To Mindstorms and Beyond:

Evolution of a Construction Kit for Magical Machines

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Introduction

When does something stop being a machine and become a creature?

From a very early age, children find movement captivating. For centuries, we have been fascinated by the inanimate brought to life. The Jewish legend of the Golem, a hunk of clay brought to life by God, has been succeeded by the story of Frankenstein, mechanical automatons, *2001*'s Hal, and a myriad of other myths. For the last fifty years, computers have allowed us to create worlds that live inside of the electronic box, creating artificial creatures in the sense of these stories. And over the last fifteen years, children have been able to play in these worlds (e.g., video games) and build in them, using tools like the Logo programming language.

But only now can children embed computation into physical artifacts. In doing so, they create objects that, in a real sense, are brought to life, animated by a computer program also created by the child. These playthings, enabled by computational construction kits and living at a boundary between the animate and inanimate, allow children a special relationship to the world of technology we are living in. The magic of technology, so much a part of all of our lives, is both revealed and revered. Children realize that sophisticated behaviors can emerge from interactions of rules with a complex world, but at the same time, are still captivated by the wonder of a machine acting like a pet.

Designing tools that allow children to add computation to traditional construction—and recognizing the learning opportunities afforded by this activity—has been the focus of our work over the last number of years. This paper explores this work as part history, part design narrative, and part vision.

In the first section, we explore a 30-year trajectory of computational design environments for children, beginning with Seymour Papert's original Logo work at the MIT Artificial Intelligence Laboratory, and ending with our recent Cricket computers. We refer both to Seymour Papert's vision of children's learning in his book *Mindstorms* (Papert, 1980) and also the Mindstorms Robotics Invention System, launched by the LEGO Group in 1998.

In the second section, we describe a set of activities oriented around science experiments, where children investigating various phenomena from a computational standpoint. In the conclusion, we present a vision of the future in which children are as fluent in combining a diverse collection of computational tools—hand-held, tangible, and inter-connected—as they are with video games and CD players today.

The first section of this paper may seem overly technical. Indeed, the focus is on the evolution on a particular set of technologies (the robotics construction kit). But our intent is to illuminate a set of design issues around which many people have explored different avenues based on their own passions. For instance, Umaschi and Urrea's work on "Con-science" (this issue) proposes robotic design activities for learning about values and identity. Turkle (1984) has explored psychological implications of computational artifacts and the process of creating them. So while we focus on technology, the intent is to reveal the process by which we were led along in creating these systems, not just the particular way-points themselves.

In our second section, we give an in-depth narration of the kinds of activities that are possible with the latest versions of our materials. This discussion is oriented around our present "Beyond Black Boxes" project, in which children perform scientific investigations with the computational construction kit. Here, we share the quality of children's experience with our tools and their relationship to them. Our hope is that the fluid, serendipitous and yet rigorous investigations that we describe would become a commonplace replacement for the school science we are all too familiar with.

In the conclusion, we discuss new technological directions, and our work in building a library of application ideas around these materials.

From Floor Turtles to Crickets

The Road to LEGO/Logo

Since the late 1960's, our research group has been developing robotic construction kits for children. Early work, led by Seymour Papert, included the development of the Logo programming language. A popular use of Logo was in conjunction with "floor turtles"—wastebasket-sized robots tethered to mainframes. With pens mounted in their bodies, floor turtles made drawings on butcher paper, commanded by children's Logo programs.

In 1972, Papert and Cynthia Solomon published a memo entitled "20 Things to Do with a Computer" (Papert and Solomon, 1972). Many of these activities involved hooking some kind of contraption up to a computer, and programming it to perform—for instance, a puppet show, a yo-yo, or a yardstick-balancer. In essence, these projects proposed robotic design activities, before a general-purpose robotic construction kit for children was available.

Over the 1970's and into the 1980's, Papert's vision of computing, in which children explore ideas by constructing their own computer programs, came into reality as the first microcomputers entered schools. Logo as a computer programming language, a philosophy of learning, and a culture of users grew with the publication of *Mindstorms: Children, Computers, and Powerful Ideas* (Papert, 1980). *Mindstorms* presented us with *constructionism*: the philosophy of learning by building ideas in one's mind as part of building artifacts in the world.

In the mid-1980's our research group began a collaboration with the LEGO Group. Combining the LEGO Technic product (which includes beams, gears, and motors) with the Logo language, we created the LEGO/Logo system. With LEGO/Logo, children could build various mechanical contraptions—a Ferris wheel, elevator, robot creature—connect them to an interface box, and then write Logo programs to control their movement.

The LEGO/Logo system became commercially available in the late 1980's, sold to schools by the LEGO Group with the name *LEGO tc logo*. LEGO/Logo was a fantastic innovation—in an important sense, it was the first true robotic construction kit ever made available widely—but it had limitations. Children's machines had to be connected to a desktop computer with wires. If the machine just had one motor, it was not too inconvenient, but once a machine had a couple of motors and sensors, each with its own cable, pretty soon there was a whole wiring harness connecting the interface box to the LEGO project. It greatly limited the capabilities of mobile machines.

