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ABSTRACT

In many educational settings, manipulative materials (such as Cuisenaire Rods and Pattern Blocks) play an important role in children's learning, enabling children to explore mathematical and scientific concepts (such as number and shape) through direct manipulation of physical objects. Our group at the MIT Media Lab has developed a new generation of "digital manipulatives"—computationally-enhanced versions of traditional children's toys. These new manipulatives enable children to explore a new set of concepts (in particular, "systems concepts" such as feedback and emergence) that have previously been considered "too advanced" for children to learn. In this paper, we discuss four of our digital manipulatives—computationally-augmented versions of blocks, beads, balls, and badges.

Keywords

Education, learning, children, augmented reality

INTRODUCTION

Walk into any kindergarten, and you are likely to see a diverse collection of "manipulative materials." You might see a set of Cuisenaire Rods: brightly colored wooden rods of varying lengths. The colors and lengths of the rods are carefully chosen to engage children in explorations of arithmetic concepts and relationships. Children discover that each brown rod is the same length as two purples—or four reds. On the next table, you might see a set of Pattern Blocks. Children can use these polygon-shaped tiles to create mosaic-like patterns—and, in the process, learn important geometric concepts.

As children build and experiment with these manipulative materials, they develop richer ways of thinking about mathematical concepts such as number, size, and shape. But there are many important concepts that are very difficult (if not impossible) to explore with these traditional manipulative materials. In particular, traditional manipulatives generally do not help children learn concepts related to dynamics and systems. Usually, these conceptsare taught through more formal methods—involving manipulation of abstract symbols, not physical objects. As a result, these concepts are accessible only to older students, with more mathematical expertise.

This paper discusses a new breed of manipulative materials that we call "digital manipulatives." These new manipulatives—with computational power embedded inside—are designed to expand the range of concepts that children can explore through direct manipulation, enabling children to learn concepts that were previously considered "too advanced" for children. The paper begins with a brief history of the educational uses of manipulative materials, then discusses several digital manipulatives that our research group has developed.

LEARNING WITH MANIPULATIVE MATERIALS

The idea that physical objects might play an important role in the learning process is a relatively new idea in the history of education. Until the 19th century, formal education focused almost exclusively on lectures and recitations. One of the first advocates for "hands-on learning" was the Swiss educator Johann Heinrich Pestalozzi (1746-1827). Pestalozzi asserted that students need to learn through their senses and through physical activity, arguing for "things before words, concrete before abstract" [12].

Friedrich Froebel, who created the world's first kindergarten in Germany in 1837, was very influenced by Pestalozzi's ideas. Froebel's kindergarten was filled with objects for children to play with. Froebel developed a specific set of 20 "gifts"—physical objects such as balls, blocks, and sticks—for children to use in the kindergarten. Froebel carefully designed these gifts to help children recognize and appreciate the common patterns and forms found in nature. Froebel's gifts were eventually distributed throughout the world, deeply influencing the development of generations of young children. Indeed, Frank Lloyd Wright credited his boyhood experiences with Froebel's gifts as the foundation of his architecture [2].

Maria Montessori extended Froebel's ideas, developing materials for older children and inspiring a network of schools in which manipulative materials play a central role. In an effort to create an "education of the senses" [10], Montessori developed new materials and activities to help children develop their sensory capabilities. Montessori hoped that her materials would put children in control of the

Jean Piaget provided an epistemological foundation for these educational ideas. Piaget argued that children must first construct knowledge through “concrete operations” before moving on to “formal operations” (e.g., [13]). In recent years, psychologists have questioned the exact nature of Piaget’s “stages” of development, but there is broad consensus on the importance of concrete operations in learning. Indeed, Turkle and Papert argue for a “revaluation of the concrete,” suggesting that “abstract reasoning” should not be viewed as more advanced than (or superior to) concrete manipulations [22].

Today, manipulative materials are well-established in the classroom, especially in the early grades. Education journals are filled with papers on ways of using manipulative materials in the classroom—papers with colorful titles like “Lima Beans, Paper Cups, and Algebra” [8] and “Activities to Grow On: Buttons, Beads, and Beans” [5].

