curlybot
designing a new class of computational toys

Philipp A. Frei

B.S. in Mechanical Enineering, May 1998
Massachusetts Institute of Technology

Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning,
in partial fulfillment of the requirements for the degree of
Master of Science in Media Arts and Sciences
at the Massachusetts Institute of Technology

May 2000

Author
Philipp A. Frei
Program in Media Arts and Sciences
May 5, 2000

Certified by
Hiroshi Ishii
Associate Professor of Media Arts and Sciences
Thesis Advisor

Accepted by
Stephen A. Benton
Chair, Departmental Committee on Graduate Studies
Program in Media Arts and Sciences

curlybot
designing a new class of computational toys

Philipp A. Frei

Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning, on May 5,2000
in partial fulfillment of the requirements for the degree of
Master of Science in Media Arts and Sciences
at the Massachusetts Institute of Technology

abstract

I introduce an educational toy, called *curlybot*, as the basis for a new class of toys aimed at children in their early stages of development – ages four and up. *curlybot* is an autonomous two-wheeled vehicle with embedded electronics that can records how it has been moved on any flat surface and then plays back that motion accurately and repeatedly. Children can use *curlybot* to gain a strong intuition for advanced mathematical and computational concepts, like differential geometry, through play outside a traditional computer.

Preliminary studies show that children can create gestures quickly, allowing them to iterate on the patterns that emerge, and successfully understanding and solving problems with *curlybot*. Programming by demonstration in this context makes the educational ideas implicit in the design of *curlybot* accessible to young children. *curlybot* can also act as an expressive tool because of its ability to remember the intricacies of the original gestures: every pause, acceleration, and even the shaking in the hand is recorded and played.

Thesis Advisor:
Professor Hiroshi Ishii
Associate Professor of Media Arts and Sciences
MIT Media Laboratory

curlybot
designing a new class
of computational toys

Philipp A. Frei

The following people served as readers for this thesis:

Reader
Mitchel Resnick
Associate Professor of Media Arts and Sciences
MIT Media Laboratory

Reader
William L. Verplank, PhD
CCRMA, Stanford University

acknowledgements

This work was produced with the collaboration, encouragement and guidance of many people. I am particularly grateful to Professor Hiroshi Ishii who has provided the environment, people, support and vision that has allow me to be creative and accomplish my work.

I would like to thank my readers Bill Verplank and Mitchel Resnick for their guidance and patience through this process.

I would also like to thank the entire TMG team over the years. In particular, I would like to thank Scott Brave who hired me as an "expert" Mechanical Engineer to build what would become the inTouch before I knew anything and waited patiently until I learned. I also am very grateful to Victor Su, who made everything work and believed in my ideas when they were just words. Of course nothing would have happened without the entire team over the years, including Matt, Paul, Craig, Brygg, John, Sandia, James, Ali, Jay, Joey, Dan, Megan, Ruji, Ian, Eric, Betty Lou, and Lisa, to share ideas, skills, and friendship. Thank you all for your enthusiasm and bearing with me for so long.

For early inspiration, I would like to acknowledge Golan Levin, Scott Snibbe, and their gesture-based animation environments that led me to look outside the computer screen to create animation.

There are many other people at the Media Lab whose time and insight were invaluable to this thesis. In particular, I appreciate all the work Brian Smith and Lorin Wilde have done over the last year to guide me through the thesis process, including their valuable feedback on this document. Rob Poor, for sharing his wisdom about electronics at every stage of my work. Professor Mike Hawley, Professor Tod Machover, and Kristin Hall for supporting my work in many ways. Of course nothing would happen without the second floor, NeCSys, Dennis and Julie. For taking last minute photographs, the freedom to use images, and helping me publish and publicize *curlybot*, I would like to thank Ellen Hoffman and Webb Chappell. Mike Ananny and Bakhtiar Mikhak for thorough reading and editing. And our friendly neighbors in ACG and SMG.

There was a good deal of support from sponsors and friends of the Media Lab. In particular, I would like to thank Interval Research Corporation and LEGO Corporation for their fellowship over the last two years. I would also like to thank Brad Niven of Interval Research Corporation for time and skill that made the final version of *curlybot* perfect. Kenny Dinkin (and the Learning Company) and Alma Wright (and the Trotter School) for their last minute feedback on my *curlybot's* educational potential. George Brackett from the Harvard Graduate School of Education for his insight on education and testing. Gary Collins for his great sketches and Lydia Sandon for amazing last minute editing.

To my friends, thank you for supporting and believing in my ideas, but also for keeping things fun. I am especially grateful to Cynthia and the KBL crew, including Ben, Lydia, Rodrigo, Dina, Oliver, Adam, Sonny and Mike. Without them things would be boring.

And of course, most importantly, I would like to thank my family.

In memory of Henning Trutschel von Holstein.

May 2000
Cambridge, Massachusetts

contents

1 introduction

Mother found the "Gifts." And gifts they were. Along with the gifts was the system... I sat at the little Kindergarten tabletop... and played... with the cube, the sphere, and the triangle – these were smooth maple wood blocks... All are in my fingers to this day... I soon became susceptible to constructive pattern evolving in everything I saw. I learned to "see" this way and when I did, I did not care to draw casual incidentals of nature. I wanted to design.

Frank Lloyd Wright, *A Testament*, 1957

The role of physical objects in the development of young children has been studied extensively in the past. In particular, it has been shown that a careful choice of materials can enhance children's learning. A particularly notable example of such materials is Friedrich Fröbel's collection of twenty physical objects (so called "Gifts and Occupations"), each designed to make a particular concept accessible to and manipulable by children [Bro97]. The presence of Fröbel-inspired objects in almost all kindergartens today is a reflection of their recognized value in the development of young children.

Most recently, Mitchel Resnick and the Lifelong Kindergarten Group at the MIT Media Laboratory have introduced a collection of "digital manipulatives" that builds on Fröbel's work, taking full advantage of computational ideas and resources not available until recently [Res98b]. Much like Fröbel's Gifts, these tools are designed to make new domains of knowledge accessible to children, inspiring them to think about the world in new ways.

1.1 *curlybot*

This thesis research adds to Resnick's initiative a new class of computational toys that are physically expressive and programmable by demonstration. *curlybot*, the first instantiation and the basis of this class of toys, is an autonomous two-wheeled toy that can record and play back how it has been moved with all the intricacies of the original gesture. Every pause, acceleration, and even the shaking in the user's hand, is recorded. *curlybot* then repeats that gesture indefinitely. This repetition can create beautiful and expressive patterns.

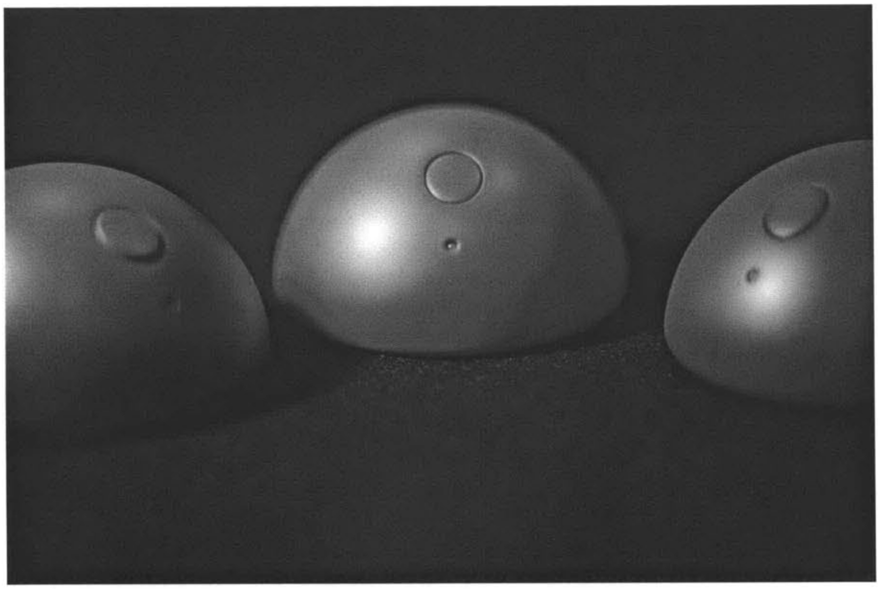


Figure 1-1

Three *curlybots* each with a large button and indicator light

curlybot is a smooth, easily-graspable, curved object with a button and an LED for indicating whether the device is in record (red) or playback (green) mode. To record a gesture, a child presses the button and moves *curlybot* through a desired path. Pressing the button a second time stops the recording and begins the playback of the recorded gesture. The playback mode repeats the gesture until the button is pressed again.

For example, if a child moves *curlybot* slowly forward and then quickly wiggles it back, *curlybot* will repeat that motion exactly, including the changes in speed (see Appendix A for still images from a video of this motion). If the child shakes *curlybot* nervously, it will shake nervously on its own.

We have observed that children find physically recording and playing a gesture to be fascinating and fun. *curlybot's* organic but autonomous movements seem to captivate the children who have played with it in our studies for long periods of time.

It is important that children become captivated by a toy in an educational context; only through repeated interactions and genuine interest can a toy's educational value be fully appreciated. Though replaying a gesture is interesting, most of *curlybot's* educational value comes from repeated experimentation with gestures.

For example, if a child moves *curlybot* forward a bit and turns it 90 degrees, *curlybot* will repeat that over and over, creating a square. The pattern created starts looking like the patterns children create with the Logo programming language [Pap80]. Logo is used in many schools to teach children computational and mathematical ideas by controlling a turtle on the computer screen with simple commands.

curlybot allows children to explore some of the same mathematical and computational concepts as Logo, but without the need to read or write. Logo requires commands, though straight forward, like "forward 50" [units] or "right 90" [degrees], to be composed. Because of the simplicity of *curlybot's* interface, children can quickly learn to use the toy to create intricate gestures, which they can refine through an iterative process. It is through this process that children can gain an understanding about the underlying concepts.

There are several augmentations to *curlybot* that may broaden the educational content, like adding sensors, music, or pens. The underlying connection between all of them is that they would be physically programmed by demonstration. This makes the toys easy to use, but also keeps them expressive and open-ended, capturing the children's interests and challenging their imaginations. *curlybot* encourages children to explore.

1.2 motivation

Most of the work I have done at the Tangible Media Group has focused on interaction design. Our group is looking for design principles that create better interfaces and interactions between humans and computers. One of the design principles we are exploring, particularly with *curlybot,* is the coincidence of input and output space. By bringing together where the input and output of information occur, we hope to create more intuitive and compelling interfaces.

The keyboard, the mouse and the screen are very appropriate interfaces for certain interactions, but they should not be our only modes of interaction with computational media. We would like to create new meaningful interactions and interfaces with computation. It is particularly important to look beyond the traditional interfaces when we want very young children to learn through rich computational experiences without having to master skills associated with "computer literacy," like reading and typing. Fröbel was making similar observations between design and literacy when he wrote that young children can and need to "learn the language of forms before they learn the language of words" [Fro04]. Also, by moving the interaction out of the screen, *curlybot* can be a more engaging learning tool, helping to encourage social interaction, and develop motor and coordination skills.

