

GoGo Board: Augmenting Programmable Bricks for Economically Challenged Audiences

Arnan Sipitakiat¹, Paulo Blikstein², David P. Cavallo¹

¹ Media Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139

Tel: (617) 253-2041, Fax: (617) 258-6264

² School of Education and Social Policy, Northwestern University, Evanston, IL, 60208

Tel: (847) 467-6752, Fax: (847) 491-8999

Email: {arnans, cavallo}@media.mit.edu; paulo@northwestern.edu

Abstract: The Programmable Brick, a small autonomous computer with sensing and control abilities, has been a topic of educational research for almost two decades. The use of this tool has now reached beyond research projects through its commercial availability. However, high cost has strictly limited its audience to only well-funded schools and institutions. Can learning activities involving Programmable Bricks take place in an economically challenged context? In this paper, we present an attempt to challenge this question by presenting a new framework that turns the acquisition process of Programmable Bricks and its necessary materials into a rich learning process. We present the GoGo Board, a low-cost Programmable Brick that allows the user to actively participate in its production process. We discuss the use of found and broken materials as sources of construction supplies. We analyze two case studies from projects developed in Brazil from 2002 to 2003. Specifically, we discuss the design aspect of the GoGo board framework that allowed for diverse and socially relevant learning projects to take place.

Keywords: Programmable Bricks, Augmenting, Low-income Communities.

Introduction

Previous research, primarily inspired by the intellectual tradition of constructionist learning (Papert, 1991), has been done demonstrating how Programmable Bricks, a small general-purpose computer with sensing and control capabilities (Martin, 1988; Sargent, et al. 1995), can be used to enrich learning activities (See Martin & Resnick, 1993; Granott, 1993, Resnick, et al. 1996; Sipitakiat, 2001; Blikstein, 2002). The activities are typically project-based and involve the construction of concrete physical objects motivated by the learner's personal interest. Common projects include robot prototypes, vehicles, interactive installations, environmental monitoring, and human-computer interfaces (See Martin, 1994; Sargent, 1995; Resnick, et al. 2000). While constructing projects, learners get in touch with ideas from various knowledge domains, such as Mathematics, Physics, Chemistry and Engineering. We share the belief that the constructionist approach can promote rich learning and deepen the learner's understanding of concepts that he or she comes across while pursuing their project.

This work draws from this existing research but focuses on the dissemination of the learning activities to broader communities, especially in low-income settings. This requires both improving access to the learning materials and the development of learning activities compatible with those settings. Access to Programmable Bricks has often been limited due to their restricted availability and prohibitive cost. This work presents the GoGo Board, a low-cost Programmable Brick that can be locally constructed. We show how access was improved in our case study of schools in Brazil. However, technology availability alone does not entail better education (Papert, 1987). Advances in learning tend to happen more felicitously when innovation takes place not only in the materials but also in the sociology and the organization of the learning environment (Papert, 1980; Cavallo, 2000; Sipitakiat, 2001; Blikstein, 2002). This work does not present the GoGo board just for the sake of technology dissemination but as a means to better study how high density of digital technology can create new pathways for learning, particularly in communities with scarce resources.

We begin by briefly introducing the Programmable Bricks. We then present the GoGo Board and the design choices that have been made during its development. Next, we introduce a framework that has been developed for the use of GoGo boards with locally available materials including found and broken materials. Subsequently, we present an ethnographical account of how they were used in workshops conducted in Brazil during 2002 and 2003. We conclude by discussing the observed two main impacts of the GoGo board framework. First, it

allowed new, diverse audiences, especially in low-income settings, to have contact with technologically rich learning environments. Secondly, it provided a new level of abstraction (building boards, using locally available materials, and repurposing materials) that resonated with ways of thinking that pre-exists in the culture.