DIGITAL MANIPULATIVES

Different manipulative materials engage people in different types of thinking. As the old saying goes: “Give a person a hammer, and the whole world looks like a nail.” Similarly, give a child Cuisenaire Rods, and arithmetic relationships become more salient for the child. Give a child Pattern Blocks, and geometric relationships become more salient.

Our goal in designing new “digital manipulatives” is to make a new set of concepts salient for children. Our basic strategy is to embed computational and communications capabilities in traditional children’s toys. By using traditional toys as a starting point, we hope to take advantage of children’s deep familiarity with (and passion for) these objects. But by endowing these toys with computational and communications capabilities, we hope to highlight a new set of ideas for children to think about.

In particular, we believe that children, by playing and building with these new manipulatives, can gain a deeper understanding of how dynamic systems behave. Until recently, dynamic systems have been studied primarily at the university level, using advanced mathematical techniques like differential equations. Computer-simulation environments—such as Stella [20], StarLogo [15], and Model-It [7]—have made it easier for pre-college students to model and explore systems phenomena (such as feedback and emergence). We expect that digital manipulatives will make these ideas accessible to even younger students, enabling them to explore these ideas through direct manipulation of physical objects. Such explorations would not be possible with traditional (non-computational) manipulative materials; computation plays a critical role in making the systems-related concepts salient.

Our development of digital manipulatives can be seen as part of a broader trend within the CHI community. While CHI researchers have long recognized the value of providing users with “objects” to manipulate, they have traditionally focused on “virtual objects”—as in object-oriented languages and direct-manipulation graphical interfaces. It is only in recent years that researchers have shifted attention to desktops to eyeglasses and shoes [4, 6, 24, 25].

Our research on digital manipulatives is part of this trend, but it focuses explicitly on the use of objects to support learning and education. Our primary goal is not to help users accomplish some task faster or more effectively, but rather to engage them in new ways of thinking. In short, we are interested in Things That Think only if they also serve as Things To Think With.

This research can be viewed as an extension of our previous work on LEGO/Logo [14], a robotics construction kit commercialized by the LEGO toy company and now used in more than 20,000 schools in the United States. With LEGO/Logo, children can write computer programs to control their LEGO constructions. Elementary-school students have used LEGO/Logo to build and program a wide assortment of creative machines, including a programmable pop-up toaster, an automated amusement park, and a machine that sorts LEGO bricks according to their lengths. In these projects, students build with an enhanced set of LEGO parts (including motors and sensors), connect their constructions to a personal computer (using wires and an interface box), then write Logo computer programs to control the actions of their constructions.

In LEGO/Logo, wires are both a practical and conceptual nuisance, limiting not only what children can build but also how they think about their constructions. In our new work with digital manipulatives, we get rid of the wires and embed computational capabilities directly in the toys themselves. We continue to use Logo as the primary programming environment. But Logo programs can be downloaded directly into these new toys (typically via infrared communication), so that the toys function autonomously.

The next four sections describe digital manipulatives that we have created by adding computation to four traditional children’s toys—blocks, beads, balls, and badges. These projects are in varying stages of development. Some of these new manipulatives have already been used extensively by children; others are still in the early prototype stage.

BLOCKS

We began our work on digital manipulatives by embedding computation in LEGO bricks—creating Programmable Bricks [9, 16]. Each Programmable Brick has output ports for controlling motors and lights, and input ports for receiving information from sensors (e.g., light, touch, and temperature sensors). To use a P-Brick, a child writes a Logo program on a personal computer, then downloads the program to the P-Brick. After that, the child can take (or put) the P-Brick anywhere; the program remains stored in the P-Brick.

In our initial work in schools, students have used Programmable Bricks to create autonomous “creatures” that mimic the behaviors of real animals. For example, one group of fifth-grade students created a LEGO dinosaur that was attracted to flashes of light, like one of the dinosaurs in Jurassic Park. To make the dinosaur move toward the light,

Figure 1. Two fourth-grade students test the behaviors of their Programmable Brick "creature."

the students needed to understand basic ideas about feedback and control. The program compared readings from the dinosaur's two light-sensor "eyes." If the dinosaur drifted too far to the left (i.e., more light in the right eye), the program made it veer back to the right; if the dinosaur went too far right (more light in the left eye), the program corrected it toward the left.