The design of *curlybot* was inspired in part by the natural and expressive qualities of Golan Levin's gesture-based animation environment system called Curly [Lev98], which builds on Scott Snibbe's Motion Phone system [Sni95]. These systems capture the gestures of the computer mouse on the screen and replay them graphically. While using the system, I was frustrated by the indirect manipulation of these very expressive graphical elements. I was using the computer mouse, which lives in our periphery, to manipulate something on a screen in front of me and in my focus of attention. At first, I thought it would be more satisfying to have a touchscreen and to be able create these graphical elements with my finger. The action on my part and the graphical creation would be more connected and in my focus of attention.

After some more thought, I questioned why there was a screen at all. Instead of having the gestural animation live behind the screen, one could create a physical object that could be taught how to move. It could then repeat that motion on its own. One would no longer have to play in front of a computer with something behind a screen or be constrained by its peripherals. And so, *curlybot* was born.

The challenge, though, was to keep the toy as simple as possible. I could very easily have put a screen and some additional buttons on *curlybot* to add more functionality, but I wanted the users to have only direct manipulation. I also wanted to show the depth of expression one can have with just one button and an LED indicator. *curlybot's* interface implies its use, letting the users focus on the task and not the controls.

Immediately after its creation, I started seeing similarities between *curlybot* and Logo. This led me to pursue in more depth how *curlybot* could add to the Logo community. I quickly found that the simpler interface allowed younger children to explore some of the same Logo concepts.

For example, like Logo, *curlybot* supports new ways of thinking about geometric shapes and patterns. Children can also use *curlybot* explore some of the basic ideas behind computational procedures, like how complexity can be built from simple parts.

Unlike Logo, *curlybot* has no intermediate language or numeric representation of the programs, which is an important aspect of Logo. *curlybot* draws more strongly on children's intuition about their own physical actions in the world to learn - what Papert calls body syntonic learning [Pap80]. In addition, the direct input and beautifully expressive patterns that result through *curlybot's* repetition of the gestures keep children playing and engaged.

Table 1-1

Interaction matrix describing the position of *curlybot* to other programming tools

Execution/Output	**Programming/Input:** Digital	**Programming/Input:** Physical
Digital	Turtle Graphics	Motion Phone Curly
Physical	Floor Turtle LEGO/Logo Programmable Bricks Crickets LEGO Mindstorms	curlybot

The table above summarizes the different ways in which children interact with the various design and expression media. This parameterization of possible modes of programming and interacting with computational media highlights *curlybot's* significance, including the coincidence of the input and the output space.

1.3 thesis overview

The thesis begins with the background and context for this work, including related work. I will then examine some of the interaction scenarios with current implementations and future augmentations to the system to give a full range of possibilities for this class of new toys. Since this thesis will attempt to show that *curlybot* can play a significant role in mathematics education research. A part of this thesis will be devoted to discussing the educational issues associated with current and future *curlybot* designs. Because issues related to interface and interaction allowed for these new possibilities, there is a discussion of the design considerations of *curlybot.* In the end, the thesis presents an evaluation of the system, including two different user studies with children and feedback from teachers.

2 background

In this section, I will place *curlybot* in an educational context and then give a brief overview of the related work. The educational context section begins with an overview of Friedrich Fröbel's work on physical objects (so called "Gifts and Occupations"), which he specifically designed to make particular educational ideas tangible and accessible. The description of his Gifts and their importance is followed by an introduction to Seymour Papert and Mitchel Resnick's work, with a special emphasis on the Logo programming language and Resnick's notion of "digital manipulatives." The end of this section addresses work that is related to *curlybot* from an educational standpoint as well as from a functional standpoint.

2.1 physical tools

Friedrich Fröbel believed that children should be intellectually nurtured at an early age; in the early 1800's, he developed the concept of kindergarten [Fro04]. As part of his kindergarten, he assembled twenty Gifts and Occupations to achieve his pedagogical goals. Fröbel's Gifts and Occupations form a system for teaching math, science, language, and design through play with simple materials. While the Gifts are solid materials to be manipulated and rearranged, such as wooden blocks, the Occupations are crafts where the materials themselves are manipulated, like modeling clay, sewing, and making origami.

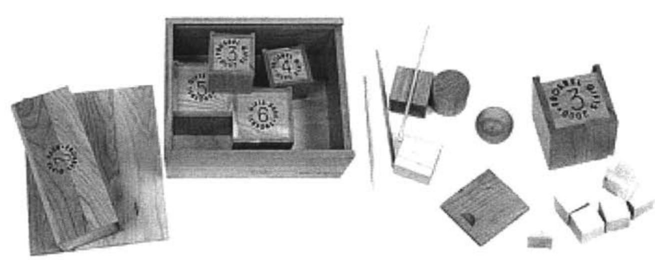


Figure 2-1

Fröbel's Gifts Numbers 1-6 in their boxes

Most of the Gifts are pieces that are meant to be arranged to create mathematical relationships, representations of things in the world, or beautiful designs. Similarly *curlybot* tries to support all three of these aspects from a different perspective, specifically through an object that is kinetic, organic and expressive.

There is one Gift in Fröbel's collection (Number 2) that addresses movement. The Gift is a group of wooden blocks with holes in different places where one can insert a stick. The wooden blocks can then be spun very quickly to create the illusion of different three-dimensional shapes. For example, if one puts a stick into one side of a cube and spins it quickly, the resulting shape one sees will be cylinder.

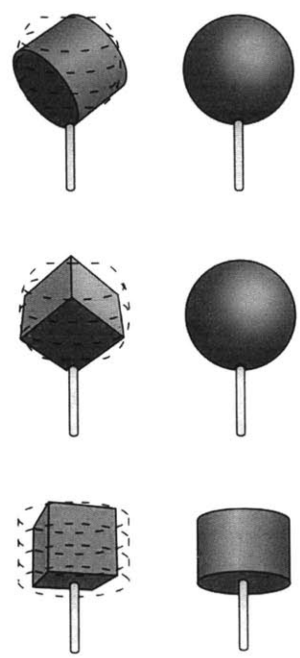


Figure 2-2

Comparing the results of spinning different shapes using Fröbel's Gift Number 2

When referencing Fröbel throughout this thesis, I will generally be referring to his Gifts and not the Occupations, since the Gifts are used as physical tools, like *curlybot*, instead of materials. See Appendix A for more information on the Gifts and Occupations.

2.2 physical/digital tools

Many of the computational/educational environments designed for children thus far have been limited to activities on the computer screen. One notable example that has enjoyed great recognition in and out of the classroom is graphical Logo. The main computational object in Logo is a turtle whose heading and trajectory can be controlled by simple programs written by children. Graphical Logo was inspired by a small robot (about one cubic foot in size) built at the MIT Artificial Intelligence Laboratory by Seymour Papert and his collaborators. This robot, called the Floor Turtle, was quite heavy and tethered to a mainframe computer. It also had a pen inside that could be raised and lowered to leave traces of where it has been. By typing commands at a terminal, children controlled the turtle and its pen to draw geometric patterns on large sheets of paper on the floor.

Figure 2-3

Children playing with the original Floor Turtle

Different interfaces to the Floor Turtle were developed to simplify the interaction for children with physical/iconic controls, like Radia Perlman's TORTIS system [Smi75].

In the 1980's, Fred Martin, Seymour Papert and Mitchel Resnick resurrected the Floor Turtle work at the MIT Media Lab by building computation and programmability into the familiar LEGO bricks [Mar88]. Children could build the Programmable Brick into their robots and program them to bring their creations to life. The most recent member of the programmable family of bricks is the Cricket [Mar99], which encapsulates the core functionalities of the previous generation, the Programmable Brick, into a much smaller package and makes the system expandable through a unique bus structure. The Programmable Brick inspired the LEGO Mindstorms Robotic Invention System [Mar99].

Robots built with the Programmable Bricks and Crickets are currently programmed in text-based or graphical programming languages that are dialects of Logo. Research has shown that children as young as ten years can successfully use Programmable Bricks and traditional construction material to build and program their own robots to exhibit the behavior they are looking for. Extending these types of activities to younger children is an active area of research [Res98a].

The Programmable Bricks and Crickets are only the beginning of an initiative by Resnick to create "digital manipulatives." Digital manipulatives are new physical/digital tools that allow children to explore advanced concepts through physical manipulation of computationally enhanced objects. They expand Fröbel's work into new domains of knowledge.

curlybot is designed to show the possibility of a new class of toys that would add to Resnick's digital manipulatives by being physically expressive and programmable by demonstration. Like Fröbel's Gifts, the class of toys is self-contained, simple, open-ended, but with access to the more advanced concepts possible with computation.

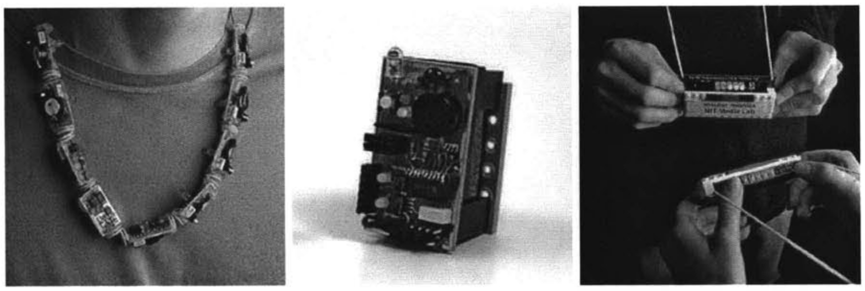
2.3 related educational work

The Epistemology and Learning Group at the Media Lab has done closely related work to *curlybot* for many years, spearheaded by Seymour Papert, Mitchel Resnick and Fred Martin. This work includes Logo, LEGO/Logo, Programmable Bricks, Programmable Beads, and Crickets.

The ideas for trading information between future versions of *curlybot* (discussed in the Interaction Scenario section) are based on the research of Rick Borovoy on Tradable Bits [Bor99]. This includes Thinking Tags [Res98b] and Meme Tags [Bor98a], which are badges that people can use to exchange and track information. For example, the badges record who talked to whom and how information was propagated through the community. His most closely-related work is the Dance Craze Buggies, cars that can teach each other a dance [Bor98b]. One can then track how the dance one created propagates (or does not propagate) through a community of buggies.

Figure 2-3

Programmable Beads, a Cricket and Thinking Tags



curlybot can also be used as a narrative tool. The work of Kimiko Ryokai and Justine Cassell, called StoryMat, is about creating a space that encourages children to tell stories with a plush toy and later have them replayed [Ryo99]. The replay is not in physical form, but occurs with a moving projection of a toy on the StoryMat accompanied by recorded audio. A future implementation of *curlybot* will let children record audio as part of their gestural storytelling.

Microsoft's ActiMates Barney, like *curlybot,* attracts a child's attention by being a character that exists in the child's physical space rather than a virtual space. One of the major differences, though, between Barney and curlybot is that Barney is a story-based toy. This means that the child's interactions with Barney are limited by a preprogrammed or uploaded set of stories. *curlybot* on the other hand, encourages the authorship of narratives, in addition to other open-ended activity. Instead of being told a story or being given a specific task, the child learns through teaching *curlybot* and exploring the results. Because this interaction is more complex, Barney is still easier to use for very young children [Str99].

Another system that is easy to use is Alison Druin's Noobie [Dru87], which is a large interactive plush animal and the main predecessor to Barney. As the child squeezes part of the animal, the animations on the screen buried in the toy's stomach changes. Children climb all over Noobie to progress the animations.