Programmable Bricks

The idea of using robotics and sensors in learning activities maps back to the early 1970s, when Seymour Papert, then at the MIT Artificial Lab, built a programmable turtle with a reflective light sensor (Papert, 1971). This idea eventually evolved into the Programmable Brick concept and was first developed at the MIT Media Laboratory in 1987. Since then, many variations of the concept have been implemented (see Figure 1) with different design goals (Mikhak, et al. 2000). The LEGO Mindstorms Kit (also known as the RCX Brick) has been commercially available since 1998. The Cricket (Martin, et al. 2000) is one of the most widely used platforms by researchers who focus on extending the use of the Programmable Brick into new learning domains. Most recently, the MIT Tower (Lyon, 2003), a new rapid prototyping system which can also function as a Programmable Brick, has incorporated new cutting-edge technologies (such as TCP/IP networking, wireless communication, and signal processing) into a highly modular design. A myriad of other, smaller scale commercial formulations also exist, despite not being directly connected to this tradition, both in the field of robotics and sensing.

GoGo Board

The GoGo board is a variation of the Programmable Brick. It has two modes of operation: autonomous and tethered. In the first mode, the board is programmed using the Cricket Logo language, and procedures are stored and executed from the onboard memory. In the second mode, the GoGo board remains connected to a computer via a serial cable, and provides sensing and actuation capabilities for any programming language that supports serial communication. We have developed several libraries for the board, allowing it to work with different environments, such as Microworlds Logo, Imagine Logo, Squeak, Microsoft Visual Studio, MS-Office, and Macromedia Director.

Design Goals

Our core idea with the GoGo board was to borrow some of the fundamental features of the Programmable Brick but to implement and use it in ways that can expand the learning experience to a broader population. The following items are characteristics of the GoGo board designed to support our goal.

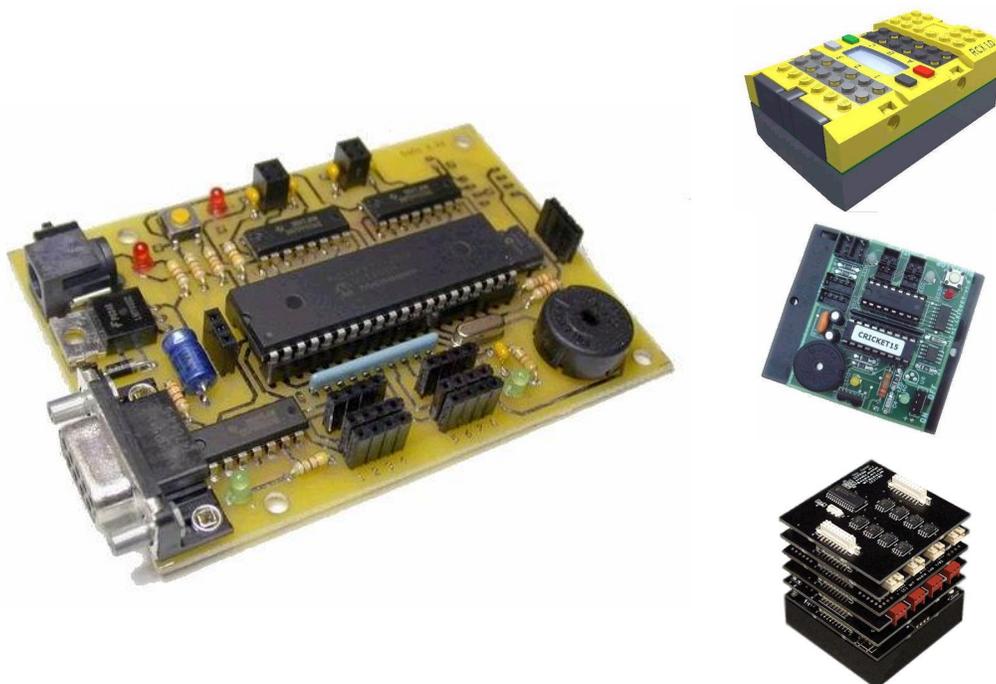


Figure 1. Variations of the Programmable Brick: The GoGo Board (left), the LEGO RCX Brick (top right), the Cricket (middle right), and the Tower (lower right)

Low-cost

Prices of commercial Programmable Bricks are high. For example, the LEGO Mindstorms kit, which includes some construction materials, costs US\$ 200 in the United States. That price reaches US\$ 400 in Brazil, due to import taxes and fees. Cheaper alternatives such as the Handy Cricket are available, but they still cost at least US\$ 100 in the United States, without construction materials. The high cost usually condemns those tools to very limited uses in school settings. In many communities (not exclusively in low-income settings), the high cost of commercial Programmable Bricks both limits how widely they can be made available and restrains ways in which people use them. For example, Sipitakiat et al. (2002) show that some promising project ideas are discarded even when the materials are available, due to the fear of breaking or losing the tool.

