LEGO Mindstorms

The Structure of an Engineering (R)evolution

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1.0 Introduction

In 1998, the LEGO Company released a new product called the LEGO Mindstorms Robotic Invention Kit that became an instant commercial success. Children and those young at heart could buy the $200 kit—consisting of 717 pieces including LEGO bricks, motors, gears, different sensors, and a "RCX Brick" with an embedded microprocessor—and construct and program various LEGO robotic creations. In fact, Mindstorms creations featured on the LEGO web site include an automated blackjack card dealer, a robot that crawls up walls, and even a robotic toilet bowl scrubber.

Figure 1.1 The LEGO Mindstorms Robotic Invention Kit consists of 717 pieces, including LEGO blocks, motors, gears, various sensors, a RCX brick with an embedded microprocessor, and software for programming Mindstorms creations.

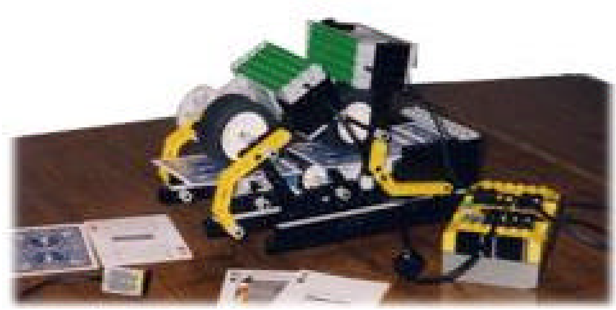
Sold in toy stores across the world, the Mindstorms kit became one of the hottest selling Christmas gifts that year in the United States, selling 80,000 units in less than three months. The *New York Times* heralded the product as a "new revolution" for LEGO, moving a toy company that was losing money from "increasing competition from electronic toys and computer games" back into the black [33].

Furthermore, the adult engineering and so-called "hacker" community embraced the Mindstorms product—a huge surprise to the LEGO Company—boosting sales by 300 percent in 1999. As a testament to this, users have created numerous Internet web sites, featuring blueprints on how to build newfangled Mindstorms creations and listing the code needed to program them. Enterprising software engineers have also developed alternative programming environments and operating systems for the RCX brick, including one called *LegoOS* and a Java-based runtime environment called *TinyVM* [37]. Publishers have even released several books about using the Mindstorms kit, including *Lego Mindstorms for Dummies* and *The Unofficial Guide to Lego Mindstorms*.

On the surface, the story of how the LEGO Mindstorms Robotic Invention Kit became a commercial success appears to be straightforward and almost cliché. The story is often trivialized in the press as a textbook example of how a MIT Media Lab project became a success commercial product. As retold by countless magazine features and newspaper articles, the Mindstorms kit was based on work done at the MIT Media Lab by learning researchers Seymour Papert and Mitchel Resnick. As the *New York Times* relates, "The very name of the Lego robot set, Mindstorms, is taken from the 1980 book of the same name by Seymour Papert, a computer scientist at the Massachusetts Institute of Technology who argued that training in computer programming may be one of the most promising ways to teach children about the nature of problem solving. Lego later financed some of his research, and an early version of the Lego programmable brick was developed at the MIT Media Lab" [33].

Figure 1.2

An "Automated Blackjack Card Dealer," a Mindstorms creation built by one of the numerous adult engineers and so-called hackers that have purchased and embraced the Mindstorms product.



Source: LEGO Mindstorms Hall of Fame

The "technology transfer," however, was not a one-way process, nor was it anything as simple as cloning a product or being aware of a new idea.

Introduction

The story behind LEGO Mindstorms is, in reality, a fascinating narrative of how three organizations—Resnick and Papert's Epistemology and Learning research group, the LEGO Corporation, and the MIT Media Laboratory—engaged in a complex social interaction, which shaped the evolution of the technology. Each group had its own interests and ideas of what success meant. Thus, each organization influenced the development of the Mindstorms product and its Media Lab prototypes in different ways.

The Epistemology and Learning group, for instance, endeavored to create and disseminate new Constructivist approaches to learning. The LEGO Company also aspired to provide Constructivist approaches to learning, while wanting their brand "to be the strongest in the world among families with children" [12]. Finally, the MIT Media Lab sought to create a new and publicly visible model of academic research that emphasizes the public impact of ideas, fosters idea transfer between academic research groups and corporate sponsors, and encourages community outreach. Ultimately, the Lab provided an environment for the research that led to the Mindstorms product to grow and mature.

2.0 Structure of an Engineering (R)evolution

2.1 The Fallacy of Technological Determinism

Prof. Neil Gershenfeld is one of the research directors of the *Things That Think* consortium at the MIT Media Laboratory. One day, he was at the Lab and found a group of students building a strange but interesting new demo:

> "The only thing they couldn't tell me is why they were doing it. Once they realized it was possible, they could not conceive of not making one." [8]

In his book, *Inventing Accuracy*, Donald MacKenzie encounters a similar attitude of inevitability [14]. He quotes some other authors writing on the subject of nuclear missile guidance:

> Teams of scientist and engineers do and inevitably will discover ways of improving system performance.
>
> On the issue of guidance accuracy, there is no way to get hold of it, it is a laboratory development, and there is no way to stop progress in that field.
>
> The possibility of greater accuracy in targeting missiles led to the shift from the "countervalue" approach, aimed at cities and economic targets, to one aimed at specific military targets, i.e., "counterforce."

McKenzie terms the notion that technology has a "natural path" independent of supporting social institutions, "the fallacy of technological determinism." [14] What people often forget is that there are multiple possible paths of development; in this project history, the technology clearly traveled along more than one direction.

We find in this project history that different organizations, with different objectives, interested in different problems make, not surprisingly, different design choices. These forces have imprinted themselves visibly on the prototypes and products under study.

Unlike MacKenzie's example of ever-growing accuracy nuclear missile guidance, no one can mistake the problem of ascertaining whether one has made a simultaneously "fun" and "educational" toy—much less constructing one in the first place—for an easy one. Far from the seemingly inevitable escalation of nuclear conflict, the adoption of the constructivist philosophy of education has been an uphill battle for the researchers in the Epistemology and Learning Group.

The academic and corporate engineers involved were guided not only by what they learned from design experimentation, but also through watching teachers and children use their toys. They were influenced by both organizational inertia (or lack thereof) and the quirks of end-user desires and adoption patterns. The "technological trajectory" of the Programmable Brick actually split off into several directions, including the LEGO Mindstorms product, the MIT 6.270 robotics competition kit, and the Epistemology and Learning Group's Crickets [18].

The question is not, then, to merely disprove the "fallacy of technological determinism" and demonstrate how organizational goals and cultural factors guided the development of this technology. Instead, we will examine how the twin influences of people and technical fact intermingle and combine.

2.2 Technology Transfer and Academic Research

Moving beyond the technology/society dichotomy, we can also see on a more sophisticated level that this is a story about the process of technology transfer from one type of social institution to another. Unlike most research institutions, the MIT Media Laboratory is funded not just by tax dollars, but also by numerous corporate sponsors.

What do those sponsors find valuable in that relationship? LEGO Mindstorms seems to be an obvious answer—this product borrowed directly from laboratory research and became a tremendous commercial success. But this is not actually the case—the RCX brick was actually designed from the ground up by LEGO, for a variety of reasons, including manufacturing practicality and a slightly different target audience.

Perhaps more important to sponsors than access to prototype ideas and schematics (some which are made publicly available anyway) is the opportunity to work alongside Media Lab engineers, to contribute to their efforts, and in doing so, absorb the unwritten expertise of these "visionaries" and technology experts. LEGO engineers benefitted from the accumulated working knowledge of both technical design and user satisfaction from participating in the project; the Epistemology and Learning Group benefited from both LEGO's experience in the industry and ability to mass-market the technology—and promote its underlying philosophy—to schools and consumers worldwide.

3.0 The Epistemology and Learning Group

Both press reports and the LEGO Mindstorms packaging credit researchers at the MIT Media Laboratory with inspiring the design of the product. The Epistemology and Learning Group, directed by Dr. Mitchel Resnick, conducted most of the research that led to Mindstorm's development. The group's mission is to use new technologies to expand the space of what people can build, how they collaborate, and how they think about what they have built and the world in general.

Formed in 1985 as a founding group at the MIT Media Laboratory, the Epistemology and Learning Group has since produced many such tools, including several generations of the "MIT Programmable Brick" and associated LOGO-based programming interfaces. This section introduces the history of the wireless LEGO/LOGO technology from the private sector to academia and back again, starting with the people behind the questions the Epistemology and Learning Group is asking.