2.4 functionally related work

Aside from the related educational work, *curlybot* is also functionally related to some robotic systems in industrial applications and the work of the programming by demonstration community.

On manufacturing assembly lines – to save time programming robotic arms – a robot is sometimes physically given end points for its trajectory and is then allowed to calculate the optimal path. If there are obstacles for the robot arm to avoid, extra points are added to create the desired trajectory. If there are many product changeovers in the plant, this can significantly reduce the changeover time. Like *curlybot*, this system is an example of physical programming.

The programming by demonstration community has, for more than twenty years, been developing systems to make programming easier for programmers and bring programming to the end user. *curlybot* applies some of those ideas to a physical system for children to learn with; a layer of complexity has been removed, hopefully making the toy more fun and easy-to-use.

David Canfield Smith created 'Pygmalion: An Executable Electronic Blackboard' which was the first system for programming by demonstration [Smi75]. Pygmalion is a two-dimensional, visual programming environment in which the programmer sees and thinks about programming as a series of frames in a movie. The programmer starts with an initial state that is then edited and transformed step by step until the desired result is reached. The program can then be played to achieve the result. A different initial state can also be set and the program will apply the abstracted transformations to the new conditions.

Allen Cypher describes the basic motivation behind programming by demonstration best when he writes, "if a user knows how to perform a task on the computer, that should be sufficient to create a program to perform the task" [Cyp93]. This concept is also part of the motivation for *curlybot*. Children usually know what they want *curlybot* to do and that knowledge should be sufficient to create the movement. There needs to be no abstraction at this point even though it will be important future step. The learning and exploring comes from the repeated patterns that are created as a result of the initial motion.

curlybot, in its current form, might not be considered programming by demonstration in a strict definition, because one cannot change the initial state and have the program execute a different result. But, if one adds sensors to *curlybot* (as mentioned in the Future Implementations of the Interaction Scenario section) *curlybot* becomes a toy that exhibits conditional behavior and variable results.

3 interaction scenarios

This section explores some of the different interactions possible using the simple technique of recording and repeating physical gestures. These scenarios illustrate the different ways in which the class of *curlybot* toys challenges children to create and explore new mathematical and artistic expression.

As a result, the Interaction Scenarios section is divided into two parts: Implemented Systems and Future Implementations, with subsections describing some of the different interactions children may have with *curlybot*. The future implementations rely on augmentations to the current system that I will discuss in conjunction with the various activities.

Figure 3-1

Three *curlybots* with a user's hand

3.1 implemented systems

This section focuses on existing implementations of *curlybot*. All of these ideas have been already realized to some extent. In order to group similar interactions together, however, some of the subsections of Implemented Systems have minor extrapolations about future ideas that have not been implemented.

3.1.1 repetition

The simple repetition of a gesture with *curlybot* allows for both educational and expressive possibilities.

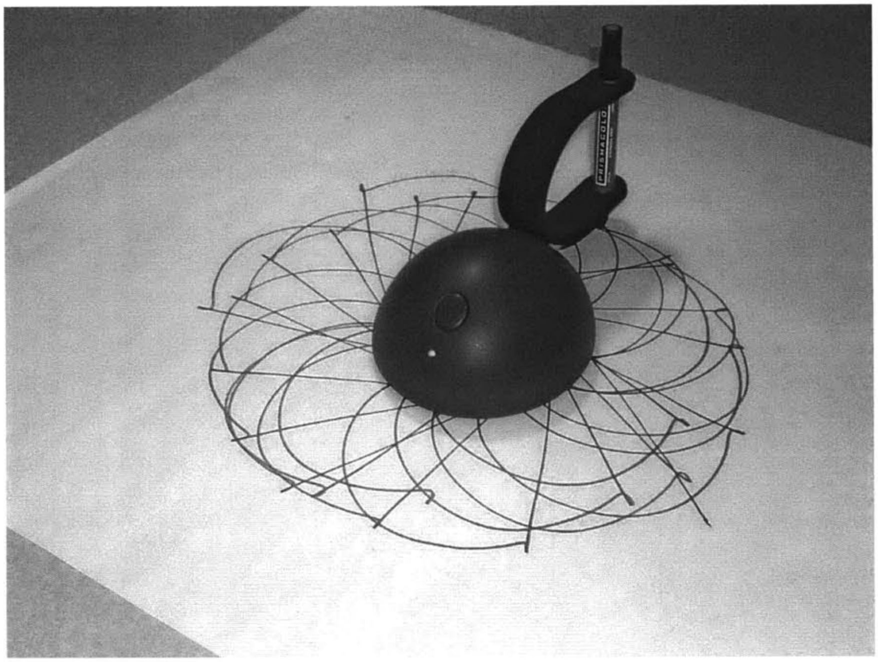
For example, children used *curlybot* to answer the question, "How do you keep the toy repeating a gesture while not falling off a table?" A child, in this case, learns to create repetitive patterns that as a rule would end up at the origin or circle around a focal point. Otherwise the difference in position between the beginning and end would make the toy repeat that difference and drift off the table. Through this direct manipulation, a child can learn many lessons by simply playing and experimenting with movement, spatialization and repetition, including ideas of computational procedures (how complexity can be built out of simple parts), differential and vector geometry, local vs. global errors, and compounded error propagation.

Another example is a child's attempt to create a star with three gestures. This activity introduces a child to the idea of building complex shapes by combining simpler elements. The child is also exploring computational and mathematical ideas, such as loops and vectors. To create a star, the child has to be concerned with point of origin and elements of a vector, such as direction and magnitude. When *curlybot* loops the recorded vector, it is also critical to start and finish with correct orientation, not just position.

A pen can be attached to *curlybot* to leave a trail of its path, making complex pattern easier to visualize. When one adds a brush to *curlybot* instead of a pen, one can begin to visualize the velocity of the toy as the thickness of the line it draws. If *curlybot* is moving quickly, the line will be thin, and if *curlybot* is moving slowly the line will be thick.

Figure 3-2

curlybot with a marker repeating a gesture



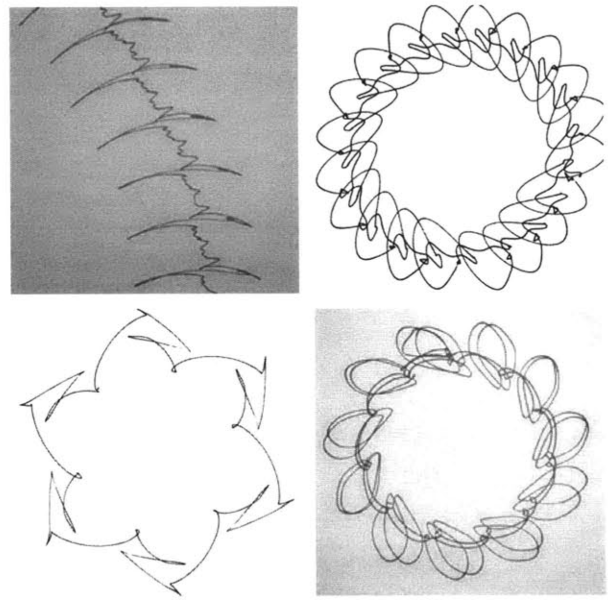
The idea of attaching pens returns the focus of *curlybot* to the expressive nature of the device. Together with the user's original expressive gesture, the final position and orientation of the device can create a beautiful and sometimes unexpected result.

An interesting result of playing with pens on *curlybot* is that its repetition of a gesture can turn what appears to be a mundane or ugly gesture into a beautiful design. Below are some simple gestures that have come alive through repetition.

Very often, children get discouraged from artistic expression because their hands cannot produce accurate representations of things around them. *curlybot* can be a tool for expression, encouraging those children who may not have traditional artistic skill to explore and discover new modes of communication and expression. For example, a child might have a very good sense of composition but not be able to sketch or paint. *curlybot,* in this case, could allow the child to express her ability without being limited by the dexterity or familiarity with a tool.

Figure 3-3

Drawings created with *curlybot*



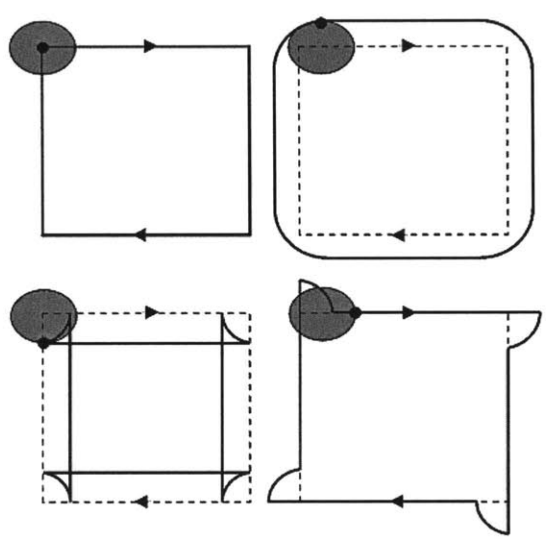
Creating a mechanism that could record and play back whether the pen is up or down would allow for a broader range of designs than the ones with our current system. This could include discontinuous lines, like dotted or dashed lines in the designs.

3.1.2 pen position

The use of pens introduces additional mathematical concepts, since the pen can be placed in different locations relative to the wheels of the vehicle.

Figure 3-4

Four different pen positions and their resultant trails on the same recorded path tern.



For example, a *curlybot* shown how to move forward and turn 90 degrees will create a square, if the pen is placed in the middle of *curlybot* - exactly between the two wheels (see the first pattern in Figure 3-4). However, a different pattern will emerge if the pen is placed further from the center. This can be contrasted with the graphical turtle, which is assumed to be a point-like object with its pen located at its center. *curlybot* allows for more surprising patterns to emerge, which encourages a child to think about the distinction between point-like and extended objects. A child might not mathematically understand the concept, but will have at least developed a basic understanding or set of limited intuitions for relative position and motion of points.

This understanding is less important in the mathematical world, where there are ideas of abstract points, but is very important when dealing with engineering tasks. For example, when you turn left, your right shoulder moves forward and your left shoulder moves back. It is important for engineers to have a good intuition for real systems; it helps them make important estimates and quickly judge the feasibility of proposed designs.

If one added an additional degree of freedom and had the pen move independently in a circle around *curlybot*, one can create more complex patterns that begin to mimic orbital patterns. If one then moved *curlybot* in a circle and had the pen move at a higher frequency around *curlybot*, one creates the orbital pattern of the moon relative to the sun. To create this pattern, the motions would have to be recorded separately.

3.1.3 different personalities

curlybot's control algorithm can also be changed to create motions with different "personalities." Depending on the setting of these algorithm variables, characteristics of the playback would change. For example, a *curlybot* could be designed to reproduce fast motions better, while another could be designed reproduce slow motions better. If the system were damped less to let the toy accelerate more slowly and overshoot its destination, it would appear like it is trying to catch up to your motion. If we over-damped the system, it would have trouble playing back slow motions or details in motions. Creating these distinct *curlybots* gives them personality outside the recorded gesture, making them individual characters which children will be drawn to in different ways.

