the states and actions of the Smart Blocks system. The only difference between the GUI and the Smart Blocks system will be the 2D representation of the blocks on the screen and the manipulation of the blocks via the mouse, while the difference between the physical blocks and Smart Blocks will be the lack of feedback.

B. Next Steps

We also intend to enhance user experience in future prototypes. Employing low-cost microprocessors within each block will allow us to provide haptic and visual feedback directly by the blocks. To reach a greater number of students, different levels of difficulty will be added, including different sets of questions, or electronic questions that adjust themselves to the level of each student, while keeping the user entertained. Introducing rectangular or pyramidal blocks may have a beneficial effect on learning the properties of these shapes.

CONCLUSION

We introduced a tangible math manipulative aimed at improving the way young students learn the abstract concepts of volume and surface area. Smart Blocks builds upon the physical mathematical manipulatives currently used in schools, the real time feedback and guidance of educational software, and research being conducted with tangible user interfaces. Smart Blocks' final design involved inexpensive hardware, making the system ideal for use in schools.

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