3.1 People

The philosophies and theories of the Epistemology and Learning group find their origins in a chain of influences that began with Dr. Jean Piaget. Piaget's teachings greatly influenced his colleague, Dr. Seymour Papert. Papert, in turn, attracted his own enthusiasts, which included Dr. Mitchel Resnick, and several graduate students and academic colleagues.

3.1.1 Dr. Seymour Papert

Born and educated in South Africa, Dr. Papert was a mathematician who, in the 1950's, became interested in using science in the service of understanding how children think and learn. In the early 1960's, he worked extensively with famed developmental psychologist Dr. Jean Piaget, a pioneer of the constructivist educational movement.

> "Seymour was among the first to see that massive change was needed in the education system, particularly math and science education, and to recognize the role that technology could play in learning. He was also one of the first to recognize that technology in the classroom was not a "silver bullet" that would solve all of education's ills. He realized long before the rest of the education reform movement, that technology in education is effective only if placed in a large context that

> combines well-prepared teachers with integrated social services." [23]

In the 1970's, Papert co-created Logo, a computer language so intuitive and simple that young children still program with it today. “Only rarely does some exceptional event lead people to reorganize their intellectual self-image in such a way as to open up new perspectives on what is learnable.”[23] To many teachers in the 80’s this “exceptional event” was the publication of Papert’s 1980 book, *Mindstorms*, after which the LEGO Mindstorms product was named. This book details the invention of Logo and the philosophical ideas that influenced the technical building of the language. Papert describes his thoughts on how computers can be used as teaching machines, and change the means by which students access knowledge. He takes from Piaget the model of children as “builders of their own intellectual structures” and describes how computers can be used to aid in the construction of knowledge. [23]

Papert’s contributions go beyond the field of education. Along with Dr. Marvin Minsky, Dr. Papert co-found the Artificial Intelligence Lab at MIT. Dr. Papert is also a founding faculty member of the MIT Media Laboratory, where he continues to work.

3.1.2 Dr. Mitchel Resnick

Dr. Resnick is the LEGO Papert Associate Professor of Learning Research and is the current director of the Epistemology and Learning Group. His studies center on the role of technology and media in thinking and learning. As Dr. Resnick explains, his goal is to “develop new computational tools and toys that help people, particularly children, learn new things in new ways.” [32]

Dr. Resnick received his bachelor’s degree in physics from Princeton University. He decided, however, not to pursue further education in physics as he feared that he would end up with “more questions than answers to paradoxes” [29] that fascinated him. Instead, he worked for six years as a journalist, writing on topics related to science and technology. In 1982, after writing a long article for Business Week about artificial intelligence research, he became passionately interested in “how people think about organized patterns and structures they see in the world, and why they resist certain ways of thinking about them.”[31] He endeavored to help people develop new ways of thinking about, and appreciating, how minds, and other systems organize themselves into complex and sophisticated wholes. In 1983, he read three books that changed his life: *Mindstorms* by Dr. Papert, *Structure and Interpretation of Computer Programs* by Hal Abelson and Gerry Sussman, and *Godel, Escher, Bach* by Douglas Hofstadter. Inspired, he matriculated as a graduate student in the MIT Media Laboratory. With Dr. Seymour Papert and Dr. Abelson as his advisors, he received his doctorate in the field of computer science in 1992. In describing his relationship with his advisors, Dr. Resnick states:

> "The two of them - Hal Abelson and Seymour Papert - formed a wonderfully complementary pair. Over the years, each of them, in his own way, has deeply affected the way I think- and what I think about. I will be forever grateful to them." [31]

3.1.3 Students and Colleagues

Randy Sargent, Fred Martin, and Brian Silverman were also influential in guiding the evolution of the MIT Programmable Brick. Randy Sargent, a former Master's student under Dr. Resnick, focused on designing the second generation of the programmable brick—the "grey" brick. Fred Martin, a former graduate student and research scientist, was one of the principal engineers of the "red" brick, the third generation of the brick, and one of the co-inventors of the 6.270 MIT Robotic Design Contest. Dr. Martin also helped develop much of the embedded computing technology ultimately used in the LEGO Mindstorms product.

Brian Silverman, a visiting scientist, wrote the LOGO compiler for the RCX brick, and influenced several of the key technical design decisions. Andy Begel, an undergraduate researcher worked with Dr. Resnick and Brian Silverman to implement a prototype *LogoBlocks*, a graphical user interface to the LOGO programming language. LEGO used this prototype to help them develop the Mindstorms RCX code. Bakhtiar Mikhak, a research scientist and former doctoral candidate, worked with Dr. Martin on designing various versions of the Crickets, a smaller, more flexible version of the MIT Programmable Brick.

3.2 The Philosophy of the Epistemology and Learning Group

The Epistemology and Learning group focused on studying and promoting the constructivist philosophy of education. Constructivism, pioneered by Dr. Piaget, states that knowledge should not be simply transmitted from teacher to student, but actively constructed by the mind of the student. "Learning is an active process," asserts Dr. Resnick, "in which people actively construct knowledge from their experiences in the world."[31]

Seymour Papert extends it to what he has termed the "constructionist" approach to learning. Constructionism adds the idea that people construct new knowledge with particular effectiveness when they are engaged in building projects that are personally meaningful. Students construct their own knowledge effectively while building creations that interest and excite them, and encourage them to learn. They learn how to analyze problems that have no predetermined answer, and come up with their own creative solutions. They actively analyze what they see, then either assimilate their observations into earlier mental models, or are sometimes forced to change their mental models to accommodate new observations which were inconsistent with their earlier ideas. Teachers play important role as knowledge facilitators, instead of dictating facts to kids, or providing them with recipes on how to build things. Teachers are also co-learners in this constructionist approach to learning. [9, 11, 27]

The constructionist approach creates an environment in which students act like "real-world" scientists, inventors and engineers. As a result, students are in much closer contact with the truly important ideas of science and engineering. They do not simply learn facts, equations, and techniques. They learn a way of thinking critically and systematically about problems, and even about the problem-solving process itself. Dr. Martin illustrates this in an example he described in a paper he wrote:

> "In the Soap Box Derby activity, for example, students have to create theories about their cars' behaviors. One student might theorize that heavier cars go further than light cars. Another might theorize that cars with large wheels go further than cars with small wheels. Students make theories, test them out, change the theories, and test them again. In later projects, students go through a similar cycle in the design and testing of gear trains, computer programs, and feedback systems." [15]

The constructionist approach also creates an environment in which students truly care about their work. The importance of personal relevance in schoolwork is certainly not a new idea. In *The Informed Vision: Essays on Learning and Human Nature*, David Hawkins explains, "Some things are best known by falling in love with them." [9] The Epistemology and Learning group equates this with science: as long as science is viewed as a collection of facts, formulas, and rules, students will never really know or understand science; students will know science only when they care about it:

> "In classes where we have run the LEGO/Logo Soap Box Derby activity, students wanted to learn about friction, since they wanted to make their cars go further. The students' level

> of engagement was obvious from the way they decorated their cars and added small people inside of them. In later sessions, when students were free to build and program anything they wanted, many seemed to become even more engaged in the activity. Students built projects like merry-go-rounds, home appliances, and walking “creatures”. Rarely did they want to go back to their regular classrooms at the end of their LEGO/Logo time. They wanted to stay and continue working.” [15]

Papert contrasts the constructionist approach with instructionism, which focuses on new ways for teachers to instruct, instead of new ways for learners to construct. Papert succinctly describes the difference between the two approaches with the aid of an old African proverb: “If a man is hungry you can give him a fish, but it is better to give him a line and teach him to catch fish himself.” [24] In instructionism, the traditional form of education, the knowledge that children should know is identified, and arranged systematically, and children are “fed”" this knowledge. For example, when teachers usually teach mathematics, they usually present students with a set of theorems and formulae, which students are supposed to digest and get accustomed to applying to various, typical problems. In Instructionism, to educate better means to instruct better; if computers are going to be used, they will be used to aid in the instruction of the students. Papert explains:

> “Constructionism is built on the assumption that children will do best by finding (“fishing”) for themselves the specific knowledge they need; organized or informal education can help most by making sure they are supported morally, psychologically, materially, and intellectually in their efforts. The kind of knowledge children most need is the knowledge that will help them get more knowledge.” [24]