The damping variables can change over time, so that the toy appears to be learning. Over time it could become a critically-damped system, where the toy appears not to be overshooting as much or learning the details or slow motions better. Though not preferable, even in a system where the variables change in a predetermined way, children would think they are teaching the toy something. If it is not predetermined, information on how the child plays with it can be stored in memory and slowly change the ability of the toy over time. The toy can "know" if you are trying to do slow motion, because it records that information and adjusts to work better in that situation. This could be much more convincing than the predetermined system.

3.1.4 gesture and narrative

It is common for children to act out stories with toys; imagine having *curlybot* boomerang back through all the obstacles and start replaying the interaction physically - pausing and accelerating in all the right places. Since *curlybot* captures not only the trajectory of movement but also the velocity and acceleration, it is used to express gesture. For example, a child could record slow creeping across a surface, and *curlybot* would do just that. This gesture-capturing capability may help children enact stories with *curlybot*.

Adding audio recording and playback to the device allows synchronizing what children say with how they move [Ryo99]. Children could learn aspects of storytelling and gesture by watching their own actions from the point of view of an observer.

One could also tell stories by lifting the toy up and put it back at the starting position, instead using the boomerang mode. The current configuration of *curlybot* does not allow for that because it starts relaying the motion immediately after the child stops recording, not leaving enough time to move it back to the starting position. Minor changes in how the button is interpreted by the microprocessor would allow for this.

Figure 3-5

Kimiko Ryokai's StoryMat.

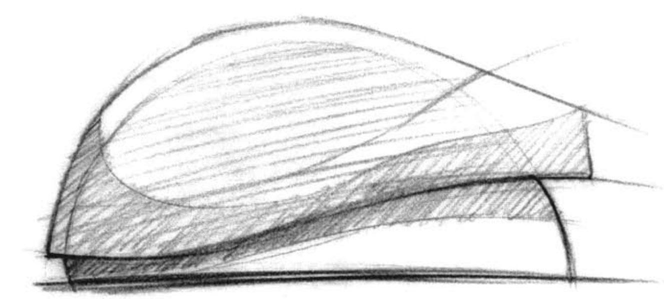
As mentioned in the Background section, some aspects of this are very similar to Kimiko Ryokai's and Justine Cassell's StoryMat project, where stories told with a plush toy are recorded, including the audio and position of the toy. During playback, a projection of the toy is seen moving over the story mat as the child moved it while telling their story. Because the system knows absolute position, unlike *curlybot's* relative position, it can play different stories that were recorded before depending on where the plush toy is placed on the story mat during the playback mode.

3.2 future implementations

Though many of the ideas in this section may be easily implemented, they have not yet been implemented and represent future enhancements to both the physical and conceptual nature of *curlybot*.

Figure 3-6

Sketches of another *curlybot* design



3.2.1 conditional behavior

Additional sensors could be added to *curlybot*, like bump and light sensors, in order to program conditional behavior. For instance, one could teach *curlybot* to move forward and it would then drive straight until hitting a wall with one of its bump sensors. At that point, the toy would stop moving. The LED on the device would turn yellow, prompting the user to record a sequence in response to hitting the wall. One could then record, going backwards a little and turning, which would now be *curlybot's* standard response to hitting an obstacle with that particular sensor. This type of conditional programming would allow *curlybot* to respond to its environment instead of simply playing back a recorded gesture and allowing *curlybot* to act as an autonomous creature with complex behavior. This also has implications to creating different personalities depending system's reactions to its environment.

This type of behavior is the similar to that of creatures made with the Programmable Bricks or Crickets. However, *curlybots* are programmed by demonstration rather than using traditional programming. Nonetheless, a child can still start exploring ideas about "if" and "while" statements. More complex branching may also be possible, but more exploration is necessary.

3.2.2 recording primitives

With communication between *curlybot* and a personal computer (via infrared (IR), radio frequency (RF) or physically moving the memory to the computer, like Sony's Memory Stick) one can start saving the gestures under different names for future use, like circle, box, wiggle and line. These elements could later be used as procedures in a programming language such as Logo. Suddenly, we return to children playing with abstract representations, which are important in understanding programming, but the elements are no longer limited to movements that are easily expressed mathematically. The world of Logo can now output expressive gestures. Separate gestures could be combined in a program and sent back out to *curlybot*. This added functionality leverages the simplicity of physical programming and gestural output with the added flexibility of a computer program. This is also a concrete example of procedural abstraction.

3.2.3 editing

There could also be other forms of input to *curlybot*, like electric field sensing, that could be used to change or edit motion during playback. The current system requires the user to rerecord to make a change, which may not be ideal in all scenarios. One could imagine a system where electric field sensing is used to detect if a hand is near the front, back or two sides of the toy. *curlybot* would move away from a user's hand as it approached. As *curlybot* plays back a gesture, children can use their hands to "push" *curlybot* into a new trajectory or even change the velocity or acceleration. For example, if *curlybot* was just moving forward at a constant velocity, one could "push" *curlybot* to one side until it was going in circles. One could then move ones hand quickly towards the back of *curlybot* and then quickly away, making *curlybot* accelerate and then slow down to speed.

The editing could also happen on the computer after the recorded information has been transferred to the computer as mentioned in the previous scenario. The computer could then display the motion in a graphical program and allow the user to edit it. This addition would move the play activity to the computer again, which we were trying to avoid in the first place. But it would be an interesting challenge to create a program that would allow you to view and edit not only the trajectory, but also the velocity and maybe even the acceleration of the motion. One way to do that is to represent the motion as if a brush were attached to the back of *curlybot*, so that the faster it moved the thinner the brush stroke would get. Another way to represent speed (suggested by Bill Verplank) would be to use tick marks. The pen could tap down at known intervals and the spacing between the dots would indicate the speed. Children could use the marks to calculate speed and begin exploring derivatives in a concrete way - a classic high school physics experiment.

To avoid the computer, but still have some editing power, a tri-state or greater switch may allow us to go from regular playback to something that can let the user speed up, slow down, enlarge, or shrink a recorded motion. The current system can switch between regular mode and boomerang mode.

3.2.4 exchanging information

The exchange of digital information is a very rich area of research. *curlybot* currently supports the exchange of its information because its memory is physically removable (like Sony's Memory Stick or Brygg Ullmer's MediaBlocks [Ull98]) and can be used to save a session or exchange it with someone else's *curlybot*. The design of the case for *curlybot* has not yet accounted for this functionality - since we wanted the first version to be as simple as possible - but could with some additional design. The memory could also be exchanged with a personal computer, where the recorded path could be displayed, or potentially altered and resaved to *curlybot's* memory. The file could also be sent to distant friends to be played on their *curlybots.*

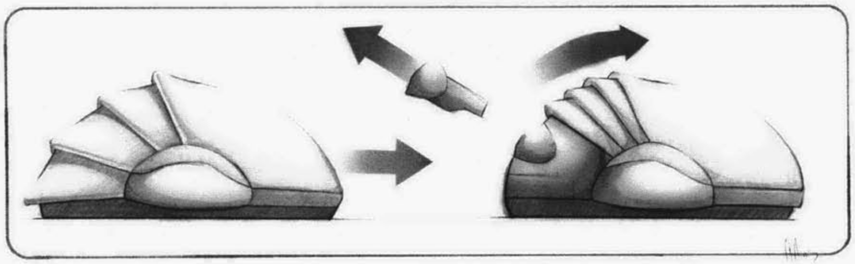


Figure 3-7

curlybot with removable memory

The exchange could also happen without a physical exchange of memory, but rather through IR or RF. One could have one *curlybot* teach another *curlybot* an interesting gesture and these could be passed on and saved. It would be interesting to see how a particular pattern spreads and to examine which gestures people felt compelled to pass on to others. One could also introduce evolutionary ideas, involving the progressive alteration of patterns over time via an exchange with different patterns [Bor98, Bor99].

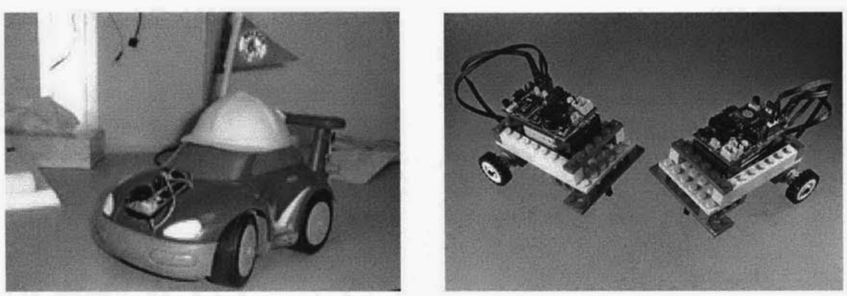


Figure 3-8

Dance Crazed Buggies and Dancing Crickerts

As mentioned in the Background section, Rick Borovoy has shown interesting examples of trading information, like his Dancing Crickets that synchronize their dancing through IR or Dance Crazed Buggies that can teach each other dances through IR.

3.2.5 synchronization and mapping

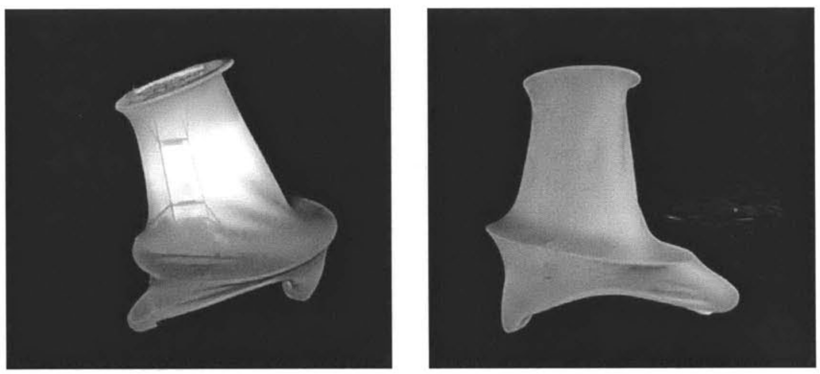
Two or more *curlybots* could be synchronized to create a medium for haptic communication, like the inTouch [Bra97], or just a fun game, like HandJive

[Fog98]. Through IR or RF *curlybots* could send their position to each other and try to remain synchronized. If one was moved the other would move. If the second was held, one would feel a restoring force on both of them. Facing *curlybots* could mirror each other and appear to be dancing. Or if there were multiple *curlybots* one could have one lead and the others follow like ducklings or line dancers.

curlybot could be mapped to some information source and display that activity, like Ambient Displays [Ish97]. Since *curlybot* is very expressive, it could also have an expressive kinetic response to the information, like Andrew Dahley's WobbleLamp and dynaLux [Dah98].

Figure 3-9

DynaLux moving its three legs and changing the light inside



Since we have multiple *curlybots*, we used the current version to choreograph dances. We have even choreographed five *curlybots* to dance together and make interesting formations and synchronized movements. As long as one starts and stops recording at the same time they will perform together. For more than two *curlybots* we would press record on each *curlybot* in series evenly timed and repeat that series and timing when we pressed the button to stop. In this way they can all start together.

Though interesting to figure out how to coordinate all the *curlybots* at once, it might be interesting to have them synchronized. One could record a particular gesture on each *curlybot*, and then given a command so they would all start moving together. Or they could negotiate the timing between each other so that they looked good together. For example, if we had three gestures of different lengths and played them together they would be out of synch with each other until a multiple of their times was reached. Small multiples could be " negotiated" between *curlybots*. For example, a five second sample and a nine second sample could be negotiated to create a four and eight second sample, so that the short sample repeats twice for every long sample.