This type of feedback strategy is typically not taught until university-level courses. But with the right tools, fifth graders were able to explore these ideas. The students also considered the similarities (and differences) between animals and machines. Were their LEGO creatures more like animals? Or more like machines? They compared their robots' sensors to animal senses, and they discussed whether real animals have "programs" like the ones they wrote for their robotic creatures [17].

Our newest Programmable Bricks, called Crickets, are roughly the size of children's Matchbox cars and action figures. Each Cricket contains a Microchip PIC processor and is capable of two-way infrared communications. Children can use Crickets to create communities of robotic creatures that interact with one another. By teaching their creatures to communicate with one another, children can learn general principles about communication. When a child programs a Cricket-based creature to communicate with a second creature, the child must have a good model of what the second creature already "knows." The general lesson: to communicate well, you must develop a model of your audience. This idea might seem obvious, but it is often

Recently, we have begun a new science-education initiative using Crickets [18]. Many educational researchers emphasize the importance of children developing their own scientific investigations (rather than carrying out pre-scripted experiments, as is common in many classrooms). We go a step further, encouraging students to use Crickets to create their own scientific instruments to carry out their investigations. For example, children used Crickets and sensor to build a bird feeder that keeps track of which birds visit and when. Our initial studies indicate that students, by building their own scientific instruments, not only become more motivated in science activities, but also develop critical capacities in evaluating scientific measurements and knowledge, make stronger connections to the scientific concepts underlying their investigations, and develop deeper understandings of the relationship between science and technology.

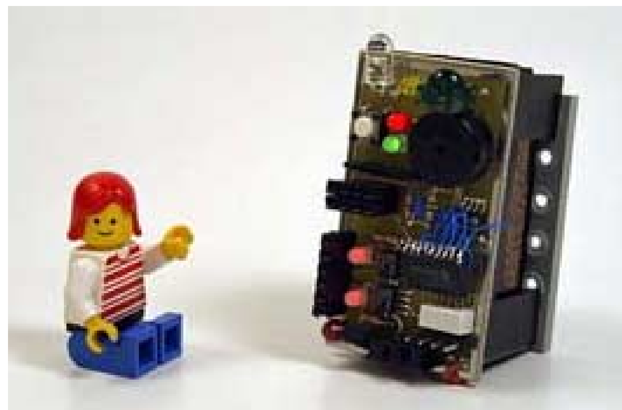

Figure 2. A Cricket (with LEGO figure to show scale)

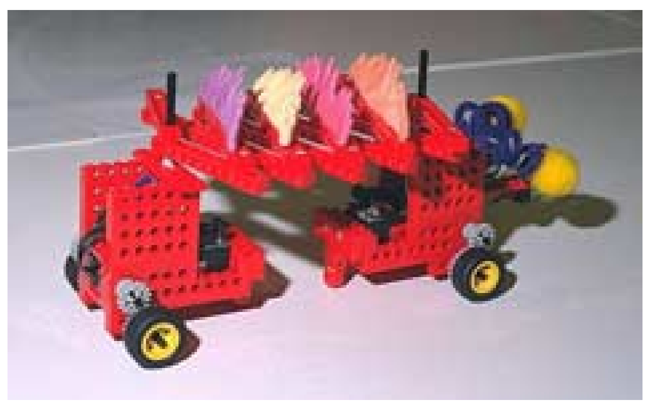

Figure 3. Creature with two built-in Crickets, which communicate with one another to synchronize their motion

BEADS

In recent years, beads have become increasingly popular among children, especially young girls. There are entire stores with nothing but bins of beads of varying colors and sizes. Children string beads together to create colorful necklaces and bracelets.

Figure 4. A necklace of Programmable Beads

With traditional beads, children create colorful but *static* patterns. Our Programmable Beads are designed to engage children in creating *dynamic* patterns. Each Programmable Bead has a built-in microprocessor and light-emitting diode (LED), and it communicates with its neighboring beads by simple inductive coupling. String beads together in different ways and you get different dynamic patterns of light. Some beads pass the light to the next bead along the string, other beads reflect the light back, still others “swallow” the light. Some beads pass the light with a particular probability—providing a context for young children to engage in probabilistic reasoning. A slight change in the behavior or placement of one of the beads can lead to an entirely different pattern of activity in the overall collection.