The prices of LEGO and other commercial Programmable Bricks are usually high not necessarily because of their intrinsic functionality, but due to the need for technical support, product warranty, cascading taxes, marketing and profit margin. This is a typical situation in a producer-consumer business model. Conversely, the GoGo board allows for a rather different model, blurring the boundaries between producers and customers by creating a possibility for consumers (at least some of them) to also play the role of producers. For example, the GoGo boards that were used in our case study in Brazil were produced locally by a private company hired by the schools. Thus, they were paying only for the components and labor while getting a product with equivalent functionality of the LEGO RCX Brick. The cost of each board was dramatically lower: approximately US\$ 30 (1).

Possibility for Local Construction of GoGo Boards

The GoGo board has been designed to make the board construction process as simple as possible. The goal is to allow boards to be produced locally by schools or motivated individuals. There are three main design differences between the GoGo board and other mainstream electronics devices. First, we do not aim to make the GoGo board to be the most “cutting-edge” or “feature-packed.” The most advanced and most capable is not necessarily the best for schools. We choose the “less but more humanly understandable” path rather than the “sophisticated but less penetrable” one. For example, the GoGo board uses a simple but widely available microcontroller rather than more powerful ones, which are arduous to find in other countries, even being closely priced.

The second difference is the focus on human-size components. The current design trend of modern electronics is miniaturization. As a result, the assembly process becomes increasingly dependent on specialized equipment and sophisticated production processes. The assembly cost increases and can only be justified when the device is mass-produced. The GoGo board, on the other hand, facilitates on-demand construction by providing a much simpler assembly process. It uses larger packaging versions of the electronic components. No surface-mount components are used, for example. The traces and pads on the printed circuit board are also designed to be large, which allows board assembly using only basic soldering equipment. This simplicity allows boards to be produced as needed and possibly by anybody with minimal soldering skills.

The final difference is the use of locally available components. This is fundamental when using the GoGo board in developing countries. The choices made for components on the current version of the GoGo board (such as the microcontroller, connectors, LEDs, and the clock) were based on our extensive research of their local availability in Brazil. We found out that the needed parts not only exist, but cost less than in the United States. Components for a GoGo board in Brazil costs approximately US\$ 18 compared to US\$ 25 in the United States.

Use of Found Materials

When using the GoGo board in a project, it is necessary to have access to sensors, actuators, and other construction material (i.e. wood, Styrofoam, paper, gears). In addition to purchasing some of these materials, we have been working with found and scrap materials. The aim is not only to lower the cost but also to broaden the possibilities of construction materials. Broken electronics and electrical appliances are rich sources for sensors, motors, mechanical parts, and casing structures (Blikstein, 2002, 2003). Many of these materials can be re-appropriated. For example, broken a CD-ROM drive tray can be used as a push and pull mechanism; the optic sensor in a broken mouse can be re-purposed for use as a presence sensor; the motor and gearing of a broken tape player can be used as a high torque mechanism; a radio dial can be turned into a circular-to-linear movement converter.

Data Collection and Analysis

The analysis presented in this research is based on our ethnographic study of two projects using the GoGo board in Brazil from August 2002 through November 2003. The case studies presented here are selected from approximately thirty projects done by students and teachers during our field-work experience. We chose to portray only a few projects but in substantial detail in order to maintain the learning context that our material innovation builds upon. This approach allows us to thicken our discussion (Ryle, 1971; Geertz 1973; Falbel, 1989) by keeping intact the social context of the situation from which the discussion arose.

Bradesco Foundation Schools

Since April 2002 we have been working closely with a network of schools run by the Bradesco Foundation, a non-profit organization in Brazil. The Foundation manages 39 schools across the country, all provide free tuition mainly for low-income families. In the past 14 months, our research group has done projects at seven of these schools, with teachers from the entire network. Fourteen weeklong introductory and follow-up workshops were conducted (25 to 40 hours each). In each of them, a group of approximately 25 people (70% students and 30% teachers, on average), divided in four to six groups, and pursued various projects around “The City That We Want” theme. They constructed computational models, robotics prototypes and video/photo documentaries of how they wanted to improve their city or community. Different kinds of materials were used, including pre-existing LEGO, crafts materials, Logo programming environments, and digital cameras. The GoGo board was introduced starting in October 2002. The Bradesco Foundation has since produced two hundred GoGo boards for immediate use in its schools, all made in Brazil and with locally-obtained parts. The projects were facilitated by MIT graduate students.