In all the cases of trading information and synchronizing *curlybots*, there are some very interesting design issues one will want to consider when wirelessly connecting them or other devices. These issues are discussed in the Design section.

3.2.6 music

One could map different gestures created with *curlybot* to musical sounds and have them loop like *curlybot's* physical motion in a rhythmic pattern. For example, use one *curlybot* to synthesize sound that is dependent on the velocity and acceleration of the two wheels. The mapping is an interesting challenge, but there are enough degrees of freedom in the system to create an interesting instrument. If one moved forward the speed of one wheel relative to the other as well as the overall speed, one could have some very subtle effects on the music synthesis. One could create a staccato note with a quick acceleration forward and back, but each staccato would sound different depending on the movement of the wheels relative to each other or the actual change in velocity and acceleration as one records it.

Each *curlybot* can be a part in a musical ensemble. The two *curlybots* would be out of synch since the recording time would not be exactly the same, but they could communicate and synchronize when put together. Alternatively, one could affect a musical piece that is played using *curlybot*. One could feel some of the musical elements through *curlybot* and push back against them physically. One could also just enjoy watching it and effect the music with electric field sensing as mentioned in the editing section before.

In all of these audio applications, the output could be transferred wirelessly to computer so that it could be played on better speakers. The output could be low bandwidth position information that the computer could then use to affect the synthesis or editing, so that the heavy computational task does not have to live on the device.

3.2.7 prerecorded audio

curlybot could have prerecorded audio sequences that could be triggered by certain conditions or be coordinated with motion. We do not need extra sensors to know how *curlybot* is moving because we have all that information from the wheels (unless they slip). *curlybot* knows where it needs to go, where it is and if it is getting there. For example, if *curlybot* is trying to move forward, and it hits a wall, the system applies more and more power to get to where it needs to go because it is not moving. At some point the toy could tell you, "I'm stuck," because it knows that condition is true. Similarly when it spins in circles too much it might say, "I'm dizzy." Usually, for toys to respond to their environment or conditions effectively they need many sensors, but *curlybot* can derive much of information from just two sensors: it knows its desired position, current position and other information about its velocity and acceleration.

3.2.8 mats

Some of the educational activities we describe for *curlybot* require adult direction or an educational context for the child to realize all the educational content. *curlybot* can deliver educational content without adult supervision or educational context, but much more is possible when they are there. For example, starting to develop an intuition about computational loops and basic vector geometry can be achieved by having children play on their own and try to keep *curlybot* on a particular surface as described in our studies in the Evaluation section. If the goal is to have children learn specific lessons, it may be beneficial to have an adult present who challenges and questions children's actions and assumptions.

If we wanted to show children new concepts or strengthen existing concepts with or without adult guidance, we could introduce mats, on which *curlybot* can run. Each mat could have a different prescribed activity. For example, the mat could have a limited area in which one can record and the goal is to get *curlybot* through the obstacles to an area on the other side of the mat. This may encourage the children to anticipate the results of their actions.

For very young children, one could design a mat that helps them draw letters with *curlybot* and a pen attachment. Instead of just seeing the letter or writing it, they also see the action of creating it over and over again. One could design simple mazes on the mats that result in letters to turn the activity into a game.

3.2.9 measuring tools

We could also attach measuring tools to *curlybot*, like a mechanism that measures an angle when it is turned or the distance that it has traveled. The angle measurement would be very useful as a pre-Logo tool. The abstract notion of turning a certain number of degrees can be meaningless to a child. But if they gain some experience moving *curlybot* with their hands and seeing the resultant angles, they might start understanding the relationships between rotations, angles and vectors. This is especially true, if they start seeing reoccurring angles for certain patterns. It may demonstrate some geometric concepts, like the fact that the sum of a triangle's internal angles is 180 degrees. It is important to note, too, that there will be a difference between an internal angle and an external angle - another concept for children to acquire.

Attaching such a tool is particularly interesting after comments I heard from teachers and students that many students starting to learn Logo do not understand the concept of degrees. One child commented that many of his classmates thought, "ouch that's hot," when they heard they need to turn 90 degrees. Children may learn degrees abstractly through Logo and a teacher, but it would be interesting to see if they could use of *curlybot* with an angle readout and then use that knowledge later in Logo. For example, they may start spinning it and realize that a full turn is 360 degrees and half a turn is 180. At the very least, with the guidance of a teacher they begin to create and internalize abstract notions of angles.

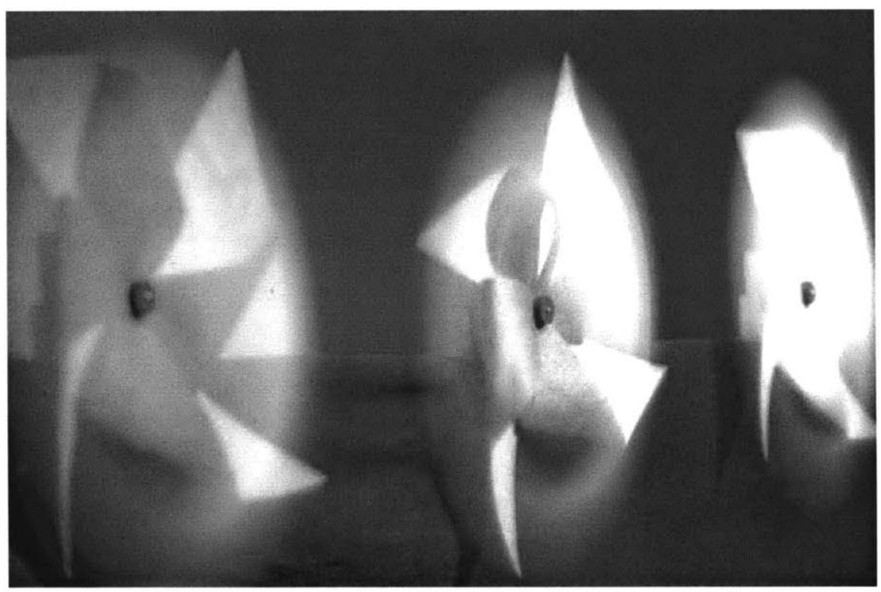
3.2.10 different architecture.

The *curlybot* system does no need to be embodied in a rolling device. If the system were applied to LEGO and a new motor unit were created with all the properties of *curlybot*, a creature could be assembled with complicated and programmable leg motions. Physical connections could be made between the motors to synchronize the motions of each leg, so that the creatures could walk. This, of course, is a difficult design task.

This example shows that the notion of a motor can be changed from a device that receives power and control from the outside to a system that just receives power and perhaps data but contains all controls within the system. This would allow for a very flexible decentralized system. One would just have to send power (and not be concerned with controllign the voltage and current down lines that would normally give the control) and data. An attempt at such a system is the new pinwheels in the Tangible Media Group, which I redesigned in accordance to this idea, but without the encoder to reduce the cost. In the new system, three functional lines (namely power, ground and data) allow us to daisy-chain many pinwheels and run them from one power source and one computer. This design keeps the system simple and easily scalable.

Figure 3-10

Pinwheels indicating online activity by spinning



The next step beyond the pinwheels would be to have something that does not receive data from a central source, but instead is programmed by demonstration like *curlybot*, sharing its information with other devices in its environment.

4 educational implications

In this section, the educational opportunities afforded by the *curlybot* family of toys are presented, specifically:

- To serve as objects-to-think-with [Pap80]
- To make new domains of knowledge accessible or old domains of knowledge approachable in new ways
- To support multiple learning and play styles [Tur90]
- To support multiple intelligences [Gar83]
- To create an affective and intellectual relationship with a child

It is important to be aware that, for some of these educational opportunities to be realized, the proper educational structure is necessary. This educational context could be a teacher or parent guiding the activity or prompting the child with the right questions. It could also be in the form of a mat on which activities are prescribed.

4.1 *curlybot* as an object-to-think-with

curlybot's physical form, size, and weight make it a natural extension of the hand. A child can map ideas from his or her mind directly into a clear physical instantiation. The process and validity of the execution is transparent because the motion involved in the act of programming is bodily syntonic, namely it draws on children's intuition about their own physical actions in the world. The immediate feedback from the observed behavior of the toy allows children to examine and reflect on their initial mental models with respect to the outcomes they observed. It gives them a chance to debug and extend their thinking.

In *Mindstorms*, Papert eloquently describes the significance of programming as a tool for thinking about one's own thinking [Pap80]. The very process of externalizing mental models and concepts in one's mind into the physical world allows for the critical evaluation of the validity of the models by oneself and others against easily understandable physical behavior. In turn, the external instantiation of an idea – and peer feedback – can be internalized again to modify the initial models. *curlybot* offers rich educational opportunities by creating and supporting such internalization/externalization feedback loops.

curlybot's open-endedness and simplicity makes it an object-to-think-with. It does not dictate a particular way to play and it does not assign specific meanings to actions. Children play with *curlybot* and discover their own associations through their experience with the physical world, math, science, design, or pattern. Making associations with existing knowledge is a successful form of learning. As Fröbel argues, if children make associations themselves, they will be drawn to further discovery and learning [Bro97].

If *curlybot* had more functionality, its focus would change. The child may not be thinking *with* the object but *about* the object. If we want children to make associations between their thoughts and the world around them then they need to think *with* the object. There is merit in thinking *about* the object, but one has to be aware that it produces different results. In addition, one might find children struggling to understand an interface rather than being creative with the toy.

It has also been found that "minimally structured material" presented to children from kindergarten through second grade produce significantly more varied themes and richer fantasies than more "structured toys" [Pul73]. This again enforces objects-to-think-with.

4.2 *curlybot* and new domains of knowledge

curlybot can make new domains of knowledge accessible or old domains of knowledge approachable in new ways. For example, *curlybot* can make core ideas in Logo accessible to even younger children. *curlybot* provides a tangible way of exploring many important ideas that have been studied extensively within the Logo community. For example, moving forward a little and turning a little will result in a circle, if one repeats it over and over again. This motion will result in a more even circle than if the child tried to create the circle out of a single gesture. This is a concrete instantiation of the idea of differential calculus as well as the local representation of a circle.

In addition to differential calculus or local and intrinsic representation of curves, *curlybot* could be used as a tool to gain intuitions for turtle geometry [Abe81], Aristotelian and Newtonian physics [Pap80], and the law of large numbers and probability [Sil91], to name a few. Many of these topics are ordinarily considered too advanced for children, but interacting with carefully designed objects can make this material accessible to them.

When trying to teach a concept, it is important to make domains of knowledge approachable in new ways. *curlybot* is not designed to replace Logo or other existing tools, but is instead meant to support these by giving children a slightly different perspective on the concepts. In some cases, *curlybot* may be one of only a few tools that can teach them a particular concept at a certain age. For example, *curlybot* allows young children, who cannot yet read or write, to explore the effects of repetition and loops, which is normally explored at a later age in Logo. As the children grow older, the ideas that they absorb and intuitions that they gain will hopefully allow them to understand related material more fully and ultimately transfer that knowledge to other domains.

4.3 *curlybot* and multiple styles of play and learning

Children's learning and play patterns can be divided into two overlapping categories: patterners and dramatists [Sho79]. *curlybot* is designed to support both forms of play. Whether a child is a platterner or a dramatist, he or she will connect to the same mathematical ideas but in ways most natural for their learning style.