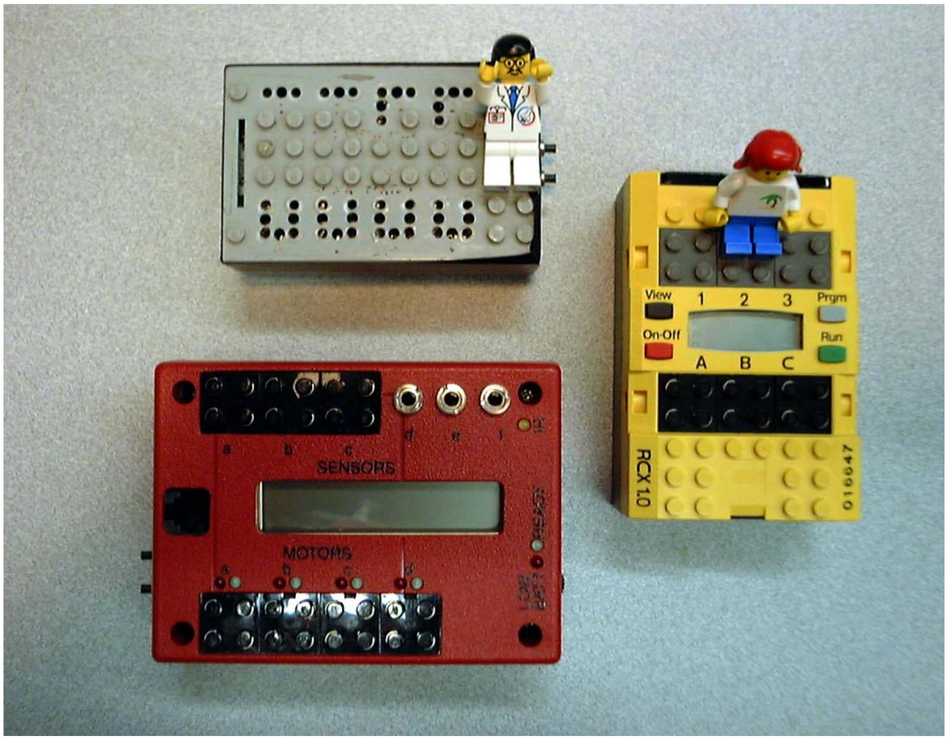

Figure 1: Progression of Programmable Bricks. Counter-clockwise from upper left: MIT Logo Brick (1987), MIT Red Brick (1995), LEGO® RCX™ Brick (1998).

The First Programmable Brick

At about the same time as LEGO/Logo was reaching schools, we began thinking about its successor.

This would clearly involve putting electronics into bricks. The question was, could we fit an entire computer into a block small enough to be carried around by a LEGO model? The answer turned out to be yes, and in 1987 we had the first prototypes of a "Programmable Brick," ready to be used with children in focused research play (see Figure 1, upper left gray brick).

A set of experiments done using our first Programmable Brick with fifth- and seventh-grade students is described in *Children, cybernetics, and programmable turtles* (Martin, 1988). In this work, we worked closely with a small number of students who built projects using the Programmable Brick along with a LEGO turtle (a small robot). With our assistance, the children wrote programs to give different behaviors to the turtle, such as light seeking and obstacle avoidance. We paid close attention to the children's relationship to the technology. Some children liked to treat the turtle-robot like a pet, and enjoyed when it displayed unpredictable behavior. Others were more interested in having the turtle perform a specific set of actions, and were challenged by the difficulty in getting it to do so.

The first-generation Programmable Brick was a success in that it allowed us to conduct closely monitored work with children. But it would wait for later designs before we had Bricks that were sufficiently reliable that they could truly become part of a classroom environment, honestly owned by the teachers and children who were using them.

Over the period from 1994 to 1996, we created our second-generation Programmable Brick, which became known as the "Red Brick" because it was housed in a bright red plastic case (see again Figure 1). This Brick was specifically designed for robustness and ease of manufacture; over its lifetime more than 100 copies of it were built for extended use in schools and community centers.

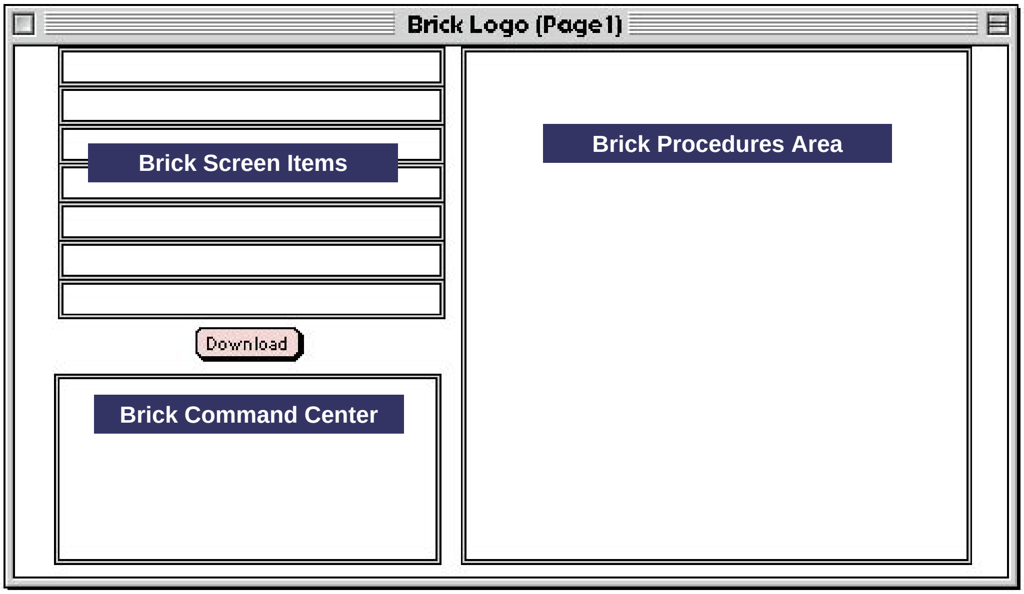

Figure 2: Brick Logo Software Interface.
In the lower right, the Brick Command Center is used to type Logo statements directly to the Brick. Procedures are composed in the Brick Procedures Area, and the Brick Screen Items are used to indicate which procedures can be started up from the Brick itself. Programs are downloaded into the Brick by clicking the Download button.

The Red Brick

The Red Brick was not fundamentally different from the original Logo Brick. In the basic concept of its use, children built a LEGO machine (often, which carried the Brick), and then plugged the Brick into a desktop computer for programming. While the Brick was attached to the desktop, children could type Logo commands directly to the Brick, or compose Logo procedures and download them. (The Logo software interface to the Brick is shown in Figure 2.)

But the Red Brick was stable and robust enough to be used extensively in classroom situations; we worked in three classrooms in the United States (Martin, 1996) and in Project Lighthouse in Thailand (Cavallo, 1999). In the United States, two classrooms were in a rural elementary school, and one was at an urban vocational high school. In this work, we developed a semester-long set of activities around the Brick in elementary school (called “Robotic Park”), and engaged vocational school students in developing robots for an international contest. This field work helped serve as the foundation for the development of the LEGO RCX Brick, a version of the programmable brick concept that is now commercially available.

During this period of work, when the Red Brick was being used heavily, we engaged in design discussions as to what characteristics the next Brick should have. One concern was size. Our Brick approximately the size of a child’s juice box or a small personal cassette stereo. Also, it was reasonably heavy, about 13 oz. This made it a challenge for kids to construct a model that could carry the Brick around.