Schools in the City of São Paulo

In 2001 our research group began collaboration with the Municipal Secretariat of Education of São Paulo, Brazil. Approximately 30 schools in the city have since participated in the project. The work in São Paulo that is addressed in this work occurred between August and December 2002. The activities were similar to those in the Bradesco Schools and were also based on projects around the “City That We Want” theme. In each school, leading teachers decided how to organize the activities in terms of number of children, hours and overall infrastructure. On average, projects took a total of 30 to 40 hours and involved approximately 20-30 children and 1-6 teachers. A team of six graduate students from MIT and the University of São Paulo facilitated the projects on a rotating basis (participating in 50% of the total hours, on average). Two hundred boards were produced locally for the schools.

Case Studies

We begin by showing concrete case studies of how projects typically take place and how they can lead to our subjects of interest. Then, we zoom out to show evidence of the need and pertinence of such devices in relatively large school systems in Brazil, which we believe represent common issues of many other developing countries.

Coqueiros Investigation: An Example of Project Development and Evolution

This example was drawn from our work with the Bradesco Foundation. It took place in a boarding school in Bodoquena, a remote city of eastern Brazil, three hours away from the state’s capital. Because of its isolation, the school produces most of its food locally with the assistance of students. While we were considering project ideas, a group of five students and two teachers reported to us that they noticed that their coconut trees (“coqueiros” in Portuguese) were not yielding as many coconuts as before. They wanted to address this problem.

Their first explanation indicated a very straightforward reasoning: provide the coconut trees with more water and they will bear more coconuts. We pushed their idea further by asking them how they could know for sure whether the problem was lack of water. We agreed that one good direction was to conduct a soil humidity test, which was a good application for the GoGo board. It could be programmed to periodically sample and store sensor data. The benefit of this method was that data could be collected over a large time period (many hours or days). Then students could upload the data to a computer to visualize and interpret it. Humidity readings could be collected together with other environmental factors such as sunlight and temperature.

After a few days of work, the focus of the project was shifted from the coconut trees to soil humidity sensing, which was a challenging problem in itself. It was one occasion where students decided to go deep into one fundamental aspect of a larger problem. This was a glimpse of the project’s long-term potential. It is worth noting that this project is still continuing (as of November 2003), since commencing in October 2002.

We did not have a humidity sensor at hand, but with some on-line and empirical research we learned that soil resistance is inversely proportional to the soil humidity. Since resistance is what determines the sensor value measured by the GoGo board, we could create a soil humidity sensor using two simple electrodes (in this case wires soldered to paper clips). There were obvious trade-offs between simplicity, accuracy, and consistency. Even though just plugging two wires into the soil worked, the readings were inconsistent from one experiment to another. We later learned about porous blocks, which are used in commercial sensors to reduce the sensor's inconsistency caused by the variance of soil properties (such as salinity) and the spacing of the electrodes. Porous blocks are made of materials such as gypsum, ceramic, nylon and fiberglass. We searched for these materials from objects that existed in the school. After some testing we settled with casting plaster scavenged from the school's healthcare center (Figure 2). The performance of this new sensor was satisfactory to the team. Purchasing a similar sensor from a commercial vendor would not only be extremely expensive but unfeasible for this rural school.

Matching the Right Tool with the Right Job

The construction of the humidity sensor spun off a new project when a few students and teachers wanted to construct a system that would automatically water a garden when the soil gets dry. Six months later (April 2003) when we re-visited this school, the teachers and students had constructed the system using a solenoid switch to control the water. The system was powered by a solar panel connected to a car battery (the solenoid switch and the solar panel were repurposed from other unused devices).