For example, a child who enjoys planning and creating geometric patterns with *curlybot* may be concerned with coordinating the start point, end point, and orientation of *curlybot* to create a desired pattern. Through exploring and designing these patterns, the child will start to gain an intuition for vector geometry. Here, the child is directly involved with the explicit educational aspects of the experience.

Another child, though, may be more interested in the expressive nature of *curlybot*. This child still has to be concerned with the start point, end point, and orientation of *curlybot* but is able to discover and express these concepts through a different and arguably personalized process. The educational features of the toy become apparent with its expressive use. Otherwise, it will not do exactly what you want it to do. In this way, *curlybot* can engage children who are more artistic and expressive. The entry point into mathematics for these children is through their artistic involvement with a tool and a medium. In this case, the critical feature of *curlybot* is that it lives up to a child's expressive expectations.

4.4 *curlybot* and multiple intelligences

Howard Gardner's Theory of Multiple Intelligences proposes that there are seven human intelligences, including musical, bodily-kinesthetic, logical-mathematical, linguistic, spatial, interpersonal, and intrapersonal [Gar83]. He argues against the focus on the linguistic and logical-mathematical intelligences in most schools. If one is not strong in those two intelligences, then one will most likely not be successful in school, even though one may have other very strong intelligences.

The most interesting part of this theory is how it is being used in practice to teach. For example, if children need to memorize a text in school, the teacher will not just give them the text to memorize, but will come up with a song. This helps the most of the class memorize the piece, because it appeals to multiple intelligences. Children with a stronger musical intelligence, for example, can still learn the piece even if their linguistic intelligence is not as strong. By bridging the linguistic and musical intelligences, the teacher has given more children a chance to learn the piece.

Similar to the example above, *curlybot* has been designed to bridge some of these intelligences. In its current form, it supports, to some extent, three intelligences, namely bodily-kinesthetic, logical-mathematical, and spatial. So, for example, if used in a classroom setting to convey a mathematical idea, like differential geometry, *curlybot* might provide a bodily-kinesthetic and spatial sense to the concept. This might allow more children, especially those with strength in bodily-kinesthetic and spatial intelligences, to grasp the concept.

Future augmentations to *curlybot* (such as those listed in the Interaction Scenario section) may create additional bridges between the intelligences. For example, a *curlybot* that records audio as well as the movements, then boomerangs back to the beginning and plays out the story again, could link bodily-kinesthetic and linguistic intelligences for some children (see section 3.1.4 for more details).

Gardner's multiple intelligences are very related to the different play and learning styles described in the previous section. Children's varied strengths across intelligences may give rise to different play and learning styles. Children may use a particular play or learning style because they have strengths in a particular intelligences and weaknesses in others.

Some of the differences between different play and learning approaches are partly semantic and partly reflective of how the styles or intelligences were divided and classified. It is necessary to consider *curlybot* within these albeit controversial categories, though, to evaluate its effectiveness as a truly natural and ubiquitous educational toy.

4.5 children's affective relationship with *curlybot*

Equally important components of any powerful learning experience are the affective and intellectual qualities of the relationship between the learner and the material. Some educational toys and software are not successful because they fail to create a relationship with the child. Unless the child is forced by parents or teachers to use the software or toy, they will not use it or learn from it. It is our goal to engage children with *curlybot*, so that they continue playing with it. Through iteration they will start to imply and perhaps unconsciously extract *curlybot's* educational content.

Papert makes a strong argument for the importance of this last idea in his book *Mindstorms*. He begins by explaining how gears taught him "advanced" mathematical ideas as a child, but then claims that giving sets of gears to children will not necessarily result in the same learning experience for most of them. The success is in part due to the child's personal attachment to the gears - Papert "fell in love" with his gears. He could project himself into the gears and "be the gear," which is what "gives the gear the power to carry powerful mathematics into the mind." If a child is not completely engrossed in their play, they will not learn very much from it [Pap80].

By capturing and performing a child's gesture, *curlybot* creates a connection with the child in two ways. One, *curlybot* appears to be alive by having some of the qualities of something that is alive; namely, it is moving on its own with the imperfection and subtle changes in human movement. Two, there is also a personal relationship between the toy and the child, because the toy has appropriated a part of the child, a child's mental construction and physical expression.

Physicality is also important in developing a reoccurring relationship between children and toys. If *curlybot* were not something that children could carry with them, had mass, moved in their space, could be touched, could push against them, could fall off the table, could break, children would not be as emotionally attached.

By attributes mentioned above, I hope *curlybot* can become to many children what gears were to Seymour Papert.

5 design

The Design section of this thesis is organized into two subsections: 1) the Interaction Design, focusing on interaction and interface issues encountered during the design process, and 2) Implementation, focusing on the technicalities of the implementation as well as technical design considerations.

5.1 interaction design

The discussion in this section will range from high-level design principles, such as the coincidence of input and output space, to interface and interaction decisions made for aesthetic and usability reasons, such as the number of buttons for the interaction.

Figure 5-1

Translucent *curlybot* showing the machined-striped texture of the plastic and the functional components inside

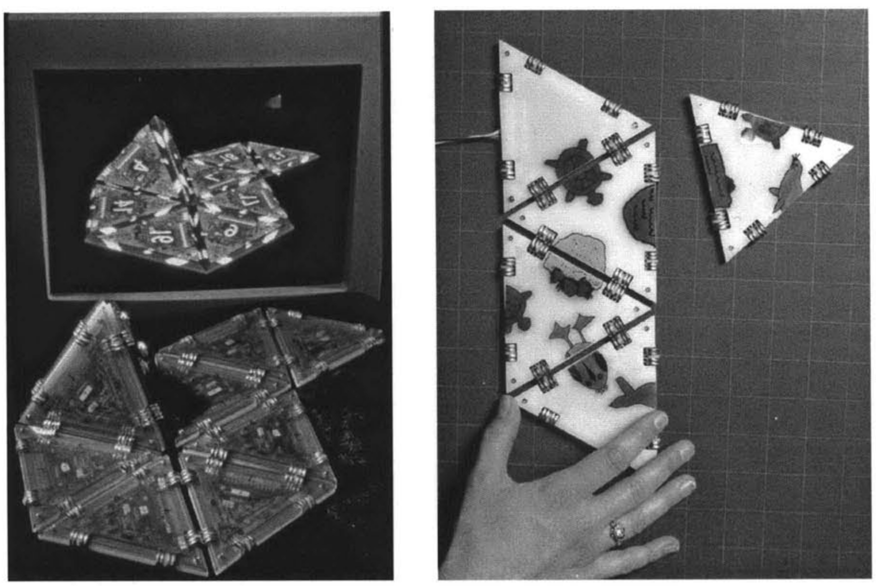
5.1.1 input and output space

One of the most important considerations in human-computer interaction design is the input and output space. In other words, where is the input happening and where is the output happening?

Consider the separation between the input and the output space in a project called Triangles [Gor98]. Triangles is a physical computer interface in the form of identical, flat, plastic triangles that together form a digital/physical construction kit. The triangles connect together both physically and digitally with magnetic, conducting connectors. Users can create both two- and three-dimensional patterns whose exact configuration is known to the computer. When the pieces contact one another, specific connections trigger specific digital events, such as displaying a web page or playing an audio clip.

Figure 5-2

Basic Triangles creating a two- and three-dimensional topology that is visualized on the screen and triangles with images of characters from a narrative



The input to the system is the triangles that the user manipulates with his or her hands. If the outputs are the triangles and a web page on a screen that is triggered by a connection, then the users have to shift their attention from what they are doing with the triangles (and the physical event that they just created) to the digital output on the screen. This disconnect between input and output is evident in certain toys that are interfaced to the computer or television, like Zowie's current line of toys. This is problematic because the design does not clearly indicate where the user's focus should be. Playing with physical objects is clear, but the design forces the users to switch their focus between the physical toy and a digital representation.

Triangles addressed this problem by executing auditory responses to connections instead of external visual responses. A nonlinear narrative was created, with images of characters, events and places on the triangles. The triangles themselves, the images on them, and the connections give the user all the visual feedback necessary to understand the system; the audio provides the content. This keeps the interaction focused and makes the computation more transparent.

curlybot was, in part, motivated by this problem. The limitations of indirect manipulation on a computer motivate moving the graphical and gestural animation from behind the computer screen into the real world. By having the device self-contained, the input and output space become coincident. You teach *curlybot* by showing it what you want it to do and the same device responds and recreates the gesture. There is no abstraction between input and output.

The inTouch system, which will be discussed more in the next subsection, also uses direct manipulation. Unlike *curlybot* – in which input and output are spatially co-located – the inTouch has temporal co-located input and output. This is a very interesting feature that takes advantage of the fact that you can do both input and output simultaneously with your hands.

5.1.2 magic (transparency of technology)

In all my designs at the Media Lab, "magic" was one of the strongest underlying philosophies. By magic, I mean creating an illusion, which in this case means making the technology behind the system invisible to the user.

For example, when designing inTouch, I did not only wanted the device to be simple and tacitly pleasant, I also wanted to hide how the two devices are linked. If you show the motors or make the device out of materials you expect to be controlled by motors or have electronics, then the user has "solved" the magic and nothing is left to the imagination.

Figure 5-3

Final inTouch system in use

The choice of wooden rollers and aluminum helped create the "magical illusion," because one never sees wood actuated by motors anywhere in our environment; wooden and aluminum components rarely contain electronics. When a user moves one roller and the same wooden roller spins on the other inTouch, it looks like magic to almost everyone who sees it. When people first see it they sometimes imagine that there might be a mechanical link between the two devices that is under the table, since the devices are so responsive and made of traditional, mechanical materials. The last thing they imagine is motors and electronics. Then when we start separating the inTouch units, they start considering other possibilities, but because possibilities are not implied by the design, the inTouch appears magical.

curlybot was designed with similar criteria for magic and illusion. It was critical to hide the wheels that drive *curlybot* because then one has expectation about the movement. In fact, when one moves it one can create gestures people do not imagine a two-wheeled device making. Many people who have seen it proudly tell me, as if they have figured it out, "So you have a ball underneath driving the toy." It is with comments like those that I know I have succeeded with the design principle of transparency. In addition, it was very important to have completely silent motors. If the motors made noise, like any motorized toy, the illusion would be broken; it would be transformed from a creature learning what you are teaching to a robot.

This led to issues beyond transparency. I wanted the toy to come alive and not be associated with a robot or electronics; cheap motors would have suggested a traditional technology toy. From children's responses like "it's so smart" and "it likes to go fast," *curlybot* appears to provide a successful illusion of life.

5.1.3 pen based vs. gesture only

Before we added a pen to the device the focus of the interaction was the gesture and creating interesting changes in velocity and acceleration to give the *curlybot* a personality. For example, one could make it spin back and forth in a dance. With the pen, though, the focus moved away from the *curlybot* itself to the trail it was leaving. The focus was almost completely on the trajectory. Also, whereas before the interaction was short – watch it do something for a few seconds and then record something new – the interaction with a pen was very long. The user would wait for the repetitive pattern to be complete, which at times would take several minutes.