Also, we revisited the discussion about how many inputs and outputs the Brick should have, and whether it should have an LCD screen. The Red Brick had four motor outputs and six sensor inputs. We considered the six inputs generous—four would have probably been enough—even though project work with children had shown that all six sensor inputs were often put into use.

We considered the LCD screen a critical feature. Time and time again, children would use the screen’s sensor display to gain an understanding of how sensors performed. Especially in the case of light sensors, a robot needed to be in its “natural habitat”—that is, the playpen specifically designed for the robot—in order for the sensor readings to be valid. So it would be no help to have to bring the robot back to the desktop computer in order to view its sensor values; the sensors had to be seen in the context of where the robot had to perform. So the display was essential.

We also discussed the number of motor outputs. Some of us felt that two outputs were not enough. For example, two outputs would be just enough to build a vehicle that could both move and turn; if there were only two, none would be for other purposes (like actuating an arm or shovel, or spinning a turret). Others did not find this argument convincing and believed that two outputs would be enough.

So essentially we convinced ourselves that the feature set of the Red Brick was basically correct. We could go with perhaps fewer motors and sensors, but the LCD screen was necessary. So only one option presented itself: re-engineering the Brick to have more or less the same circuitry but packed into a smaller box. Unless the box were substantially smaller, however, making a slight tweak to the size would not be worth the engineering effort involved.

There was one change that was obvious from a cost/benefit standpoint. The original battery pack we selected for the Red Brick was both heavy and provided what turned out to be unnecessarily long battery life. In a later version, we choose a substantially lighter battery pack, reducing the weight of the Brick while still providing adequate battery life.

The Red Brick and the work we did in schools served as a foundation as the LEGO Group determined what sort of product should follow up on their tethered-interface control products. The LEGO RCX Brick (see again Figure 1, right side) shares many features with the MIT Red Brick, including motor outputs, sensor inputs, and an LCD screen.

The LEGO Group believed in the robot design concept so strongly that they launched the LEGO Mindstorms brand, a new product line to bring these ideas directly to children in their homes (the previous control products had been marketed exclusively to schools). Our work on iconic programming, which we called Logo Blocks, was adapted by LEGO to serve as the programming environment for the retail version of LEGO Mindstorms (known as “RCX Code”).

These design issues are all part of providing tools that are both flexible and powerful. We thought that we had reached the end of the line with the Red Brick, that it was optimal in some sense of these trade-offs. We then took what we thought might be a detour in creating “Thinking Tags,” but later realized set us off in a direction that would circle back to computational design environments for children.

Thinking Tags

Postponing the task of designing a new small Programmable Brick, our team created the Thinking Tag, an electronic nametag that had infrared communications capabilities (Borovoy et. al., 1996). The Thinking Tag was created to experiment with people’s behavior at social gatherings, allowing people first meeting each other to learn quickly a bit about their shared interests.

In addition to having one’s name printed on it, the Thinking Tag had five LED lamps that could light either red or green. We performed the initial trial of the Thinking Tag application at a Media Laboratory research consortium meeting. At the meeting, visitors each received a Thinking Tag in place of the traditional nametag.

Set up in the reception hall was a set of five kiosks, each displaying a multiple-choice question and three buckets representing the answers. The questions were designed to be provocative, humorous, and relevant to the technology-savvy audience of research sponsors; e.g., “How would you like to spend your 15 minutes of fame? a. Profile in the New York Times; b. Interview with Oprah Winfrey; c. Hyperlink off main page of Yahoo.”

When visiting a kiosk, participants could program their Tag with an answer simply by dunking it into the bucket color-coded to correspond to their answer. An infrared transponder in the bottom of each bucket would program the Tag with the selected response. If they changed their mind about an answer, participants could simply dunk their tags into a different bucket.

Later, when two participants met, their Tags would invisibly exchange their answer data, and light up LEDs to indicate how closely they matched. For each answer the pair had in common, a green

LED would light. For each answer the pair disagreed upon, a red LED would light. The LEDs were unsorted, so the participants would have to have a conversation to determine which questions they had answered similarly and which they differed on—the point of the Tags was to stimulate conversation, not replace it.

In the several meetings in which we performed “Tag events,” we found the Thinking Tag to be a great conversation-starter. When two people met, the Thinking Tag effectively displayed something about their *relationship*—what they had in common—not just the typical static display of name and affiliation. Since a main benefit of the research consortia is to bring together people from different companies into informal relationships leading into professional collaborations, it was quite valuable for sponsors to find it easier to meet each other.

After the Thinking Tag consortia, we collected the Tags from our sponsors. The design of the Tag had been driven by the particular concept of the question/answer kiosk and red/green affinity displays just described, but afterward we stepped back from this specific application and thought about the technology we had created. What we had on our hands was a collection of several hundred tiny computers that could be worn on one’s shirt, and could communicate with each other. Surely these could be instrumental in a wide variety of learning and play scenarios, not just the affinity party game!

From Learning about Communities to Learning About Science

In brainstorming that followed, we realized that the Tags could keep track of who had met whom (in a rudimentary way, subject to limitations of their computational power). In the affinity application, other than the programming of the answers to the kiosk questions, the Tags were stateless. How your Tag reacted to another person was not affected by whom you or your conversation-partner had met in the past.

But the Tags’ operating program could readily be re-designed to perform such tasks as passing a “magic token” from person to person. This idea was taken up by Vanessa Colella, a graduate student in our research group, who created a classroom activity for high school students around a Tag re-designed to model the propagation of a virus throughout a population. In Colella’s project, called “Participatory Simulations,” a classroom of students each received a specialized “Virus Tag” that could propagate a simulated virus to other such Tags (Colella, 1998).

In the simulation, propagation parameters such as latency—the amount of time between when a Tag “got infected” and when the Tag displayed a visual indication of said infection—could be varied, and students could re-run simulations with various parameters modified or left constant.

In Colella’s design, the Participatory Simulation included two key ingredients: first, the participatory component in which students wore the tags and attempted to meet each other without catching the virus, and second, a discussion/analysis component in which Colella would lead the group of students through an analysis of what had occurred. The Virus Tags included the ability to reveal the unique ID of each person they had met, and which person had given them the virus; these featured allowed the group to reconstruct the spread of the electronic virus and thereby test their theories about how the virus worked.

From Tags to Crickets

In parallel to the continuing work on wearable computers, we realized that the core hardware of the Thinking Tag could be put in place in a new and radically smaller Programmable Brick. Whereas the Red Brick was about the size of a juice box, a Brick based on the CPU in the Tag could be truly tiny—about the same size as the 9v battery that would serve as its power source.