The construction of the irrigation project required autonomous sensing and control. At the time, the GoGo board did not support output controls. Thus, the teachers and the students were trying to use the LEGO RCX brick instead. The RCX worked well but had one unfortunate glitch: it powers itself off after a short time period, which cannot be deactivated by the user. More important than this technical catch is the concern about the suitability of using the RCX for this application. The school wanted to use this project as a model to inspire more students to become involved. For example, they have recently started a fish farm project and engaged students in learning issues around water quality management. This could involve sensing and control in ways similar to the soil humidity and irrigation example. In spite of this potential, the idea of using the RCX in the field was perceived with concern. The sense of these projects becoming reality grew much higher when they realized that the new version of the GoGo board supports output controls and could thus be used in place of the RCX. A straightforward reason for this is the much lower cost of the board. The teachers also felt more comfortable leaving a GoGo board in the field than the RCX brick. To them, the RCX brick was a fancy and expensive device that seemed out of place in the fields.



Figures 2 and 3 (left to right): Locally-Made Soil Humidity Sensor and a Teacher Adding a Memory Chip to the GoGo Board

Becoming More Involved

The GoGo boards that were originally made available to the school did not contain the memory chip and some other components. This was done to further reduce cost and was decided by the managers of the Bradesco Foundation. Two teachers from the school who participated in a follow-up workshop in early November 2003 learned that their projects needed the memory feature. They learned how to solder the memory chip to the board (Figure 3) and were excited to see that the upgrade worked. This was the kind of situation when the benefits of the GoGo board design could be clearly seen. The use of human-size components and the large soldering pads on the board allowed teachers with no soldering skills to solder the memory chip. Furthermore, because the memory chip can be acquired in Brazil, it is possible for the teachers to upgrade the rest of the boards whenever needed.

A Low-cost Alternative for Large-Scale Deployment of Programmable Bricks

During the introductory workshops of the São Paulo project in 2001, we learned that the public schools had an extremely limited budget. For the first five pilot workshops, we had to bring our own LEGO Mindstorms kits (the GoGo board was still under development), to demonstrate the possibilities of using robotics and ubiquitous computing in the school. The first reaction of teachers and students was to ask about the price of the LEGO kits, since the LEGO toys were renowned for their high cost. Learning that each Brick was worth more than a teacher's monthly salary made many of them skeptical. Comments like "our school can't afford these materials" started to spread among the teachers. Indeed, despite the many trials from commercial vendors, the school system could not afford LEGO Mindstorms, and a city-wide purchase (which typically takes 15 months) became highly unlikely.

The situation changed in July 2002, when we introduced the GoGo board to the Secretariat of Education. Because of the board's much lower price range, they decided to use it in the project. Two-hundred boards were produced by a private company and donated to schools, as a pilot experience. We were able to extend the activities to thirty schools simultaneously. The total investment on the boards and low-cost sensors kits was US\$ 6,500: an amount which would have been barely enough for 20 commercial LEGO Mindstorms kits – an order of magnitude of difference. The cost issue turned a previously prohibitively expensive project into a feasible reality.

Increasing the Diversity and Density of Learning Activities

After five months of work in the Sao Paulo schools, the Secretariat of Education organized an exhibition for students to display their work. Hundreds of students and more than fifty selected projects from all regions of the city were present at the event – most of which involved the GoGo board. One of the projects was a model of an intelligent bus that signals waiting passengers when no more seats are available. The bus was made from a broken keyboard, which the keys served as sensors for the seats. Another project was a model of energy-saving street lights, which would only light up when a car was present. The model was made of cardboard, flashlight bulbs, ice-cream sticks, a light sensor and a touch sensor (the sensors were inexpensive and bought at a radio repair shop). One of the most notable projects was a computer-controlled automatic water recycling system, which took the students three months of research and development. The structure was built with plastic bottles, plywood, and household pipes. The moving parts were adapted from two broken CD-ROM drives and a tape recorder, and water valves were made using spheres from broken computer mice. This project won one of the main prizes at the Brazilian Science Fair in 2003.

Reflections

The case studies reveal several dimensions of the GoGo board framework. We focus our discussion on two levels: first, the benefits gained from the unique characteristics of the materials used. Second, we discuss how the increased diversity of the materials allowed an approach towards construction and learning that connects to pre-existing traditions in the culture.