When creating a gesture or dance, the focus is not always on the details. We are very good at seeing details, but a nervous shake can be created in many different ways and still be interpreted as a nervous shake. When a pen is attached, the focus is on the details. It is very important to be aware of those interaction differences when designing toys. Though the addition of a pen might seem minor, it can have a large effect on the play.

The pens also leave a very uniform trail. Softer pens or paintbrushes that can leave thick trails when moving slowly and thin trail when moving quickly, could be used to create slightly more complex patterns and take advantage of *curlybot's* ability to reproduce changes in velocity. Brushes could make the pen interaction more interesting, because of the subtleties about the gesture that can now be recorded on paper. There would then be an additional degree of freedom. The user would have to focus not only on the trajectory, but also on the speed of *curlybot's* movement to create a pattern.

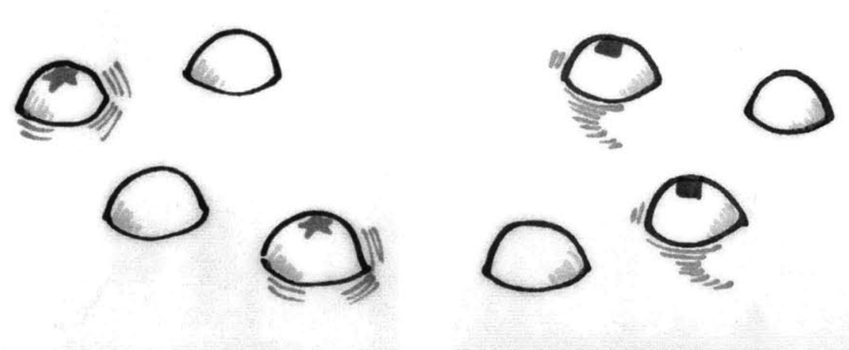
5.1.4 connecting wireless devices

Infrared and radio frequency communication can be very magical and create interesting toys, but if the interface is not designed well then the magic can end and the interaction becomes confusing. For example, how do you know what is talking to what? Or, who is sending information to whom?

That is why removable memory seemed to make the most sense and was designed into *curlybot*. It is simple and easy to understand as demonstrated by Sony's Memory Stick or SmartMedia. But there are other interesting approaches to this problem. On a different project at the Media Lab, I was trying to find a good interface to make and break connections between wireless devices. I employed a system called the *marbles*. There were physical icons (*marbles*) of different shapes and colors that could be connected to the wireless devices. If two or more devices had the same icon, then they were connected.

Figure 5-4

curlybots with physical icons to control with whom they are talking



This could be a simple interaction technique to synchronize *curlybots* or have them trade information. Otherwise the designer might have to introduce a complicated touch pad, screen, or central control to indicate which ones are talking to which. With the *marbles* users could have a complex system of *curlybots* that are talking in groups. By just changing the *marble* on one of them one can change whom that *curlybot* is talking to and have a representation on the device that clearly indicates its connection to others. This could be very difficult to orchestrate in any other way.

5.1.5 one button vs. two buttons

The first and the current system only have one button, but the interaction was also explored with two buttons, to give the user more flexibility. Instead of being constrained by having a single button for recording and playback, we thought that it would be useful to have a button for record and a button for playback. This gives us the freedom to record, and by pressing the record button again, stop recording. The *curlybot* is then free to move and be placed anywhere before one presses the playback button. To rerecord, a user just presses record again without having to go through the play mode. Similarly, with the playback button, if you want to stop playing, but do not want to record over what you have done, you can just press the play button again. Since *curlybot* uses a solid state eeprom, it retains the last gesture even if the power is turned off. It is also possible to remove the memory. To do this and put the memory in another *curlybot*, it would probably be best to have a separate playback button to avoid rerecording over the traded memory. Similarly, a separate button may be useful when connecting to a computer.

Though there are many reasons to have an extra button, the goal of this first version was to explore the flexibility that can be achieved with just one button. There is also a simplicity argument for designing *curlybot* with a single button: it needs no label.

We also implemented a few hidden options in some *curlybots*. The double click will skip us over the record mode to just playback. This is very useful when saving a gesture. The boomerang mode that allows *curlybot* to repeat the gesture backwards is also hidden. If the user presses the record button while turning *curlybot* on, it is in boomerang mode until turned off. Hiding some of these functions kept the system simple. The user does not have to know about the advanced options to be satisfied playing with *curlybot* and as users become more experienced they can experiment with advanced features.

5.1.6 two-states vs. three-states

Originally, the device has only two states - record or play. Though, this may seem very simple, it is a little confusing when the user does not want to record or playback the motion. When users want to stop a motion and start recording something new, they usually do not want to press the button to stop and have it start recording right away. What is really needed is a stop button to enter a "dead" mode where a user can think about what to do next and bring *curlybot* to the desired start position.

It is interesting to note that people figured out ways around this problem with the two-state system. When they wanted to stop, they would record nothing by double clicking, and the *curlybot* would just sit still. They could then think about what they wanted to do and press the button to record. There were some users who would leave *curlybot* in record mode, which allows it to move freely and stand still, until they were ready to record. Then they would double click over the playback mode into record again. While it is interesting to note people's solution to this problem, in the end we decided to use a three-state button in order to create a dead mode in which *curlybot* is just free to move around. This has been very successful and easy to understand, especially because the LED is off during this mode.

5.1.7 recording pauses

While it was suggested a few times by early users that we eliminate the pauses that are recorded, we decided that the recorded pauses are a very important part of *curlybot*. Not only are pauses required to create certain gestures, they are also crucial to the idea that the gesture played is identical to the gesture recorded. This creates a clear causality and allows the toy to be understood easily.

It is also a challenge, for example, to try and remove the initial pause when one plays with it by moving it while one presses the button. The pause that is introduced at the beginning, if *curlybot* is not moving while one starts recording, can also give the user a very clear indication of the start and finish of a gesture. This can be useful in understanding *curlybot's* behavior and how to debug a geometric shape.

5.1.8 different form factor

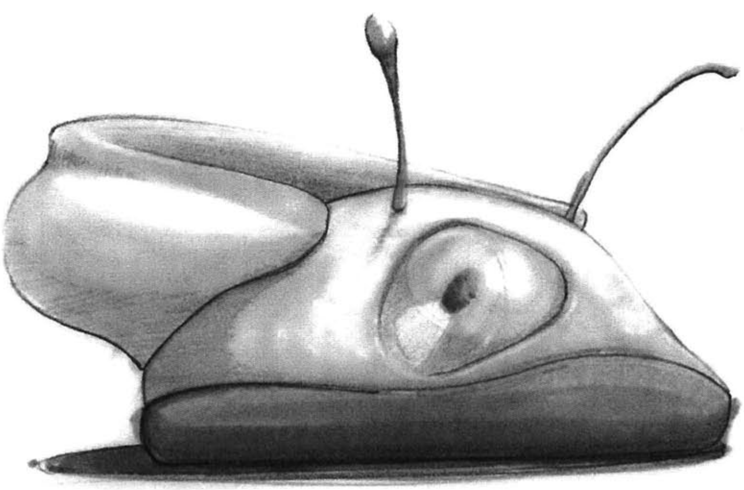
Play patterns can change significantly depending on the form factor. That is, in part, why the current design is so abstract. It allows the child to project what they want onto the toy. For example, the goal of the first user study was to determine all the various ways children would play with the abstract *curlybot.*

A recognizable shape limits the play patterns possible. For example, if the toy were in the form of a car, children may tend to do fewer of the expressive patterns, like dancing. They would probably move the toy like a car even though it has other degrees of freedom and maybe make more geometric shapes. On the other hand, if *curlybot* were a fuzzy animal, a child might be less likely to make geometric shapes and instead would probably do more gestural and narrative patterns.

curybot also tries to remain gender neutral with its form factor to attract all children to the toy. It has been shown that children play more with same-sex toys than opposite-sex toys but play most with neutral toys [Eis84]. As mentioned before, having more play with the toy is critical for children to explore the educational content.

Figure 5-5

Sample sketch of *curlybot* as a character



Once the abstract and neutral design was set, we were concerned that the choice of color might specify a gender. For two of them, we chose blue and bright red, which seemed relatively neutral. We were still concerned that they might appeal more to boys, so we made one a deep purple to appeal to girls (this was based on Interval Research's work on gender). The last one was made translucent just for fun. In all our studies, most of the children wanted to play with the bright red one, regardless of gender.

It is very important to consider form factor, especially in a research context. It is not just the children who are influenced by the form factor, but also the researchers. Had I decided in the beginning that this was going to be a character, I may not have made an association with Logo or attaching pens. The abstract shape left my mind open to project new things.

5.1.9 teaching by demonstration

Teaching *curlybot* by demonstration is important for two reasons; it makes *curlybot* easy to use and it is the easiest way to make organic movement. The easy-to-use aspect is critical because children are often attracted to toys that are immediately gratifying and require little overhead or investment before experimenting. Within seconds of taking *curlybot* out of the box, children can make something interesting happen. Then, because the toy is only as successful as what you are able to teach it, *curlybot* challenges you to be creative. It is also the easiest way to create an organic movement because there is no abstraction. It would be very difficult to program a gesture and, even if one could, it may take too much time.

The one existing toy that is close in terms of creating organic motion is a remote control car, but the limitation is that you have to keep telling the car what you want it to do. This requires the child to always do something for the toy to do something. children often enjoy the fact that they can be spectators *and* the fact that the toy can have a life of its own. This life is most simply achieved by teaching *curlybot* what to do, unless the toy comes preprogrammed with a story or a set of reactions, like Furby.

Even though it may be simpler to program *curlybot* by demonstration than to program a Cricket or the Programmable Brick, the procedural abstraction is missing, which is important to teach a child programming and programming concepts.

5.2 implementation

This sections starts with a focus on the current implementation of *curlybot*. Many of the technical consideration will compare changes to the previous version. The section concludes with a smaller version of *curlybot*, which is about a quarter in volume.

5.2.1 current version

The *curlybot*'s two wheels have independent drive and sensing capabilities controlled by a microprocessor. Mechanically, the toy consists of two 10 Watt Maxon motors with Hewlett-Packard Optical encoders. They are mounted on the bottom of *curlybot* in such a way that, after gearing the torque up 4:1, the shafts of both wheels are co-linear. This configuration allows it to not only move forward and back, but also rotate freely about its center. This arrangement is also the most compact design that allows the device to easily fit in the user's hand. The physical configuration also simplifies what needs to be recorded. If both motors are moving forward, the device is moving forward. If they are moving in opposite directions, then the device is turning.