An example which illustrates the power and advantages of constructivism over instructivism in learning mathematics can be taken from the experiences of Shamia, an 8-year-old girl who attended an “alternative” community school. Shamia’s project included using LogoWriter, a constructionist tool that used the Logo software as its basis. During the course of her class project, Shamia had to create a rainbow for the sky for the animation she was creating. Creating the rainbow was an illustrative part of her work because the process required her to pose her own questions concerning several mathematical ideas, including decimals, the geometry of circles, relationships between division and multiplication, and linear relationships. She became enchanted about thinking about these ideas in order to design a procedure to draw her rainbow. With initial guidance from her mentor, Shamia developed her “rainbow maker” by trying out different ideas, testing which ones worked, and debugging those that didn’t. In the end, she developed a deep knowledge of the mathematical skills that were needed to implement her project, and she was very excited to learn and apply these skills to a project that she initiated and owned. Resnick reflects:

> “Some teachers might have designed other activities for Shamia when it became clear that she was struggling to figure out factors of 180 or relationships between shapes of different sizes. They might have interpreted her struggle as an opportunity to pose tasks for her such as describing patterns in tables of numbers or comparing perimeters of the same shape in different sizes. The motivation behind these strategies could have been to help Shamia learn what she needs to know if order to be able to figure out the answer to her question. This kind of teaching, however, would have required Shamia to suspend the path of thinking that she had formed on her own. This pedagogical choice would have taken her away from the path of learning that she had constructed for herself, requiring her instead to engage in a teacher’s path requiring her trust that it lead her to the answers she wanted.” [31]

With this philosophy, the challenge for the Epistemology and Learning Group is to create new tools and environments that engage learners in construction, invention, and experimentation. As Prof. Resnick describes, “the process involves (at least) two levels of design: educators need to design things that allow students to design things.” [31] The MIT Programmable Brick was such a tool; it was designed to facilitate the adoption of constructionism.

In education today, the instructivist approach prevails. In promoting the constructivist approach, Drs. Papert and Resnick face an uphill battle of going against the established norm. The challenge is to convince educators that, while their current teaching strategies work and produce results, there is a different and perhaps better way to educate students. There is an expected resistance to change—an attitude of “if it ain't broke, don't fix it” amongst educators. Furthermore, mere adoption of constructionist tools is no guarantee of the acceptance of the underlying philosophy behind them.

Another challenge that the Epistemology and Learning Group faces is ensuring their tools and technologies are correctly promoted and adopted in educational institutions. Proper adoption dictates that teachers should not simply hand students recipes on how to build creations. Students should go off on their own and teach themselves how to build things that they are interested in. Thus, the correct promotion of the Programmable Brick is important. The brick was designed to be gender and age neutral, so as to appeal to a wide range of children to use in a variety of ways.

Members of the Epistemology and Learning group wanted the brick to be promoted and used as such. [29]

3.3 From Corporation to Academia and Back Again

In 1985, Dr. Papert, Dr. Resnick, and Steve Ocko formed Microworlds Learning, Inc. and began working on a new type of "toy." They envisioned a construction set that would allow children to build things and machines, as they had done for years with erector sets, Tinker Toys, and Lego bricks, but with additional functionality: users would be able to animate the creations they had built. They wanted to enable children to build things in the real world and control them on PCs using computer programs that the children themselves had written. They chose LEGO bricks over the other kits because they were more "playful" and worked well as a system. One could easily build a wide variety of mobile objects using gears, motors, and other things that LEGO was already manufacturing. LEGO bricks also embodied a "low-barrier to entry and high-ceiling" design goal that the group valued. They were simple enough that novice users could easily pick up how to use them, but they enabled experienced users to build whatever they imagined, with few constraints. [29, 19]

In the fall of 1985, Papert, Resnick, and their team began collaborating with the LEGO Company. LEGO was interested in their work. LEGO and Microworlds shared the same constructivist learning philosophy and were both intrigued by the novel uses of their system. [29] The Microworlds team began linking LEGO building bricks with the Logo programming language, in a combination that they called LEGO/LOGO. Daniel Bobrow, Wallace Feurzeig, and Seymour Papert developed Logo in the late 1960s as a programming language for children. It was chosen because the Microworlds team was particularly familiar with it. It was also a learning-oriented language with a simple but powerful syntax that embodied the "low barrier, high ceiling" design philosophy. In 1986, Papert and Resnick moved to the MIT Media Laboratory, where they formed the Epistemology and Learning Group. Resnick became a graduate student of the lab and continued his research on LEGO/LOGO. Furthermore, he studied StarLogo, a programmable modeling environment which he designed to help students explore decentralized systems and self-organizing phenomena. At the same time, LEGO became a founding sponsor of the Lab, indirectly funding the research of the Epistemology and Learning Group. Thus, the nascent technology was transferred from private corporate hands into the academic arena through a wholesale movement of people.

The first generation of the Programmable Brick was developed by 1989. It was named the “6502 Programmable Brick” because of the microprocessor it used. It was wireless—meaning that it was not tethered to a desktop computer—and ran its own LOGO interpreter. The second generation brick, dubbed the “grey” brick, or the “Pocket Programmable Brick”, was designed in 1995. The “grey” brick was smaller, more portable, and more flexible. It facilitated multiple paths of entry to kids, so that it could appeal to kids for a variety of reasons. However, because it was very difficult and expensive to produce in quantity, it was only used in small numbers. Development continued, and the “Red Programmable Brick”, or the “Model 120 Programmable Brick,” was designed in 1996. (There was also an earlier, intermediate prototype called Model 100 which Dr. Martin used in a teacher workshop in 1995). It maintained several of the important design features of the “grey” brick, but was more “economical and robust,” to improve it's suitability for use in classrooms.

Currently, the Epistemology and Learning Group has developed “Crickets,” a smaller, more flexible version of the Programmable Brick. Crickets are currently in use today by the Epistemology and Learning Group, as they are smaller, more economical (e.g. cheaper to product), and can support a wide variety of different sensors.

Figure 3.1 The “Red” MIT Programmable Brick, circa 1996, developed by the Epistemology and Learning Group at the MIT Media Laboratory.

3.4 Design Decisions and Tradeoffs

The MIT Programmable Brick was designed to be flexible. The design team wanted the Brick to be able support multiple activities. This was motivated by the fact that different kids have different interests; the engineers realized that they could not predict things that will fascinate different groups of kids with dissimilar backgrounds. Also, enabling the Brick to be used for a variety of activities facilitated numerous children, with different interests, linking up and combining their talents to make new projects. [19]

An example that illustrates the importance of this design goal was an experience at The Computer Museum in Boston, where Randy Sargent attempted to interest junior high school students to use the brick to make musical instruments. The students lost interest quickly, and were drawn to a LEGO train set at the other end of the room. The programmable brick could be interfaced to the train as well, and once it was, the kids became much more interested in programming. [34]

The programmable brick attempted to connect computing to the "real world" in as broadly and deeply as possible. It had to be able to act and react to it's environment, and the more ways the brick could sense, the wider the variety of activities it could be used for. Thus, the brick was wireless—it no longer required a "tether" to a desktop computer when running, and thus, it had its own processor and programming environment.