This was possible because of two important technology shifts: (1) the Microchip PIC processor, and (2) our byte-coded interpreter software strategy. The PIC processor (coupled with a serial memory connected by just two wires to the PIC processor) allowed us to put the processor/memory into a much smaller space than with traditional processor/memory architectures. In our software design, much of the complexity was off-loaded to the desktop, allowing us to build a device that is programmable by children and yet requires only the computational horsepower that is typically put into a standard computer mouse.

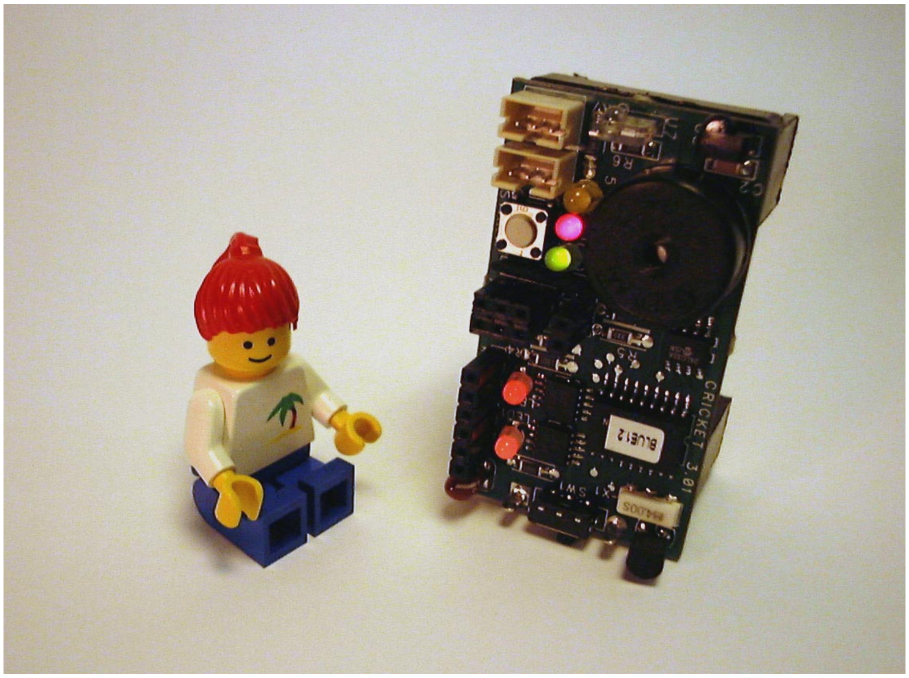

Figure 3: The MIT Cricket, with LEGO® Mini-Fig for size reference.

Core Cricket Design

The first Cricket was demonstrated at a Media Lab event in March 1996. This Cricket had the following feature set:

- An infrared communications system for inter-Cricket messaging and program download;
- two motor output ports;
- two sensor input ports;
- a pushbutton switch for starting and stopping the Cricket’s program;
- an audio beeper and three status LEDs;
- powered by a 9v battery.

One significant shift in our thinking that led to the Cricket was the success of the Red Brick in the classroom. We realized that a single design did not have to satisfy all needs; we could use Red Bricks where they were best suited and Crickets where they were best suited. For instance, the Crickets do not have a built-in display; if one were important, the project could use a Red Brick. (This limitation was removed with the addition of Bus Devices, described shortly.)

Because Crickets were simple and easy to revise, we created a plurality of Cricket designs. We realized the limitations of the first Cricket (two motors and two sensors), so we designed other Crickets:

- A “Display Cricket” that had a bank of eight bi-color (red/green) LEDs that could be lit under user program control. It also had three sensor inputs but no motor outputs.
- A “MIDI Cricket” that contained a versatile waveform synthesizer chip, along with sensor inputs.
- A “Science Cricket” that provided true analog-to-digital converters on the sensor inputs (allowing the use of a greater variety of sensor devices), along with support for 16-bit numbers in the Cricket software. (The Science Cricket employed a more powerful version of the Microchip PIC controller.)

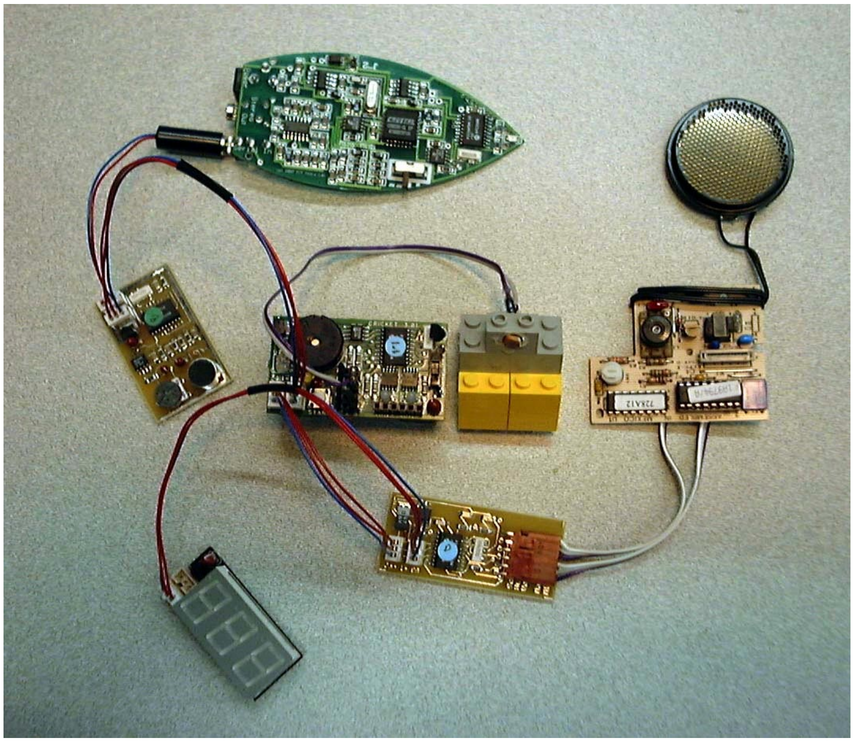

Figure 4: Cricket with Bus Devices.