Board Design

Although we made the design of the GoGo board available and we invited learners to become involved in the underlying design, we do not expect every learner to become engaged. Many people would prefer to be only a user of the board. Thus, we always made sure there were pre-constructed boards ready for use. On the other hand, the GoGo board design allowed motivated learners to become involved at a level that was not possible before with other Programmable Bricks. This new level of abstraction not only opened up new learning opportunities in digital electronics but was also attractive and rewarding to many learners. This became evident when both students and teachers added components to upgrade the board and when they tried to assemble the entire board, even without prior knowledge in electronics.

In terms of increasing the availability of boards, they can be partially assembled just enough to fulfill a particular task, thus further saving both time and cost. Schools can obtain boards by partnering with technical experts to assist with their construction. For example, a group of schools can subcontract a company, a technical institute, a TV repair shop or a group of electronics enthusiasts to assemble boards to supply their immediate need. Being copyright-free, the design of the board can also be customized for specific purposes

Use of Found and Broken Materials

The impact of using found materials and broken electronics goes beyond the mere increase of materials or the low-cost aspect. Teachers and students who disassembled broken devices (VCRs, radio-clocks, hard drives, tape recorders, radios, TVs) often discover how the underlying mechanisms worked. That led to rich discussions about objects of everyday life and their mechanical principles, and a feedback between the thinking about their own projects' construction and the mechanisms already present in the devices. As noted by Blikstein (2002), rather than starting from scratch, they had a rich set of exemplars from familiar objects.

Moreover, the idea of disassembling and re-purposing materials was very present in the culture of the lowest income areas of São Paulo. Our ethnographic research showed that, before buying a replacement, the population would try every possible alternative to fix or repurpose the broken device. By building on a strategy that was already present within the culture, we were able to introduce technology, with was extraneous and unfamiliar, through a recognizable and familiar way.

Future Directions

The GoGo board research is ongoing and has long-term potentials. The idea about programmable bricks in Brazil is still in its early stages. The schools are just beginning to grasp the learning possibilities. Boards were made available for immediate use to support this initial process. We hope to advance the projects by providing means for consultancy and communication among the schools in their network and with other domain experts. Some communication has already begun through on-line services such as mailing lists and video/audio conferences.

To move the idea of the GoGo board forward, we hope to sustain the availability of boards and the materials. An important step towards this goal is to establish a group of developers (possibly in Brazil). There are a couple of roles for this group. One is to keep up with changes in technology. Components become obsolete and new ones replace them. The design of the GoGo board must be modified to reflect this change. Another role for this group is to invent, adapt or extend the design to fit particular needs. The features on the GoGo board are finite and demands for new functionalities will eventually arise.

Conclusion

We started this article describing the Programmable Brick and the challenges for its implementation in low-income settings. We then introduced the GoGo board as a low-cost, open-source implementation of a Programmable Brick. We showed the design choices that allowed it to be more affordable and transparent to users. Next, we discussed case studies that revealed how the GoGo board and the use of found materials made the implementation of learning activities involving Programmable Bricks richer and more feasible in the settings considered.

We argue that the GoGo board framework serves well as a means to support rich and socially relevant learning in communities where resources are scarce. We have shown how the board has been designed to allow motivated users to become involved in its construction process. This led interested users to explore and become familiar with the underlying electronics concepts. Similar explorations of "how things work" were evident in the use of found and broken materials. This mode of thought resonated with the local culture in Brazil, where tinkering with objects to find solutions for everyday problems is a common cultural practice. This approach towards the learning tools was key to create the *critical capacity* (Resnick, 2000) that made the GoGo board framework practical and socially accepted.

We conclude by emphasizing that any attempt to improve access to educational materials would create a deeper impact, and allow for a more diverse audience, if the materials are seen as both process and product. Making Programmable Bricks affordable to schools, while proved important, does not ensure that good learning would follow. In this work, our endeavor was to discuss both the learning environment and the learning opportunities that arose from the multiple levels of involvement with the tool: from its application to its construction.

Endnotes

- (1) Please visit the GoGo board website (<http://www.gogoboard.org/new/gogo22/>) for more information regarding the components and their prices.