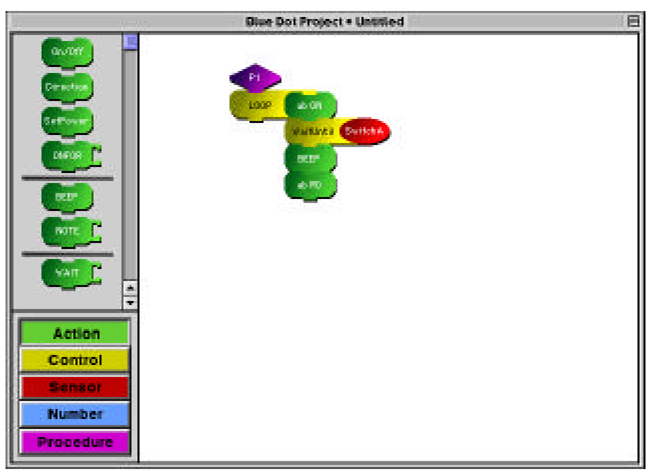
Having several input/output (I/O) modalities, such as light, sound and temperature sensors, was another important design choice for the brick. Besides increasing the number of ways the brick could be used, this also allowed multiple bricks to interact with one another. The number of I/O ports to integrate on the brick was controversial. There was pressure to increase the number to facilitate more flexibility. However, there was also pressure to decrease the number to make the brick simple, cheap and easy to make. In the end, the conflict was resolved in the final implementation process. The "grey" brick had eight sensor ports and four motor ports, omnidirectional infrared input and output, and 8-bit sound input and output. The "red" brick was an effort at a more economical model with similar functionality. It had six input ports and four motor ports, simple infrared input, and sound output; other features could be added via external devices, such as a microphone or infrared output. These design decisions were much in keeping with the overall vision for the project as kids did not have to limit their creations to things inside a desktop computer or to things that had to be connected to a computer. Their creations could be "alive" and interact with other objects in the real world. The brick was designed to "break children free" from the desktop computer mentality, and bring them to a ubiquitous computing world, in which computers are connected to and spread throughout the environment. Children were empowered to be architects and engineers, and not just simple users. [19]

Several programming environments were considered for use with the programmable brick. Environments considered included traditional, text-based programming languages, as well as graphical programming languages. The first two generations of the brick were programmed using a text-based Logo interface. [21]

While this was very powerful, children were somewhat slow to learn the language [19]. In order to more fully satisfy the "low barrier" design goal, Andy Begel, under the direction of Dr. Resnick and Brian Silverman, implemented LogoBlocks, a graphical version of the interface. [18] Students could program the brick by arranging the blocks on the screen. Each one represented an action ("turn on motor 1"), an element of control logic ("loop 5 times"), or the value of a sensor, a number, or a whole user-defined procedure. Blocks take input from and give output to each other; they define a program that is compiled into byte-code and then downloaded to and run on the brick's microcontroller.

LogoBlocks made it difficult to produce more sophisticated programs, however, and so later research produced a hybrid interface that was both "low-barrier" and "high-ceiling." In the hybrid, any program can be viewed in either form—as a text program or in graphical form, regardless of how it was constructed. It gives beginners the advantage of an easy graphical interface, but also allow them to learn LOGO syntax as they go along, and eventually move to text-based coding as they become more sophisticated.

Figure 3.2 The *LogoBlocks* graphical programming environment for the MIT Programmable Brick, developed by the Epistemology and Learning Group.



This group of engineers has thus seemingly changed course several times with regard to the number of inputs and outputs, and the emphasis on text-based or graphical interfaces. While the optimal tradeoffs on these spectra for a given application (if any actually exist at all) may have eventually been found, the winding roads seemed mostly to be the result of historical accident. There's nothing to say that someone couldn't have invented a graphical programming language, and only later realized it could be integrated with LOGO. The Epistemology and Learning Group might have maximized for economy first and flexibility later, and might (or might not) have ended up with the same product in the end. Regardless, as we shall see shortly, the LEGO Company, which had many (but not all) of the same goals, took the same technology in a slightly different direction. The choices that the Epistemology and Learning Group made were driven not by some overarching vision hatched at Microworlds or upon arrival at the Media Laboratory. Instead, the force driving change was the lessons that the group was learning from trying to design and produce the bricks, and from watching children play and create with them.

3.5 From Programmable Brick to LEGO Mindstorms

The collaboration between LEGO and the researchers of the Epistemology and Learning Group started in 1985, shortly after the founding of Microworlds. The President of LEGO had read Papert's *Mindstorms*, and realized that the two groups shared similar convictions about how children learn. Furthermore, LEGO was interested in and intrigued by the novel use of their system. [29]

Once the project moved to the Laboratory, researchers were freed by the Lab's legal arrangements from consideration to issues of intellectual property on a daily basis. Designs and papers produced by the lab were to be published openly. As a lab sponsor, LEGO had acquired the rights to make commercial derivatives royalty-free. This allowed the two groups to more freely share ideas and concentrate more on engineering and experimentation, rather than on issues of ownership. [22]

Dr. Resnick described the relationship between the two groups as "very open." Dr. Resnick further stated that his research group never had to compromise in its philosophical ideals in its relationship with LEGO. Despite the shared intellectual and evangelical mission of the two groups, there were differences in emphasis.

For example, at the time the decision was made to commercialize Mindstorms, LEGO could have invested the resources to develop a hybrid graphical/text programming interface [21]. Instead, LEGO went with a LogoBlocks-like GUI, emphasizing the ease of use critical to enjoyment of its products. (The company is now actively pursuing the incorporation of the latest hybrid technology into the next generation of Mindstorms to achieve a "high ceiling" of utility.) It is possible that the existence of this "low barrier" interface contributed to LEGO's decision to go ahead with Mindstorms.

The Mindstorms software is revealing of perhaps part of this motivation. It contains a considerable amount of audio narration, animation, and video footage documenting the use of interface and the construction of RCX-based LEGO robots. One quickly realizes that consumers, unlike the students participating in research experiments, will not have the advantage of an experienced, MIT-trained engineer familiar with the operation of the system. LEGO needs to explicitly deliver to the consumer much of the tacit knowledge that Epistemology and Learning personnel would otherwise convey. As such, they appear to have successfully done so through the creative use of high-bandwidth multimedia channels.

When asked what about the Mindstorms kit he would change, Brian Silverman spoke about the interface. "[The Mindstorms software] was designed by people who make video games," he said. A simpler, less distracting design would have been appropriate, to allow children to "focus more on building rather than playing with the software." Silverman preferred the more minimalist interface that LogoBlocks offered, which would not distract users or impede their creativity by suggesting that they build the sample robots featured in the "how-to" videos included on the Mindstorms CD-ROM. [36]

The immediate social context of the technologies' development *and* end-user environment played a direct role in defining and shaping deliverables. MIT and LEGO also made different choices in some places. Other differences in approach and implementation will be discussed in Section 4.3.2.

LEGO used the mature Red Programmable Brick as a prototype for Mindstorms. However, they designed their equivalent, the RCX brick, from scratch. Silverman explained, "We really didn't know anything about production engineering. LEGO needed to make [their] product cost-effective and robust, and the Programmable Brick really wasn't geared towards that." [36]

How did the actual "technology transfer" work? As mentioned in Chapter 1, it was not solely a matter of transferring design documents from one building to another; nor was it unidirectional.

There was a two-way flow of information—and more importantly—*people* between the two groups. Allan Tofte, an engineer from LEGO, spent six months with the Epistemology and Learning Group, learning the technology, contributing extensively to the circuit-level evolution of the brick, and facilitating the transition from a research project into a commercial product. Allan Tofte was the principal technical link between the Group and LEGO [19]. The Media Laboratory, in turn, sent team member Kwin Kramer to Denmark to work on ideas that led to the RCX Code programming environment, which was based on Begel's LogoBlocks program.

In 1994 (in the "red" brick era), Dr. Martin collaborated with elementary and high school teachers in the design and assessment of curricula for introducing the technology to classrooms. LEGO specifically consulted these educators in determining the necessary specs for the RCX brick. They decisively contributed to the decision to include an on-board LCD (which was a relatively expensive feature) so that kids could review sensors values in the field.

The LEGO relationship with the Epistemology and Learning Group continues to thrive today. LEGO employees visit (either personally or electronically) with Epistemology and Learning and the other groups at the lab on a regular basis to talk about the latest research, discuss directions for new products, and generally "breathe the air" [3]. Epistemology and Learning Group researchers also visit LEGO headquarters in Denmark for the same reasons.

3.6 Success and Spinoffs

In terms of achieving Epistemology and Learning's mission to create new tools for thinking and learning in new ways, the Programmable Brick has been a celebrated success. As a result of the Mindstorms spin-off, the Programmable brick one of the Media Laboratory's most famous projects. The well-attended Mindfest conference—dubbed as a "gathering of playful inventors," held in 1999, drew enthusiasts from all around the world, and is just one example of this popularity.

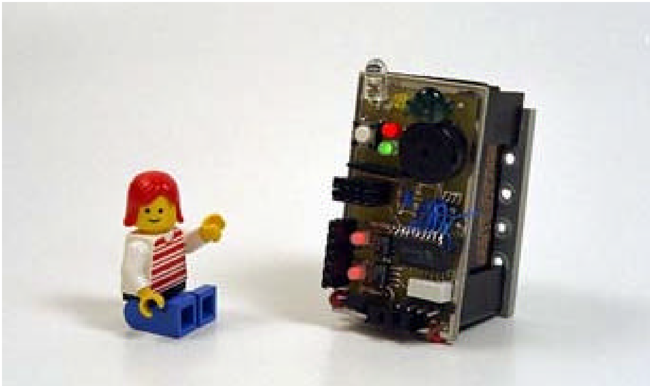
The presence of hundreds of thousands of Mindstorms and other LEGO-produced kits in homes and RoboLabs (a related LEGO product) in classrooms worldwide is a major victory for the proponents of constructionist learning. But as previously mentioned, many teachers still use the toys in an instructionist fashion. These teachers tell kids what to build and how to build it. This was not a flaw in LEGO's marketing of its product, though members of the Epistemology and Learning Group were concerned about how teachers were using the product in their classrooms [22].