At center is the “Blue Dot” version of the MIT Cricket with a simple light sensor to its immediate right. Arranged around, from top going clockwise, Bus Devices: MIDI Boat music synthesizer, Polaroid ultrasonic distance sensor, 3-digit numeric LED display, and sound sensor.

The Cricket Bus System

In parallel with this development of multiple Crickets, we were working on a different way of supporting multiple devices—the Cricket Bus system.

As we were designing devices to interface with the Crickets, we realized that often a custom circuit would be required to connect a particular device to the Cricket. Up to this point, we had been designing entirely new Crickets with different capabilities each as a result. For example, to get an LED display, we created the Display Cricket; to get music, we created t he MIDI Cricket.

We came to realize that instead we could bundle the specific circuitry required to make a new device work with that device itself, in a sort of object-oriented hardware strategy. Then, a simple communications protocol could let the new devices talk to an existing Cricket. Thus was born the idea for the Cricket Bus.

Our first Cricket Bus device was an optical distance sensor that employed a special part manufactured by the Sharp Microelectronics Group. This component used a specific, unusual communication method to interface with an external circuit. By conceiving the Sharp distance sensor as a bus device, we were able to bundle the special hardware and software required to talk to the device with the device itself, yielding a common protocol to talk between the Cricket and the bus device (see diagram).

Over time, we have come to develop a large collection of bus devices, all of which can communicate with a standard cricket design (see Figure 4).

The Bus System also allowed us to converge on a single Cricket. Our so-called “ Classic Cricket” (with two built-in motor drivers and two resistive sensor ports merged with the “Science Cricket” (true analog sensor inputs and 16-bit number support) to become, with the addition of the Bus Port, our standard design. The need for different Cricket versions became drastically reduced, since nearly any device can be interfaced to this standard “Blue Dot” Cricket using the Bus system.[1]

Applications and Research Focus

> “The things that scientists do are the same things that you have to do to help you design technology.”
>
> A fifth grade student

The design of Crickets was heavily influenced by its anticipated applications in our work with children in the context of the Beyond Black Boxes (BBB) project. The BBB project provides a theoretical framework, computational construction kits (both hardware and software), and a collection of project ideas for a constructionist approach to science education. We hope that this material will inspire and enable children (and educators) to design their own scientific instruments for investigations which they personally find meaningful. Through designing their own instruments, children gain a deeper appreciation and understanding of many scientific concepts.

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[1] We labeled our software revisions of the Cricket operating program by the colored dots we physically placed on the Crickets to identify them.

And, this happens in two important ways: Children not only reflect on and apply already familiar concepts, but may also come in direct contact with other scientific ideas in a natural way.

In addition to gaining a deeper and more concrete understanding of scientific ideas, children also develop a much richer sense of the interplay between science and technology. In the process of building their own instruments, they come to appreciate the importance of good design and sound engineering practice. In this regard, existing technological and scientific artifacts are excellent resources for ideas. BBB projects allow children to gain a new perspective into the tools and instruments around them. By examining and critiquing the systems around them, children get to peer into these modern “black boxes,” see their inner workings, and reflect on the many powerful ideas hidden behind the design of many of these devices. Since they are engaged in design activities themselves, discussions about good and bad designs, give them and us a window into what they have internalized in the process of interacting with the many opaque tools and appliances around them. In this process, beyond uncovering and discovering the mechanisms and programs that they may want to use to activate and control their creations, children also express their own expectations and sensibilities towards the design of devices and systems.

We believe that it is important to encourage attention to and reflection on design not only in an engineering sense but also an artistic sense. In this regard, the BBB project differentiates itself from many other “hands-on” approaches to science education in that it recognizes the power of and provides tool for integrating children’s interests in the arts and music with scientific explorations. The importance of enabling children to take part in projects that are multi-disciplinary in nature cannot be overstated. Construction material and project ideas that appeal to a broad range of interests allow multiple entry points into science, mathematics, engineering, design, art, and music for all types of learners. These materials not only make new knowledge domains accessible, but also provide new ways for children to relate to domains of knowledge to which they have already been exposed.

As a part of the BBB project, we work with students, teachers, and mentors in a number of different settings. In this section, we will focus on a number of investigations that they have proposed and carried out. In the following discussion of some BBB projects, we will focus on the educational goals that inspired and remain at the core of our research. In presenting the following case studies and our future research plans, we invite you to think about the following core questions with us: What educational opportunities do these new tools afford? What scientific and social values do these types of projects nurture? What implications do these activities have for classroom structure and practices?

Crickets as a Scientific Tool

Martha Greenawalt is one of the many excellent teachers who have been working with us on the BBB project. She is a science coordinator and teacher in the Bronx public school system. Following our BBB workshop last summer, she designed a series of heat/temperature activities for her 4th and 5th graders, using only Crickets and temperature sensors. Having already worked with small groups of children on some Cricket projects, she wanted to try the technology in the regular school setting. She worked with groups of 25 students during the regularly scheduled science classes.

She spent a couple of weeks introducing the Crickets hoping that as their novelty wore off they would assume the status of a tool for scientific investigations and discussions. She showed them how to write simple programs for the Crickets to collect data, upload the data to the desktop computer, and graph it using our graphing software. She also designed short activities that highlighted the communication capabilities of the Crickets.

After introducing the Crickets and some of their capabilities, she allowed her students to have some free exploration periods with the Crickets and temperature sensors. The temperature sensors for the Crickets give raw sensor readings without conversion to Celsius or Fahrenheit scale equivalents. When she shared the Crickets and the activities she had designed with her fellow science teachers, they wanted to know the conversion factors to be able to use the established temperature scales with their students. Martha could have easily modified the software to show the temperature readings in Fahrenheit, but she had a very different idea about using this feature of the Crickets. She wanted to bring her students into the discussions that would ground the process of defining a temperature scale into their everyday experiences.