Children can work with the beads at two different levels. For starters, they can string together pre-programmed beads (each with a fixed behavior), and observe the dynamic lighting patterns that arise from the interactions. More advanced users can write new programs and download them into the beads.

A string of Programmable Beads can be viewed as physical instantiation of a one-dimensional cellular automata (e.g., [21]). In cellular automata, each cell changes its state based on the states of its neighboring cells. Cellular automata have proved to be a rich framework for exploring “emergent phenomena”; simple rules for each cell can lead to complex and unexpected large-scale structures. But cellular automata seem best suited as a tool for mathematicians and computer aficionados, not for children. The idea of writing “transition rules” for “cells” is not an idea that most children can relate to. Programmable Beads allow children to explore ideas of decentralized systems and emergent phenomena in a more natural way, through the manipulation of physical objects.

Programmable Beads also provide a context for children to learn about “programming paradigms.” There are two very different ways to think about programming the beads. Paradigm 1: Children can program the behaviors of the beads themselves, telling each bead to turn its light off or turn on this bead’s light for two seconds, then jump two beads down the string and turn on that light for three seconds). The important point is not for children to learn which of these paradigms is better (in fact, neither is inherently better). Rather, the important lesson is that there are often multiple approaches for describing behaviors, each with its own advantages.

BALLS

Probably the most popular of all children’s toys is the ball. How could computation possibly improve the ball? We are exploring that question with our BitBall—a transparent, rubbery ball (about the size of a baseball) with a Cricket, accelerometer, and colored LEDs embedded inside.

To customize a BitBall, a child writes a program on a desktop computer (using a modified version of Logo), then downloads the program to the BitBall via infrared communication. A child can program a BitBall to turn on its LEDs based on its motion, as detected by the accelerometer. One child, for example, might program a BitBall to flash red light whenever it undergoes a sharp acceleration or deceleration (i.e., whenever it is thrown or caught). Another child might create a ball that “wants” to be played with: If the ball doesn’t experience any sharp accelerations for a certain period of time, it begins flashing its lights in an effort to attract someone to play with it.

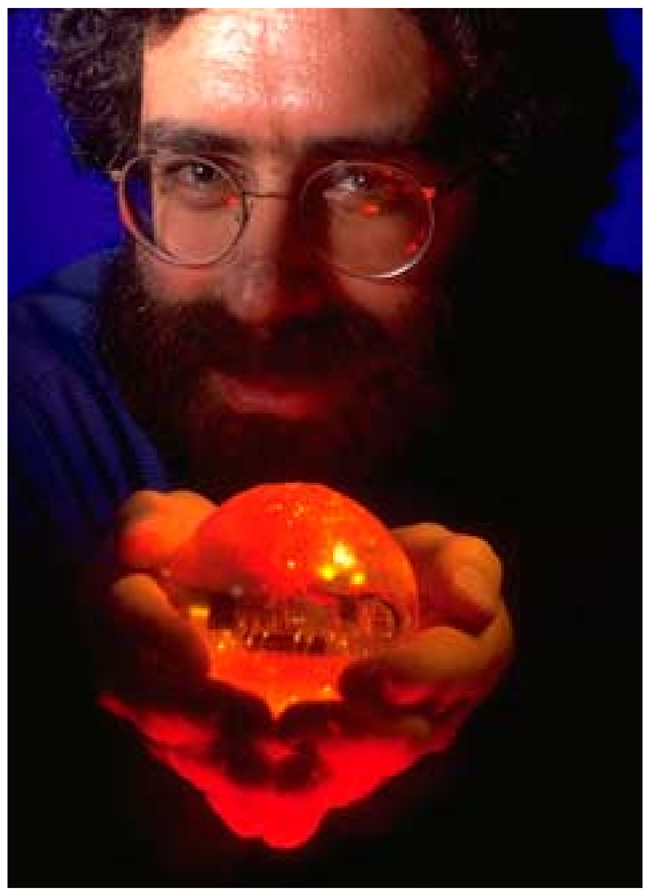

Figure 5. The BitBall

communicate with other electronic devices. For example, a child might program the BitBall to send its acceleration data to a MIDI synthesizer in real time, in an effort to "hear the motion" of the ball.