Dr. Resnick is personally involved in directly promoting constructionist learning to underprivileged children and their teachers through the

Computer Clubhouse project, sponsored by the Intel Corporation. Children are given access to a rich "invention workshop" environment, including LEGO/LOGO systems, computer workstations, and professional and academic mentors. They are also given the freedom to dream up and implement their own projects. The program is also attempting to bridge a perceived "gender gap" by establishing Mondays as "Girls Day" at the clubhouse, so that female students may increase their confidence expressing themselves with the new technologies.

Dr. Martin adopted the programmable brick (as part of his Ph.D thesis, under the direction of Dr. Resnick) for use in higher education. MIT's wildly popular annual 6.270 contest employs a higher-power version of the LEGO/LOGO system that AI-savvy engineering students push to its computational limits. The freedom to design and program their own robots does carry a large element of the constructivist philosophy, even though the problem to be solved is given by the teaching staff. (Though students never seem to have a problem finding the project personally relevant in a constructionist sense- the class is always quite oversubscribed and participants and audience members quite enthusiastic.)

Figure 3.3 Prototype version of the Cricket, a much smaller version of the MIT Programmable Brick.



Source: Fred Martin

Bakhtiar Mikhak noted another interesting property of the Cricket system, the smaller, easily networkable, and highly mobile next-generation programmable brick. The incredible flexibility of the system to assume almost any physical shape and adopt a wide variety of programmed behaviors, combined with a growing variety of sensors and actuators, makes the system a very versatile rapid prototyping tool. Mikhak has demonstrated the Crickets in this context to both LEGO toy designers and Media Lab researchers in other groups. Both experienced "wow, I never would have done that!" moments as they experimented recreating old projects in the new, more flexible medium, or implementing spontaneous ideas. The critical phenomenon here is a tight iterative feedback loop between person and technology, which puts the long-term design process in an interesting perspective. Mikhak also emphasized the importance of "feeling out" a particular part of the design space in generating exciting self-inspired discoveries in this way [21].

Future directions for the Programmable Brick include an embedded programming interface (housed in a Nintendo Gameboy or Microsoft PocketPC) to allow quick debugging in the field—yet another example of the "tight iterative feedback" model in action [18]. It is also notable in this regard that the computing power of the PC, on its "technological trajectory" in compliance with the so-called Moore's Law has so completely surpassed the needs of this project that a mere handheld device will now suffice.

4.0 The LEGO Company

The LEGO Company has a long history of valuing a learning-by-doing methodology. Since 1949, the company has been producing the basic plastic building blocks that are etched permanently in the minds of millions of children. Researchers at the University of Chicago and MIT argue that the elegance of the LEGO blocks (and an explanation for their long-term success) is their simplicity; they have also studied and endorsed the constructivist approach espoused by LEGO Dacta, the educational division of the LEGO Company. LEGO's affiliation with MIT researchers and the Media Lab was instrumental in developing Mindstorms, bringing the product to market, and guiding it since.

This chapter will explore the goals, history, and personalities at LEGO, as well as its role in moving a technology from academia to market.

4.1 Company Background

Founded in 1932, the LEGO Company takes its name from the two Danish words *LEg GOdt* meaning "play well." The toy maker continues to be family owned and operated. The Dutch toy company's current president, Kirk Christensen, is the grandson of the original founder. LEGO's web site boasts:

> "The concept of "Play Well" continues to serve as the philosophy for all LEGO products today. A philosophy encouraging children to be open and curious. To stimulate their creativity, imagination and learning – while they're having fun." [12]

As found in several corporate press releases, "In concrete terms, our goal is for the LEGO brand to be known as the strongest brand in the world among families with children by 2005." [12] To this end, LEGO is explicitly laying out one of its goals or objectives. The following section will detail other such objectives and will provide context for engineering decisions influences by decidedly non-technical factors.

4.1.1 Educational Philosophy

The Dacta group, as the educational division of LEGO, is specifically charged with directing its operations in the educational arena. The group designs toys that encourage students to use their creativity and natural curiosity through hands-on experiences. The philosophy embodied in the group's work is the same constructivist philosophy detailed in Section 3.2

In particular, the Dacta Group believes that:

1. children learn best by doing or making…
2. learning should be an enjoyable, as well as an educational, experience…
3. extensive scientific research into fields such as cognition, psychology, evolutionary psychology, and epistemology support these beliefs…

As reiterated by all members of the group we interviewed, LEGO's constructivist approach to learning is a very close match with the philosophy of choice at the MIT Media Laboratory's Epistemology and Learning Group. This played an important role in laying the groundwork for the long-standing relationship between the LEGO Company and the Media Lab.

Once again, however, different institutional realities mean different priorities. As a corporation responsible to its owners, LEGO must consider *financial viability* in its choice and design of products. (Over its nearly seventy-year history, the company has only failed to be profitable in one year, 1997.) Additionally, as a product-oriented company, its public image is important. To this end, LEGO must consider *public relations impact* resulting from business decisions. We shall soon see how these organizational priorities manifest themselves in the design decisions of the Mindstorms RCX brick.

4.1.2 Previous Artificial Intelligence Toy Efforts

On previous occasions, LEGO has released artificially intelligent toys to its educational customers, including TC Logo and Control Labs. These toys both aimed to teach children to learn new things in new ways. In a sense, they may be considered early ancestors of LEGO's programmable brick undertaking. LEGO's own hindsight revealed that several "constraints" were manifest in the very design of these early iterations. Specifically, both were extremely dependent upon the PCs with which they interacted. The "programming language" allowed little in the way of flexibility and a very low ceiling. Moreover, these early AI toys were tethered. That is, they were connected to the PC via a communications wire at all times. Mitchel Resnick, of the MIT Media Laboratory, remarked that this "imposed both physical and imaginative constraints." [29]

Robert Rasmussen, LEGO representative and liaison to the MIT Media Lab, remarked that LEGO's decision to work with the programmable brick represented a "natural progression" for the toy company.

4.2 LEGO and the Media Lab: The Decision to Commercialize

While much of the relationship between the LEGO Company and the MIT Media Lab is detailed in Section 3.5, this history has not yet examined LEGO's decision to commercialize the programmable brick. This section will briefly explore what influenced this decision.

As LEGO had been working hand-in-hand with the Media Lab for years on the brick, the toy company continued to be well aware of the technology. LEGO, itself, offered input on the development path of the brick, and worked beside the MIT researchers to determine how children learned from the toy. LEGO had long expressed interest in bringing such a product to market. Its history with artificially intelligent toys made LEGO a fantastic candidate for brick commercialization. By the early nineties, some LEGO representatives had designs to do just this. Several market conditions, however, prevented such an early release of the toy. For one, a programming interface relied on a PC, which were not as commonplace in homes and schools in 1990 as they were in 1998 (when the product was actually released). Additionally, cost of materials was much too high (e.g. memory, processing power, etc.) for modest pricing. Lumped together, there was a lack of general market readiness for such a product.

By the mid-1990s, the company was ready to move forward with commercialization. Under the leadership of LEGO CEO Kirk Kristiansen and LEGO Dacta VP Torbin Sorensen, money was allocated to fund such a "programmable brick" project. This project was to be the Dacta Group's first to reach into the home educational (as opposed to school-based) market. Kristiansen and Sorensen were advocates of high technology in their new product development. As such, Mindstorms was given high priority among LEGO research and development efforts.

4.3 Design Decisions / Trade-Offs

In order to best understand the design decisions or technical trade-offs LEGO made, it is important to examine the product's starting point, the MIT programmable brick circa 1995. First, several key differences exist in design philosophy. These are outlined in Figure 4.1

Figure 4.1 Differences in the design objects of the MIT Programmable Brick and LEGO Mindstorms RCX Brick.