On the BBB mailing list, in response to another teacher's posting in which she asked about the conversion factors, Martha posted her lesson plans and her approach to exploring the educational opportunities afforded by the Cricket's raw sensor readings. As the discussions on the mailing list continued, she posted many of her observations and reflections. Her discussions with her students and her fellow teachers capture the spirit of the BBB projects very well. We will reproduce one of her postings to the list to give the reader a sense of the level and nature of the discussions in her classrooms. Our clarifications are added in italics:

> "I am working with 4/5th graders who have widely varying experience with and understanding of traditional temperature scales and what those values represent. We decided that we wanted the kids to attach the Cricket temperature number to a real value rather than another abstract number. In other words, we want them to equate 215 with something hot, like hot water in a cup, rather than to push them to connect it to (often partially grasped) numbers from a temperature scale.
>
> "We plowed ahead. Kids did investigations using the receive box (*on-screen display of sensor values*) and recorded the Cricket's temperature value of a variety of items. (In retrospect this was a good move, because it grounded the numbers in real life. We can look at our notebooks and say x value is cold, y value is hot etc.) One class went on to collect temp data over time on a variety of walks. When they started looking at the graphs there were absolutely no questions about the values we were seeing! The kids appear to have bought into the Cricket system as a system. They work with it on its own terms: kid, Cricket, and world. They don't seem to care about the Celsius and Fahrenheit systems at all.
>
> "I sent out those early graphs to a number of tech people in the Center for Collaborative Education circle for comment. The man with the most solid scientific background immediately requested translation of the Cricket values to familiar temp values. He also wondered if we had talked about the x and y axis of the graphs to clarify what they meant. His questions made me realize that the kids, because they had created the thing, had a deep understanding of how the numbers and the graph worked. The definitions he was requesting would have been very "teacherly" (in the old chalk and talk sense) if we had introduced them to the class. The kids simply don't need or want the C and F conversions

> now. Within our little intellectual circle of the classroom, there is no need to make conversions. My sense is that we will only develop that need if/when we attempt to communicate with people who don't have experience with the Cricket system.
>
> "Of course, I had to explore this some more, so we tried something else with the second class. Before we did any temp walks (to explore Crickets' capacity to collect data and store it) we looked at the data that everyone collected in their initial/immediate receive investigations. As a compromise, we thought we would create a scale of the Cricket temp values. (One of the girls in class suggested calling it "Cricket temp number ratings") The idea was to create a set of benchmarks: each benchmark establishing a range of possible temp values for a given event or thing that the kids had investigated. In other words: the kids would know that x range of numbers was hot like hot water or cold like ice water, or warm like the monitor screen. I thought benchmarks would be a good compromise between absolute experiential knowledge (like the class that I already described) and conversion to another scale.
>
> "I thought. Inquiry teaching and learning is fun because you never know exactly where you're going to go! Suffice it to say that we didn't create the benchmarks. Kids left for the day with the question; "Do you trust this data? Why, why not?" for homework.
>
> "The readings were not reliable at all; Wacky, in fact. Which leads me to ask a number of ideas/questions about how we use Crickets and the temp data we are collecting with Crickets. (Later for that) Calibration would seem to be the order of the day in the second classroom.
>
> "Perhaps many of the BBB students working with Crickets are older or more fluently literate/numerate than my kiddies and conversion to familiar temp scales makes sense. However, the Crickets are allowing us to discover amazing variation in thinking and understandings among our 4th and 5th graders. We're really trying not to play fast and loose with words, numbers, pictures or concepts and because it's all so new to all of us it has been easier for us (adults) to slow down, look and listen to what the kids are making of this.
>
> "I could go on and on. And have. I would be delighted to receive feedback. I am curious to hear others' experience around this topic."

Martha's reflections represent the core values of what BBB would like to cultivate in the culture of our classrooms. Our image of students and teachers is that of investigators in an active dialog. In this image Martha and her students are colleagues in a genuine scientific exploration. They are not reproducing a known experiment with known outcomes; instead they are getting a chance to appreciate scientific inquiry as rich and engaging human activity.

Figure 5: The Nail Salon

The Nail Salon: An Artistic Approach to Science and Engineering

Many children, primarily boys, when they find out that Crickets can control two motors, decide to build cars as their first projects. We have designed other introductory activities that suggest other alternatives to cars. In one particular activity, we provide everyone with traditional construction material (such as LEGO and balsa wood) and other arts material, and ask them to make kinetic sculptures that sense something about the world and generate a musical or kinetic reaction. At Sensory Design, a workshop held in the summer of 1998 at the Media Lab, Elise (10 years old) was inspired by this initial activity and decided to make something very different from a car. She made a Nail Salon (Figure 5).

Her Nail Salon consisted of:

- a place for her to insert her hands;
- a sensor to detect her hands in the proper place;
- a gear system that move a number of cotton-balls back and forth to polish her nails;
- a rotating feather to dry off your nails when she was done, and
- a background music for her to listen to while her nail was being done.

As we have often found to be the case, the art materials were a critical addition to the construction kit. Elise spent a long time, intertwined with tweaking with and fine-tuning the mechanical parts of her project, decorating her nail salon. Her attention to detail and the aesthetic quality of her project mattered to her a lot. It was her affective relationship with what she had made kept her engaged. She worked on both the engineering and the artistic aspects of her design to make her device behave and feel as she envisioned it.

And, what did Elise learn in the project? She experimented with various sensors, compared their outputs for conditions under which she thought her device would be used, and decided on the reflectance sensor or the light sensors as the best candidates for detecting the user's hands. She also went through a number of iteration for the gear mechanism responsible for polishing your nails. She tried many motor settings to determine the most suitable power levels. All through her creative process, she was mindful of the most natural and comfortable design for the actual use of the device. As an added bonus, she programmed the Cricket to play music while one would get their nails done. Her project, even though may not have appeared technical or scientific at first, had much science, engineering, industrial and artistic design. These types of projects present an excellent path into and preparation for scientific thinking.