References

- Blikstein, P., & Cavallo, D. (2003). God hides in the details: design and implementation of technology-enabled learning environments in public education. *Proceedings of Eurologo 2003 Conference*. Porto, Portugal.
- Blikstein, P. (2002). *The Trojan Horse as a Trojan Horse: impacting the ecology of the Learning Atmosphere*. Cambridge, MA: Media Laboratory Master's Thesis, Massachusetts Institute of Technology.
- Cavallo, D. (2000). Emergent Design and Learning Environments: Building on Indigenous Knowledge. *IBM Systems Journal*, vol. 39, nos. 3 & 4, pp. 768-781.
- Falbel, A. (1989). *Friskolen 70: an ethnographically informed inquiry into the social context of learning*. Cambridge, MA: Media Laboratory Doctorial Thesis, Massachusetts Institute of Technology.
- Geertz, C. (1973). *The Interpretation of Cultures*. New York: Basic Books.
- Granott, N. (1993). *Microdevelopment of Co-Construction of Knowledge During Problem Solving: Puzzled Minds, Weird Creatures, and Wuggles*. Cambridge, MA: Media Laboratory Doctorial Thesis, Massachusetts Institute of Technology.
- Lyon, C. (2003). *Encouraging Innovation by Engineering the Learning Curve*. Cambridge, MA: Department of Electrical Engineering and Computer Science Master's Thesis, Massachusetts Institute of Technology.
- Martin, F. (1988). *Children, Cybernetics and Programmable Turtles*. Cambridge, MA: Department of Mechanical Engineering Master's Thesis, Massachusetts Institute of Technology.
- Martin, F., & Resnick, M. (1993). LEGO/Logo and Electronic Bricks: Creating a Scienceland for Children. *Advanced Educational Technologies for Mathematics and Science*. Springer-Verlag Berlin and Heidelberg GmbH & Co.
- Martin, F., Mikhak, B., & Silverman, B. (2000). MetaCricket: A designer's kit for making computational devices. *IBM Systems Journal*, vol. 39, nos. 3 & 4, pp. 795-815.
- Mikhak, B., Berg, R., Martin, F., Resnick, M., & Silverman, B. (2000). To Mindstorms and Beyond: Evolution of a Construction Kit for Magical Machines. *Robots for Kids: Exploring New Technologies for Learning Experiences*. Morgan Kaufman / Academic Press, San Francisco, CA.
- Papert, S. (1971). *Teaching children thinking*. Cambridge, MA: MIT Artificial Laboratory Memo no. 247, Massachusetts Institute of Technology.
- Papert, S. (1980). *Mindstorms: Children, Computers, and Powerful Ideas*. New York: Basic Books.
- Papert, S. (1987). Information technology and education: Computer criticism vs technocentric thinking. *Educational Researcher*, 16(1), pp. 22-30.
- Papert, S. (1991). Situating Constructionism. In I. Harel & S. Papert (Eds.), *Constructionism* (pp. 518). Norwood, NJ: Ablex Publishing.
- Resnick, M., Martin, F., Sargent, R., & Silverman, B. (1996). Programmable Bricks: Toys to Think With. *IBM Systems Journal*, vol. 35, nos. 3 & 4, pp. 443-452.
- Resnick, M., Berg, R., & Eisenberg, M. (2000). Beyond Black Boxes: Bringing Transparency and Aesthetics Back to Scientific Investigation. *Journal of the Learning Sciences*, vol. 9, no. 1, pp. 7-30.
- Ryle, G. (1971). Thinking and Reflecting. *Collected Papers*, Vol. 2, pp. 465-496. New York: Barnes & Nobel, Inc.
- Sargent, R. (1995). *The Programmable LEGO Brick: Ubiquitous Computing for Kids*. Cambridge, MA: Media Laboratory Master's Thesis, Massachusetts Institute of Technology.
- Sargent, R., Resnick, M., Martin, F., & Silverman, B. (1996). Building and Learning with Programmable Bricks. *Constructionism in Practice*. Lawrence Erlbaum, Mahwah, NJ.
- Sipitakiat, A. (2001). *Digital Technology for Conviviality: Making the Most of Students' Energy and Imagination in Learning Environments*. Cambridge, MA: Media Laboratory Master's Thesis, Massachusetts Institute of Technology.
- Sipitakiat, A., Blikstein, P., & Cavallo, D. (2002). The GoGo Board: Moving towards highly available computational tools in learning environments. *Proceedings of Interactive Computer Aided Learning International Workshop*. Carinthia Technology Institute, Villach, Austria.