	MIT Programmable Brick	Lego Mindstorms RCX Brick
Robustness	Designed for "concept." As the toy was in a constant state of change, it did not make sense to allocate too many resources to making it "unbreakable," as engineers were available to repair equipment.	Designed for "production." Any marketed toy would have to withstand both an individual child's wear and tear as well as that of a classroom environment.
Target Audience	All children. The Epistemology and Learning Group was interested in exploring how "new technologies could help [all] children learn new things in new ways."	10 – 14 year old boys. While adhering to a similar educational philosophy, LEGO also maintained a financial responsibility. Executives felt the toy company's best bet was its bread-and-butter market.
Cost to End User	Mostly irrelevant. MIT was decidedly not marketing a commercial product. Media Lab sponsors fully fund all research costs.	Important. LEGO hoped that parents of 10-14 year old boys would be buying this product. As such, a quest for a relatively low retail price drove some design decisions.

These differences in design philosophy drove many of the "changes" evident between the "red" programmable brick and the RCX brick found in the Mindstorms Robotics Invention System.

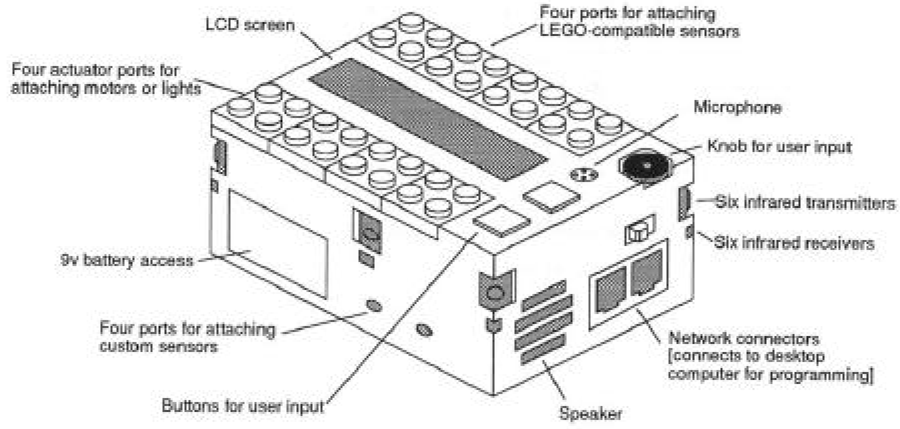
The balance of this section will examine some of the key physical and non-physical differences of the two bricks and will include information on some of the non-technical influences in the decision process.

4.3.1 Two Bricks, Side-By-Side

This section will serve to describe several of the differences between the "grey" programmable brick, which is well documents in Randy Sargent's 1995 M.S. thesis, and the RCX brick, which is available with the Mindstorms commercialized kit.

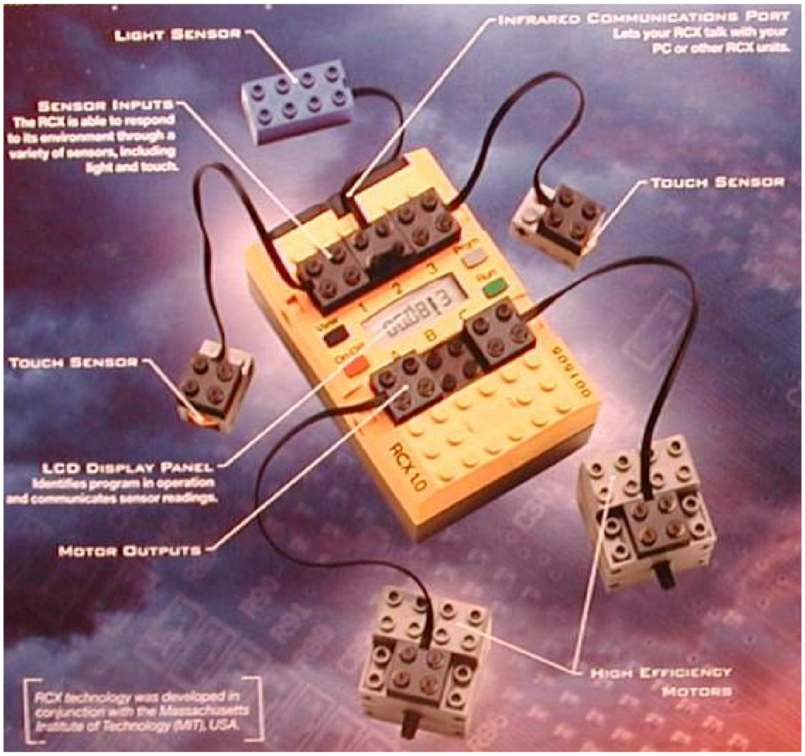
Figures 4.2 and 4.3 (below) the MIT Programmable Brick and the LEGO RCX Brick. Figure 4.4 (below) outlines several of the properties of the two bricks. This information will serve as a basis for analysis of a few key design decisions made by LEGO.

Figure 4.2 Some features of the “grey” MIT Programmable Brick, circa 1995.



Source: Randy Sargent’s MAS Master’s Thesis, 1995

Figure 4.3 Some features of the LEGO Mindstorms RCX Brick, circa 1998.



Source: LEGO Mindstorms Packaging

Figure 4.4 Properties of the "Grey" MIT Programmable Brick and LEGO RCX brick.

	"Grey" MIT Programmable Brick	Lego Mindstorms RCX
Number of inputs	4	3
Number of outputs	4	3
Primary Brick Color	Red	Yellow
Secondary colors	Black	Black, Gray, Red, Green
LCD Screen?	Yes	Yes
Microphone?	Yes	No
Power Source	9V Battery	6 AA Batteries
Number of buttons	2	4
Brick-PC communication	RJ-45	Infrared
Software Interface	Logo (text only)	RCX Code (GUI)
Target Audience	All Children	10-14 year old boys

4.3.2 Discussion of Design Decisions

Two decisions the company made had a large impact on the final product: the choice of a target audience and the design of the programming interface.

Targeting an audience. While the ideal scenario would have LEGO market its product (and its philosophy) to all children regardless of age or gender, the necessity to realize a return on investment drove a decision to market to a more specific segment. At the same time, executives at LEGO felt that the toy company could hit a public relations "home run" if it identified a target market and outsold expectations.

Once a decision was made to limit the target audience, the choice of 10-14 year old boys was an obvious one. This market segment has long been LEGO's "sweet spot." Additionally, market research done by the toy company indicated that boys would be more attracted to "computerized" toys than girls would be. It should be noted that this finding does not agree with what the Media Lab researchers found. Rather, Media Lab researchers were explicated non-gender specific in designing the brick. Moreover, they targeted equal numbers of boys and girls when performing cognitive experiments field anecdotes from Media Lab researchers. [22]

The decision to market to 10-14 year old boys brought with it several influences over brick design. Namely, the choice of colors (primarily yellow and black, which mimicked a construction zone) [26] and the type of sample applications (e.g. robots, etc.) [21] were directly related to the target market. In a discussion about combative robots built with

Mindstorms, Media Lab researcher Bakhtiar Mikhak remarked, “We [Epistemology and Learning Group researchers] would have never done anything like that” [22].

Software point of entry: The programming interface. During early development, researchers at the MIT Media Lab used the Logo programming language as an interface with the programmable brick. While precise, the language did not meet the expectations of the researchers in terms of “low floor, high ceiling.” In terms of “low floor,” it missed because the barrier to entry was too high for someone who had never programmed before. In terms of “high ceiling,” it missed because it lacked some characteristics such as multiple threads (though Dr. Resnick later implemented MultiLogo to address this very problem.)

Before LEGO chose to commercialize the brick, the MIT researchers had developed and deployed LogoBlocks, a graphical programming language that allowed those without programming experience to program the brick. This helped achieve the “low floor” goal for the language, but still did little to address the “high ceiling.”

When LEGO moved forward with the Mindstorms project, it literally borrowed people from the Media Lab to design a programming language from the ground up. Kwin Kramer, then a Media Lab student, spent several weeks in Denmark helping LEGO develop RCX Code—the language used with the commercial brick. LEGO executives decided to follow LogoBlocks example and chose to draw the functional requirements for RCX Code from the previously implemented language. The details were motivated largely by two factors: Media Lab successes with LogoBlocks and children, and the products target audience.

4.4 Metrics for Success

As we have seen, LEGO made a particular set of business decisions which took the RCX brick in a slightly different direction than its MIT counterparts. While it would be difficult to predict the commercial success of a “different” Mindstorms kit, we can (and will) evaluate the marketed product against the company’s stated goals.