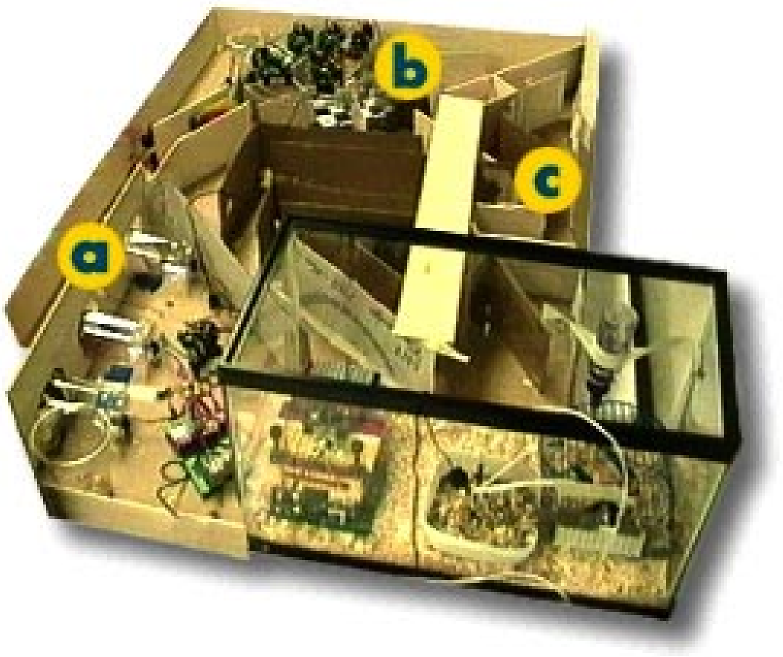

Figure 6: The Gerbil Maze

In section A, the plastic cups were covered with different colors of fabric; the children were testing to which colors the gerbils were more attracted. Section B was the “Food Court”; the gerbil’s food was separated into different colors, again separately sensed. Section C was the entrance to the maze in which the path that the gerbils took was recorded.

The Gerbil Maze

Another activity that interests children very much and leads to rich discussions is that of building sensors and instruments for monitoring pets. The Sensory Design was held in a space where we also kept a couple of gerbils in a cage. We told the group that some of us were interested in building things for the gerbils and anyone who wanted could join us in brainstorming about what things to make. At the beginning only one student, Veronica, connected to this idea strongly, but by the end, it became a community project and everyone contributed something to it.

Veronica began by building the gerbils their first LEGO house. After observing the gerbils go in and out of their new home repeatedly, she made them a second house which was much smaller than the first. She wanted to see which house they preferred. Her theory was that they preferred smaller and darker houses. After building the second house and observing the gerbils for a couple of days, she was beginning to see evidence in support of her theory. She wanted to have a better way of determining which house they preferred and by how much.

Her first idea was to use the sensors we had to see how often they visited each house and how long they stayed in there. She build doors for each house and used a LEGO light and a light sensor to count the number of visits made to each house. She plugged the light sensor into a Cricket, experimented to find out how much the sensor readings were affected when a gerbil passed by, and wrote a program to detect an entry/exit and counted them. She added a numeric display to see the current count easily. At this point, she wanted to know if she could determine the time they spent in the house. This led to very fruitful discussion.

One of the two high school students who had some previous programming experience with the Crickets offered to help her write the program for tracking the gerbils' activities. The program involves using the timer primitive in Cricket Logo to calculate the length of the time interval between two consecutive events registered by the sensor at the door. At this point, they realized that they needed to detect an entry and that their current scheme was not distinguishing between entry and departure. So they designed a different doorway with two light/reflectance sensor arrangements. Now by looking at the order in which the events occurred, they could determine whether the gerbils were leaving or entering the room.

Another one of the participants, Jose, suggested using a temperature sensor for detecting whether there was a gerbil in a house or not. He added a temperature sensor to the smaller house and wrote a program that successfully detected if there was a gerbil in the house. This technique was not as effective in the larger house unless he used more than one temperature sensor. The most challenging aspect of this project for Jose was the calibration to account for the variations in the ambient temperature. What was important in this project was that he could build a system that did the right thing at least in the special case. Then as he used his setup in different conditions, he was able to build on what he had to account for the other subtleties that he was discovering.

As the workshop went on, the gerbil house got more and more attention from the other kids. They would all take a break for their own project and talk to Veronica about their ideas for the gerbils. In one case, John spent a day building a counter for the gerbil wheel. He mounted a magnet on the wheel and used a Hall effect sensor and a Cricket to write a program that counted the revolutions. Every time the magnet passed the sensor, the counter increased by one. The counter value was displayed on a numeric bus device. At our prompting, he began to change the program to display the average speed of the gerbils on the exercise wheel. John and one of the other high school students in the group worked through the timing issues involved in writing this program.

When the other kids saw this display, there were suddenly a lot of ideas about the other things to monitor about the gerbils. For example, Monica wanted to know how frequently the gerbils drank water and exercised during the night. One idea was to video tape the cage the whole night and look through the tape the next day. John thought that reviewing hours of video would be too tedious and boring. Inspired by one of the sample projects we had shown them at the beginning of the workshop, he proposed to build a contraption that would be triggered by a Cricket to film the cage for one minute. This presented a very nice challenge.

He and one of the high school student mentors, David, went off to design the needed mechanism. Monica was interested in working on the sensor arrangement for detecting the gerbils at the drinking bottle. She successfully used a reflectance sensor for this purpose. Everything was ready to go on the following day and everyone went home in anticipation of the video clips on the following day. On the following day, we only had two minutes worth of video after which they gerbils had chewed through the cables from the sensors to the Cricket outside the cage. In addition to rebuilding and reinforcing the cables, the children decided to not only record the data about the gerbils' activity on their exercise wheel, but also tape the gerbils running. So they modified their program to start taping for as long as the gerbils were on the wheel or at the drinking bottle. The next day they had footage of the gerbils doing both those things.

The gerbils provided an enormous learning opportunity. In addition to the individual projects we have mentioned so far, the children collectively, designed a maze for the gerbils with a lot of sensors all over the maze to monitor to check for food and color preferences. By the end they had provided each sensors in multiple contexts. They had become fluent with their use and their range of applicability. It is our hope that the tools we are designing would make it easier for many classrooms to engage their students in these types of generative and open-ended activities.

Musical Stress Meter

Marcos, after spending the first few days of the workshop on building and refining a Cricket-controlled car, started to make a musical instrument. His instrument mapped reflectance sensor readings from color fabric cutouts to musical notes. One of the early challenges in this project was that the readings from the reflectance sensor were inconsistent and at most only distinguished between four different colors. Marcos spent a day playing around with different sensors such as a light sensor to see if he got any better results. The improvement was marginal.

The next day we introduced a few body-monitoring sensors (heart-rate monitors, galvanic skin response sensors, and electrocardiogram [heart response] sensors) to the group. For a couple of hours, everyone used the graphing software to generate and analyze real-time graphs of the data from a Cricket monitoring an electrocardiogram sensor. Some students made visual displays for their heart rates. One student in particular made a display with a LEGO figure running in place at speed that varied in response to variations in his heart rate.