BitBalls can also be used in scientific investigations. A BitBall can store its acceleration data and later upload the data to a desktop computer for analysis. For example, a child might drop a BitBall from the top of a building, then use the acceleration data to figure out the height of the building. Such investigations are likely to lead to a deeper understanding of kinematics. Imagine a child who throws a BitBall in the air and graphs the acceleration data in an effort to find the top of the trajectory. The child will discover that there is no change in acceleration while the ball is in flight, so it is impossible to determine the top of the trajectory from acceleration data alone.

It is important to note that the BitBall is significantly different from most commercial toys with embedded electronics. For example, some companies sell yo-yos that turn on a light while they are moving. That might seem similar to a BitBall, but it is different along a very important dimension. The light-up yo-yo is pre-programmed to always do the exact same thing. The BitBall gives much greater flexibility and creative power to children. With the BitBall, children themselves decide how the toy should behave.

BADGES

Many children like to wear badges (such as a sheriff's badge) and buttons with slogans. Our Thinking Tags are based on these traditional badges, but they have built-in electronics so that they can communicate with one another (via infrared)—and also change their displays based on those communications.

We first developed the Thinking Tags for a conference (for adults) at the Media Laboratory [1]. The Thinking Tags served as name tags, but each tag also contained information about the interests and opinions of its wearer. When two people met, their badges exchanged information and turned on lights to show how much the two people had in common. In this way, the badges acted as a conversational prop to get people talking with one another. Other research labs have also developed "smart badges" (e.g., [21]), but our Thinking Tags are different in an important way: While other badges are designed to support interaction between people and machines (e.g., to track the location of a person within a building), our Thinking Tags are designed to facilitate communication among people.

More recently, we have begun to use Thinking Tags in educational applications with pre-college students. In particular, we have organized "participatory simulations" in which students themselves play roles within simulations [3, 19]. For example, some students have used Thinking Tags to simulate (in a very first-hand way) the spread of an epidemic, with an electronic "virus" jumping from one student's Thinking Tag to another. Some students start as carriers of the disease, others might be immune to the latency period? Is transmission probabilistic? Are some people more susceptible than others? As part of their analysis, students can get additional data from their Thinking Tags, which keep track of who each person has interacted with and when.

We have run similar activities using somewhat different metaphors. In one case, we explained that ideas (or "memes") could jump from one badge to another. Some people were "resistant" to new ideas; others were active carriers. The goal was to help people develop a better understanding of how ideas spread through a population—and also to engage them in thinking about the similarities (and differences) between the spread of disease and the spread of new ideas.

This type of activity is very different from traditional science education. Science is usually taught as a process of detached observation of phenomena, not active participation within phenomena. We believe, however, that role-playing can play a powerful role in science education—especially in the study of systems-related concepts. Our preliminary analysis indicates that participatory simulations (supported with Thinking Tags) leads to a richer learning experience than is possible with traditional computer-simulation activities—or with traditional group activities without computer support.

Figure 6: Thinking Tags

set of separate projects, but as an integrated family. The same underlying software environment is used for programming all of these new toys, and the toys are designed to communicate and interact with one another. A BitBall, for example, can send information (via infrared) to the Thinking Tags—in effect, using the Thinking Tags as a remote display peripheral. Our goal is to create a unified "community of things" that children can use in a wide variety of explorations and design activities.

Our work with digital manipulatives is still in the preliminary stages. Our plan is to conduct more in-depth empirical studies of how and what children learn through their interactions with digital manipulatives. Such studies will undoubtedly yield ideas for the redesign of our current digital manipulatives (and the design of new ones). More broadly, we hope that these studies will help us to develop a richer theoretical framework for understanding the role of physical objects (and, in particular, computationally-enhanced physical objects) in the learning process.

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