Mindstorms sales far exceeded LEGO’s expectations. In the first three months of production, over 80,000 units were sold. [20] These numbers prompted interested in add-on products. Several such products are currently available ranging from the “Dark Side Development Kit” (based on the popular Star Wars theme) to “Vision Command,” which incorporates machine vision.

Mindstorms' market is broader than anticipated. LEGO was surprised to find that communities of adults and hackers of all ages have formed around the product. Mindstorms has been featured several times on the Slashdot website—a place frequented by numerous members of the engineering community [35], and has been the subject of several recently published books. A recent Associated Press article cited a LEGO executive who attributed "a nearly 300 percent increase in Mindstorms sales" to adults [20].

Constructivist learning has been deployed… sort of. While LEGO has successfully sold hundreds of thousands of Mindstorms kits and add-ons, it would be naïve to surmise that this represents a win for constructivism. Both LEGO and Media Lab researchers have remarked that many schoolteachers are not using the toy as intended (i.e. they are using it as an "instructivist" toy, rather than a "constructivist" one.) [21]. On the one hand, this may be considered a loss. On the other, though, the tools have been deployed; this is a critical element involved in disseminating the LEGO learning philosophy.

5.0 The MIT Media Laboratory: A Fostering Environment

Each year, as many as 10,000 visitors tour the MIT Media Laboratory. They see the various research groups' work areas, which typically consist of bean bags and stuffed animals sharing space with state-of-the-art video monitors, circuit boards and radio transmitters. The unique architecture of the building itself, named after one of the founders of the Laboratory, then-MIT president Jerome Weisner, reveals some of the research ideals and philosophies of the Laboratory.

The building incorporates large open spaces, with interior walls made of glass, and offices furnished with movable furniture. This reflects the Media Laboratory's ideal of knowledge transfer—the sharing of knowledge betweens the many disciplines that the Laboratory brings together. This ideal of knowledge transfer can be seen in the role the MIT Media Laboratory took in the development of the Programmable Brick and LEGO Mindstorms—that of a facilitator for the relationship between the Epistemology and Learning Group and LEGO.

Figure 4.3 The MIT Media Laboratory in Cambridge, MA.

A study of the MIT Media Laboratory helps explain how the MIT Programmable Brick evolved and why the MIT Programmable Brick and LEGO Mindstorms took the shape they did. We found that the Media Laboratory exerted its influence both through facilitating the relationship between Epistemology and Learning Group and LEGO and through creating an environment where a unique group such as the Epistemology and Learning Group could conduct their research in an effective manner.

The Epistemology and Learning Group might not even have existed if it were not for the Media Lab. "It's possible," reflects Randall Pinkett, a current Ph.D. candidate in Resnick's group, "that our group would not exist without the interdisciplinary focus of the lab" [25]. Pinkett points out that in a traditional education research environment, there would not be the necessary expertise or support to enable the technology-based research in their group. Likewise, the educational research focus of Resnick's group would not fit perfectly in a strictly computer science focused Laboratory.

The Media Laboratory's emphasis on technology and knowledge transfer between all parties involved also affected the development of the Programmable Brick and LEGO Mindstorms. The sponsor - research group relationship provided by the organizational infrastructure and collaborative culture of the Media Laboratory allowed information, ideas, and knowledge about the design of both products to flow between the Epistemology Group and LEGO. In short, the Media Laboratory provided the environment that enabled the Epistemology and Learning Group to survive and cemented their relationship with the LEGO Company.

5.1 Interdisciplinary, Diversity, and Playfulness

Several of the over-arching goals of the Media Laboratory created an environment where Resnick's Group could flourish. The lab places a high value on the generation of creative and innovative ideas. The Laboratory has several characteristics that facilitate creativity, including the cross-disciplinary nature of the Laboratory, the diversity of the Laboratory members and sponsors, and the Laboratory's emphasis of "playfulness." [10]

The Media Laboratory was founded initially with the aim of addressing the convergence of computing, publishing, and broadcasting. What resulted was a research laboratory with a strong focus on interdisciplinary skills. Faculty members include physicists, computer scientists, psychologists, linguists, historians, and visual and performing artists. Bakhtiar Mikhak confirms that extensive cross-fertilization of ideas between the various research groups of the Laboratory takes place. Mikhak himself took the idea of creating a musical instrument utilizing the electrical conductivity of Play-Doh, a popular brand of modeling clay, and surprised his colleagues by quickly re-implementing it using Crickets technology. [21]

In addition to the interdisciplinary focus of the Laboratory, the diversity of Laboratory members and sponsors also contributed to the success of the Programmable Brick and Mindstorms. This diversity is necessary for adaptability and creativity [10]. Within the Epistemology and Learning Group, numerous disciplines were represented. Dr. Resnick's background was in physics and science technology journalism, working for five years for Business Week. Seymour Papert's background is in mathematics and was an early pioneer in the field of Artificial Intelligence. Fred Martin studied Mechanical Engineering as an undergraduate at MIT.

Along with faculty diversity, sponsor diversity also aided the success of the Programmable Brick. The Media Laboratory currently benefits from over 160 corporate sponsors ranging from greeting card publishers to microchip manufacturers [5]. Ken Haase describes the importance of sponsor diversity in his essay entitled *Why the Media Lab Works – A Personal View*:

> "Creativity usually arises from the transfer of solutions between domains, and a diversity of sponsors assures that [the researchers at the Laboratory] will be thinking in many different domains in the process of developing and packaging our work." [10]

A final aspect of the Laboratory that facilitates creativity is the emphasis on playfulness [10]. Playfulness involves actively engaging in designing, creating, and inventing – not just accessing or manipulating information [28]. The Laboratory's emphasis on playfulness was well-aligned both how the Programmable Brick was developed as well as the very nature of the Programmable Brick itself. As described earlier, the development of the Brick was very much a "try it out" methodology. Likewise, the purpose of the Programmable Brick and the LEGO Mindstorms project was to promote a constructivist, hands-on method of learning. The Media Laboratory provided a natural setting for the development of technologies that accomplished these purposes.

5.2 Sensors, IP, and Trading Places

Another important aspect of the Media Laboratory that affected the development of the Programmable Brick and LEGO Mindstorms was the Laboratory's enabling of the easy transfer of people, knowledge, and ideas between Resnick's research group and LEGO. The Laboratory facilitates knowledge and idea transfer both between its various research groups and between the Laboratory and its corporate sponsors.

The Laboratory's unique sponsorship agreement encourages this transfer of knowledge, ideas, and people between research groups and sponsors. Instead of providing funding for a specific project or research group, sponsors donate general funding used throughout the Laboratory. In return, sponsors are given royalty-free access to any technology developed by any group within the Laboratory. Media Lab Director of Community and Sponsor Relations Debroah Cohen states that the value for the sponsor revolves around the "Media Lab's focus on developing enabling technologies – technologies too far-fetched for companies to pursue in traditional commercial [research and development] environments. [3]" Research from the Media Laboratory many times proves a concept, or develops a technology that could be applied to solutions of other problems.

There are various levels of sponsorship within the Laboratory, including the introductory level of Affiliate Sponsorship, which requires $100,000 donations per year for a minimum of three years, to the highest level of sponsorship - Corporate Research Partner, of which LEGO is an example. Corporate Research Partners fund larger research agendas of the Laboratory including corporate fellows programs or special Laboratory facilities. In addition to automatically becoming members of each Media Laboratory Research Consortium, Corporate Research Partners are granted the right to have an employee work within the Laboratory. The annual budget for the Laboratory is approximately $35 million with over 90 percent coming from corporate sponsors. [38]

This unique sponsorship relationship grants researchers at the Laboratory greater freedom in choosing a focus for their research. As Bakhtiar Mikhak commented, "The Media Lab is a place where people can do what they want to do. [21]" Indeed, without the pressure of a specific sponsor's demand for a specific product, researchers are able to focus their research on more innovative, enabling technologies, rather than products with immediate commercial value.

The intellectual property policies of the Laboratory also affected the development of the project. Unlike other MIT Laboratories, which require financial backing from a specific laboratory sponsor when filing a patent, the Media Laboratory files its own patents. The Laboratory does this in an effort to ensure the accessibility by all sponsors of all technologies developed within the Laboratory. [38]

With the technology and ideas behind the Programmable Brick available to all of the Laboratory's sponsors, Resnick's group was free of the pressures of developing a product specifically for LEGO. Instead of developing the Programmable Brick with the explicit intent of producing a commercially viable product, the relationship between the Epistemology and Learning Group and LEGO took on more of an idea-sharing relationship. This seems to run contrary to the popular notion of what research sponsors desire.