Marcos was playing around with the galvanic skin response (GSR) sensor. The GSR sensor measures the skin conductivity of an individual, which increases when people are stressed, anxious, disturbed or shocked. Marcos had the same Cricket he was using with his musical instrument without having reprogrammed it. When he ran the program on the Crickets, he was pleasantly surprised. He liked the variations in the notes caused by the variations in his GSR reading. This prompted a two-day investigation into other people's GSR readings. He carefully divided the most common ranges of sensor readings into pieces that mapped nicely into different notes. He set up the graphing software for the real-time data collection and invited people to try to change the musical notes being played by startling each other or asking embarrassing questions from each other.

In this project Marcos's interest in music brought him much closer to the data from a sensor, which he would not have normally found very engaging. At the end, he wished he were able to control various qualities of his favorite pieces of music. We are currently working on improving the Midi and other music output and control capabilities of the Crickets. We are redesigning and expanding on the current design of the Midi bus device for the Cricket.

Future Directions

Our work continues along two fronts, mirroring the structure of this paper: research into new technologies, and research into new applications and ways of learning. These two activities are intertwined and interdependent; a new application idea can lead to new technology, and vice-versa.

For example, in the musical stress meter project, Marcos did not have access to a high quality musical output device; he made do with the simple piezo beeper that is built into the Cricket. After working with him, we were inspired to revisit our earlier work on the Midi Cricket, which resulted in the Midi Boat, a bus device that could be plugged into our current Cricket.[2]

As an example in the other direction, of new technology leading to a new application, consider one of our latest bus devices, an acceleration sensor. This device has many applications to the Beyond Black Boxes project, acting as a motion, inclination, and shock sensor. Yet these devices did not exist as inexpensive, easily-packaged units until most recently. We are always staying abreast of new technologies that are valuable to our interests.

One of our challenges is build a collection of project and activity examples around theme of children pursuing scientific explorations. In the robotics domain, there are many examples of project ideas and curricula (for instance, robot contests modeled after MIT's 2.70 and 6.270 projects) to draw from, but we are only now building such a collection of ideas (this paper; Resnick, et. al., 1999). We are particularly focusing these efforts to leverage new technologies that are commercially available, such as the LEGO Mindstorms Robotics Invention System.

An important aspect of the Beyond Black Boxes program is our focus on the engineering aspects of scientific inquiry. Much of the work of real scientists involves the construction of new apparatus that allows better observation of phenomena or exploration of a physical principle. Yet this design process is often absent from science in school settings. With the BBB program, we argue for a more integrated approach to science, mathematics, and engineering, a sort of "Engineering for All Americans" in the sense of the 1989 *Science for All Americans* manifesto of the American Association for the Advancement of Science.

In our Digital Manipulatives initiative (Resnick, et. al., 1999), we are exploring ways of bringing these ideas to younger children, ages five to eight. By embedding computational power in traditional children's toys such as blocks, beads, and balls, we hope to provide children with new ways of connecting to scientific and mathematical concepts. For example, we have created Programmable Beads, a string of bead-like elements that can pass messages and programs along the string. In one application, a string of beads passes a light down the string and back, but some beads are probabilistic, and randomly reflect the light rather than passing it. With materials like this, young children have a new of playing with ideas of chance.

As we have built more and more, smaller and smaller intelligent devices, it becomes evident that these objects need to talk with one another, and not become isolated islands of technology. These devices and the everyday devices in children's world—cassette stereos, Gameboys, and

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[2] The Midi Boat was designed by Josh Smith and Josh Strickon, two Media Laboratory graduate students. We adapted their design to our Crickets.

cameras—must be interlinkable. More importantly, children should see them as building-blocks in larger construction set, rather than as special-purpose devices (Mikhak et. al., 1999).

One concern about the widespread introduction of technology into children's lives is that we are becoming enslaved to technologies we do not understand. Instead, it is important that the next generation of children gains a sense of control, ownership, and empowerment, and become active participants in understanding and designing our future. The construction kits we propose enable children to become authors of rich and wondrous technological artifacts. The magic of technology is only better appreciated as children not only use technology, but also create it.

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References

American Association for the Advancement of Science [AAAS], 1989. *Science for all Americans.* Washington, DC: AAAS.

Borovoy, R., McDonald, M., Martin, F., & Resnick, M., 1996. "Things that blink: Computationally augmented name tags," *IBM Systems Journal*, 35 (3), 488–495.

Braitenberg, V., 1984. *Vehicles: Experiments in Synthetic Psychology*. MIT Press, Cambridge, MA.

Cavallo, D., 1999. "Project Lighthouse in Thailand: Guiding pathways to powerful learning." In *Logo Philosophy and Implementation*, Logo Computer Systems Inc., Montreal, Quebec.

Colella, V. S., 1998. *Participatory simulations: Building collaborative understanding through immersive dynamic modeling.* Unpublished Master's thesis, Media Laboratory, Massachusetts Institute of Technology.

Martin, F. G., 1988. *Children, cybernetics, and programmable turtles.* Unpublished Master's thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology.

Martin, F. G., 1996. "Kids Learning Engineering Science Using LEGO and the Programmable Brick," presented at the 1996 meeting of the American Educational Research Association.

Mikhak, B., Martin, F., Berg, R., Resnick, M., and Silverman, B., 1999. "The Children's Machines: Handheld and Wearable Computers Too," *Proceedings of the 1999 International Symposium on Handheld and Ubiquitous Computing,* Karlsruhe, Germany.

Papert, S., 1980. *Mindstorms: Children, Computers, and Powerful Ideas.* Basic Books.

Papert, S. and Solomon, C, 1972. “Twenty Things to Do with a Computer,” *Educational Technology Magazine*, Englewood Cliffs, N.J.

Resnick, M., Berg, R., Eisenberg, M., Turkle, S., and Martin, F., 1996. Beyond Black Boxes: Bringing Transparency and Aesthetics Back to Scientific Instruments. Proposal to the National Science Foundation. Available from MIT Media Laboratory.

Resnick, M., Rerg, R., and Eisenberg, M., 1999. “Beyond Black Boxes: Bringing Transparency and Aesthetics Back to Scientific Investigation,” *International Journal of the Learning Sciences*, in press.

Resnick, M., Eisenberg, M., Berg, R., and Martin, F., 1999. “Learning with Digital Manipulatives: A New Generation of Fröebel Gifts for Exploring ‘Advanced’ Mathematical and Scientific Concepts.” Proposal to the National Science Foundation, May 1999.

Turkle, S., 1984. *The Second Self.* Simon and Schuster, New York, New York.