LEGO's relationship with the laboratory started when the it first opened its doors in 1985. Ms. Cohen further remarks that LEGO is the Laboratory's "best citizen sponsor," referring the company's high priority on providing educational products. She further states that LEGO "has a real commitment to learning and has many of the same philosophies as [the Epistemology and Learning Group]. [3]"

As a Corporate Research Partner with the right to have an employee work in the Laboratory, LEGO sent Alan Tofte to collaborate with Resnick's research group in 1995, as previously mentioned. Tofte contributed to the development of the Programmable Brick, providing insights to design specifications, just as any research assistant from the Media Laboratory might do. However, Tofte also served as a liaison between LEGO and the Epistemology and Learning Group, bringing back ideas and knowledge to LEGO when the company decided to launch the commercialization effort of Mindstorms.

This open flow of ideas, knowledge, and people facilitated by the Media Laboratory directly affected the evolution of the Programmable Brick and LEGO Mindstorms. It allowed different motivations of the different parties involved to mix, shaping the development of the project. We see specific examples of this exchange of ideas and influence in the inclusion on the LEGO RCX brick of an LCD display, as discussed in Chapter 4.

5.3 Outreach

A final cultural aspect of the Media Laboratory was the goal of the lab to foster an environment of community outreach. The Laboratory promotes various forms of community outreach such as the Computer Clubhouse program and the newly-formed Digital Nations consortium. The Computer Clubhouse, started by Dr. Resnick, promotes the use of technology to enable under-served youth to acquire the tools, problem solving skills, and confidence for successful lives [4]. The Digital Nations initiative aims to use technology to tackle some of the developing world's most vexing problems, like illiteracy, poor health and economic instability [7].

The culture of community outreach evident in the Laboratory facilitated the Epistemology and Learning Group's need to receive feedback from children who interacted with the Programmable Brick. Dr. Resnick's research group conducted numerous sessions with local school children, in which the children were encouraged to interact with the Programmable Brick, solving problems and developing new projects of their own. From these sessions, the research group learned a great deal about the programming interface and what specific aspects of the brick and the problems presented were interesting to the children, as we see in Chapters 3 and 4.

5.4 Metrics for Success

In evaluating success of the Programmable Brick and Lego Mindstorms, from the point of view of the MIT Media Laboratory, we must again examine the goals of the organization in question and, from that, extrapolate its metrics for measuring success.

One of the primary goals of the institution is to support its form of operation, that is, an interdisciplinary model which promotes collaboration, sharing of ideas and knowledge, and the idea of playfulness. The successful commercialization of LEGO Mindstorms from the Programmable Brick shows that by this metric, the Programmable Brick project was a resounding success. The extensive sharing of ideas, knowledge, and people between the Epistemology and Learning Group and LEGO, facilitated by its sponsor relationship with the Laboratory, supports the collaborative nature of the Laboratory's research methodology. Also, the playfulness exhibited in the development of the Brick showed that this aspect of the Laboratory's methodology, as did the nature of the commercialized product itself.

The Media Laboratory can also point to the Programmable Brick and LEGO Mindstorms as a success because it is an example of the Laboratory producing tangible results. While the Laboratory is more focused with enabling technologies than immediately applicable products, the overwhelming commercial success of LEGO Mindstorms serves as an important benchmark in the value proposition of the Laboratory. The commercial success of LEGO Mindstorms can be viewed as a culmination of a long, intimate relation between the Laboratory and one of its sponsors. All of the individuals consulted for this study have agreed that the existing relationship between LEGO and the Media Laboratory played a key role in the eventual commercialization of the Programmable Brick. LEGO Mindstorms showed that while the Media Laboratory is still a place focused on technologies of the future, it can add significant, tangible value in the present. [6]

Although there are many reasons to view Lego Mindstorms as a successful product of the Media Laboratory, it can also be viewed as example of one of the faults of the Laboratory. Many detractors criticize the Media Laboratory for "getting an awful lot of attention just for churning out cute, flashy toys. [5]" Technologies developed at the Laboratory "almost never break technological ground, prove significant scientific theories or end up as important products. [5]" Many view much of the research conducted at the Media Laboratory as having questionable academic value, including John Anderson of Carnegie Mellon University's Human-Computer Interaction Institute, who states, "We all recognize and envy the high profile the Media Lab has. We also recognize that some of the work is kind of questionable. [5]"

While the Programmable Brick and LEGO Mindstorms cannot be viewed as technologically groundbreaking or proof of a significant scientific theory, from the points of view of both the Epistemology and Learning Group and LEGO, they can be viewed as important products.

For the Epistemology and Learning Group, the Programmable Brick served as an important product promoting the idea of constructivist learning. The Programmable Brick also achieved Mitchel Resnick's goal of enabling children to learn things in new ways by providing a new technology to do so.

In the eyes of LEGO, Mindstorms was a huge success. Not only did the commercial success play a large part in improving the financial situation of the company, the release of Mindstorms marked LEGO's targeting of a new market for its educational products. Mindstorms was the first product developed by LEGO Dacta, the educational branch of LEGO, to be marketed to the home-education market as well as the strictly educational market.

6.0 Synthesis

From Microworlds to the Media Laboratory, to LEGO, to homes and schools, the wireless Programmable Brick changed social contexts several times. It moved physically and intellectually from person to person and group to group, taking an imprint of each and contributing a little something back each time. Each group of people had different aspirations for the technology, which is why it evolved in so many different directions, and why there are so many different ideas of why it was or was not successful.

If there is one lesson from this case study, it is that design is an entirely, goal-driven process. No engineer can work effectively without some way to measure, however incompletely, how close they are to being finished. Nor will they necessarily know where to go next until they have built a prototype and watched someone try to use it. People and technology are *both* integral parts of the system to be engineered and one cannot be fully evaluated in the absence of the other.

7.0 Appendix: The Media Laboratory as a Solution to the Innovator's Dilemma

The story of the MIT Programmable Brick's evolution into LEGO Mindstorms can also be treated in the context of a theoretical framework we have not so far introduced.

Clayton Christensen, in his book *The Innovator's Dilemma*, discusses the danger to a business presented by so-called "disrupted technologies" [2]. These are low-performance, low-profit products which thrive in alternative markets and at first, for that reason pose no particular threat. However, over time, development effort translates into higher performance, undermining the higher-profit "sustaining technologies" that business tend to focus on in response to customer demand. [2]

The MIT Programmable Brick was not a low-performance version of older LEGO tethered-robot technologies. It was really just an advancement on the older technology, albeit potentially non-obvious and motivated by research and educational goals. So it does not entirely fit the model of a "disruptive technology." On the other hand, it was thriving in an alternative arena, and it was receiving Research and Development dollars and attention.

Christensen recommends that companies concerned about successfully identifying disruptive technologies establish autonomous subsidiaries. These subsidiaries would be freed from red tape and a need to directly serve customer demand, and would be provided with resources and a mandate to innovate new products and cultivate them in new markets [2]. In some sense, the Media Laboratory fits this mold. While LEGO obviously does not own the Laboratory, it does provide both financial and intellectual resources to it, and is allowed royalty-free access to its innovations, just as it would a research subsidiary.

The Laboratory clearly has the freedom to do undirected research without the need to please any particular set of customers. It also frees, as much as possible, its employees from the bureaucratic process of justifying resources spent, and actively encourages "playful" endeavors into new areas. The Media Lab has a mission to identify technologies that will be important in the next generation of engineering artifacts, and to be a hotbed for plans to recombine existing technologies in novel ways. For sponsors concerned about identifying new technologies that could affect their business, keeping in touch with developments at the lab would seem to be an excellent first step in that discovery process. There is an inside joke at the lab that best illustrates this: “We [at the Lab] get paid to fail where our sponsors cannot afford to do so.” [3]

Contrary to what many people might think, not every Media Laboratory sponsor necessarily needs such direct inspiration for so-called ”enabling” products as LEGO happens to have garnered. Merely being party to gossip about new technologies and seeing them explored in a non-dismissive fashion might be important enough to a company's well-being to justify dollars spent on undirected research. The Media Lab provides a common vehicle for many companies to participate in this process all at once, while at the same time serving an interdisciplinary academic role.

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