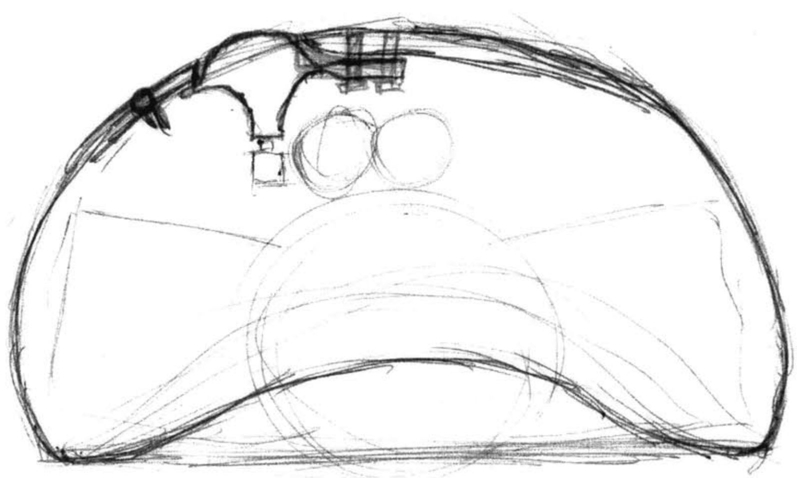


Figure 5-6

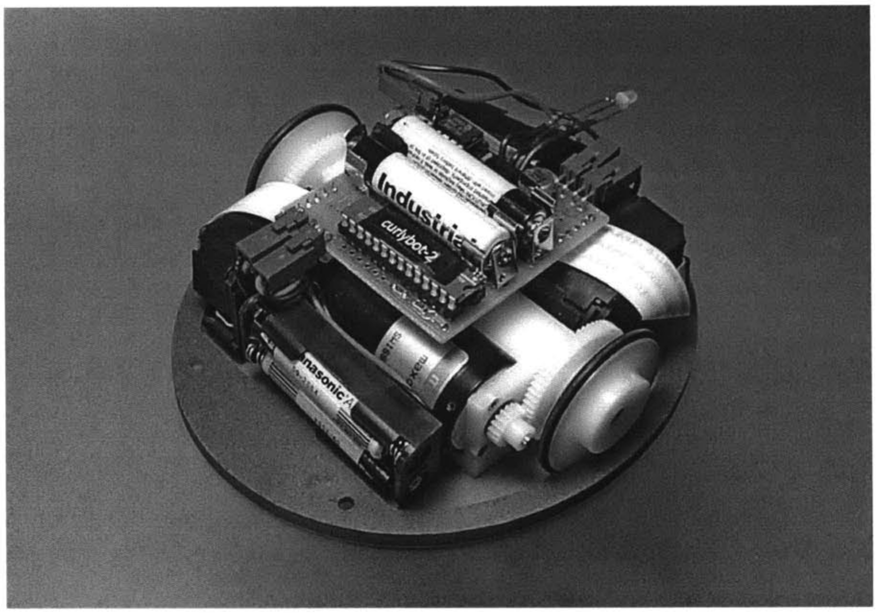
One of many mechanical design sketches of the *curlybot* case and button

The 10 Watt motors are very efficient and power is not lost in heat dissipation. The use of these large motors gives us additional mass, which is useful in creating sufficient friction for the drive wheels. In this way, users can feel resistance when they push against the direction of the wheels. Also, the additional weight creates sufficient inertia for play and limits the acceleration.

A 20MHz Microchip microprocessor with built-in pulse width modulation controls the motors. The encoders available to us had 500 counts/revolution. Because of the gearing, the resolution of the wheel is 2000 counts/revolution. If *curlybot* is moving quickly, the encoder interrupts the microprocessor continuously, which does not allow other processes to be run. To overcome this, we divide the encoder information by four using a counter, so that the resolution of the wheel is only 500 counts/revolution.

Figure 5-7

Inside of *curlybot*



The encoder information is stored on a separate 32 kilobyte memory chip (256 kilobits) at a rate of 100Hz. At this rate, we can record the encoder information of both motors for about two and a half minutes. We felt that this would be sufficient for most play patterns, including some narratives. The device currently runs on six AAA batteries – four for the motors and two for the circuit board.

Originally, we used two 9 Volt batteries in parallel for the whole system, but the following two problems arose. First, the capacity of 9 Volt batteries is much less than that of AAA, so a *curlybot* would not run continuously for more than two hours. Second, when the motors draw a lot of current, the voltage for the circuit board drops below 5 Volts and the circuit resets. We also originally used a one-megabit serial eeprom memory chip, since we were not sure with what frequency we wanted to record. When we finally decided that 100Hz would be enough, this memory chip gave us about ten minutes of recording time, which is much more than what we needed. We then switched to our current eight-pin 256 kilobit eeprom memory chip that can be easily removed from the board and replaced with any other 8 pin eeprom. It also has a fraction of the leads, since one reads and writes to it serially.

The motor is run on pulse width modulation with feedback from only the encoder. The performance of the playback could be improved by monitoring the current feedback from the motor.

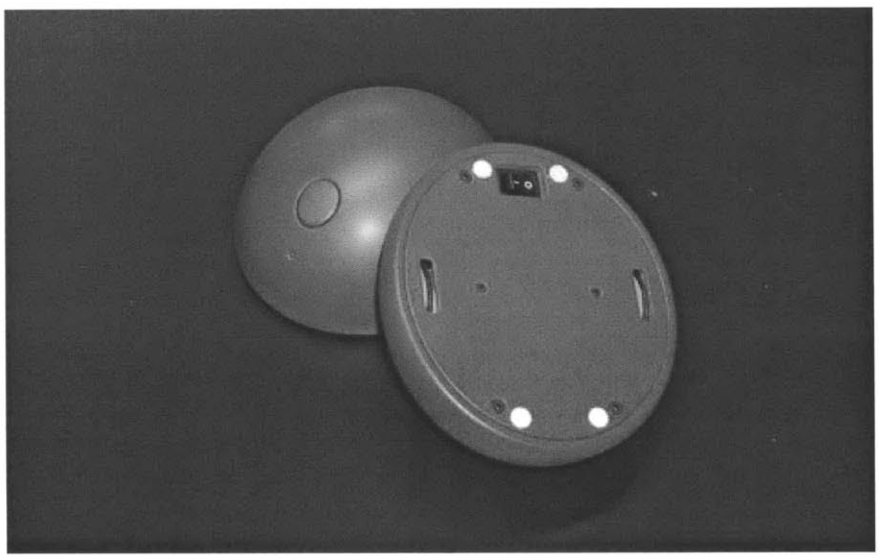


Figure 5-8

Top and bottom of *curlybot*

To record, the user presses a button that lights up a red indicator LED. When the user is done recording a sequence, the button is pressed again and the indicator LED turns green. At this point, the processor runs a PID (proportional, integral, and differential) control function that calculates the force that the motors need to exert to reach the recorded position. The processor compares its current position (from the encoder) to the desired position (from the memory) and then applies the necessary force to move from one to the other. When the button is pressed again, the indicator LED turns off and *curlybot* is in neutral mode. Here, it is free to roll around, and nothing is recorded or played back. This sequence can be started again by pressing the button one more time.

We can also switch *curlybot* into boomerang mode by pressing the button while turning the device on. In this mode, the toy boomerangs back through its recorded path to its starting position, where it then begins to repeat the motion again. In this mode, *curlybot* repeats the changes in velocity and accelerations in both forwards and backwards.

5.2.2 smaller version

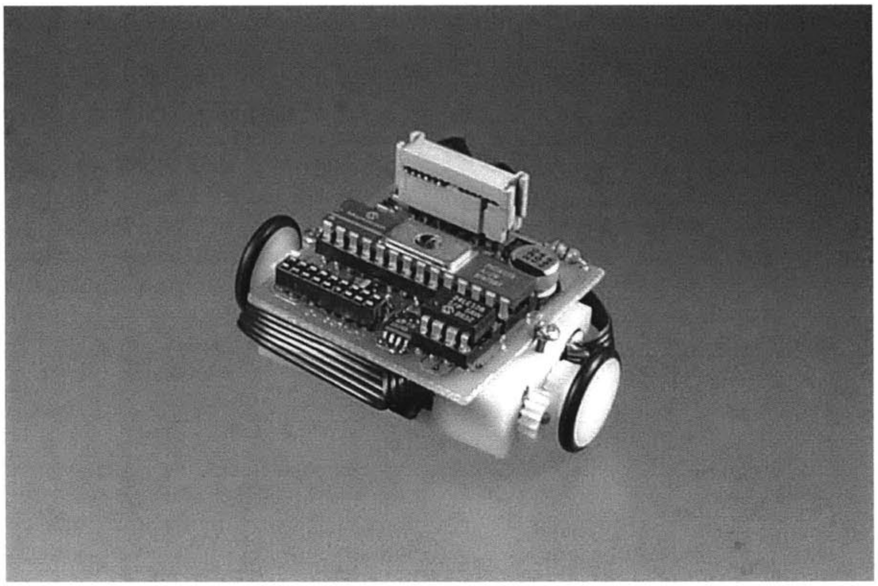


Figure 5-9

Small *curlybot* without case

In order to test some of our other interface ideas, we decided to design another version of *curlybot*. First, we added a two-button interface with separate record and playback buttons. This allows users to re-record a motion without playing it back or, likewise, to stop playing a motion and then start again without re-recording. We have also explored using a double-click on the single button interface to click over the record or playback mode. We though this might provide the additional functionality of the two-button interface without making it more confusing for novice users. After some informal use, we decided that the one button interface was still better because it did not require labeling.

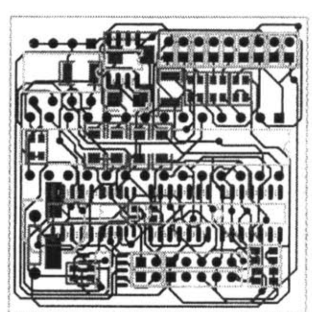


Figure 5-10

Traces of the printed circuit board for small *curlybot* (life-size)

We have also reduced the size of *curlybot* to something smaller than a computer mouse. This version uses 1 Watt Maxon motors that are about the size of a AAA battery, including a 12 count/revolution encoder and 4:1 gearhead. Though the resolution of the encoder is lower, we still managed to maintain about the same resolution on the wheel circumference. To keep the toy small, we used two AAA batteries to run both the circuit board and the motors; even though we knew we could run into problems with high current draws. The main problem with this prototype was that, because it was lighter and smaller, the wheels' traction was not enough when a user pushed against the direction the wheels turn.

6 evaluation

This section evaluates *curlybot's* design and educational potential. It begins with an overview of the evaluation process and then presents in detail the design and findings of the two studies with children and a summary of the feedback on *curlybot* from the teachers. The first study with children was an exploratory study on *curlybot's* use and potential. The second was a task directed study on children's ability to understand and solve problems with *curlybot*. The feedback from teachers was used to find future potential for *curlybot*.

In the beginning, the evaluation of *curlybot* was based on very informal observations of sponsors and visitors to the Media Lab and visitor to our exhibition at Siggraph '99. Through these venues, several hundred adults and some children played with *curlybot*. The most interesting finding was that many of them discovered new gestures and patterns we had not anticipated. This was a promising result, since our goal was to design an open-ended toy that would continue to be used over time.

In these venues, it was interesting to see people take advantage of different aspects of *curlybot*, such as the fact that it records every pause one makes. In one case, a user had *curlybot* do nothing for a long time and then shake around. This resulted in an interesting behavior during playback: *curlybot* would appear inactive or off, but then surprise the audience by suddenly starting to shake. Another user recorded a pause, a shake forward and back, a pause, and then a shake from side to side. When playing back, he asked *curlybot* if it liked him, and it moved forward and back. He then asked if it liked his friend, and it shook from side to side. By having others play with *curlybot*, we discovered new behaviors and patterns, like the ones mentioned above. It is always satisfying to learn or see something new and unexpected with the toy, especially as its designer.

Once we realized that *curlybot* was engaging and that adults wanted to spend time playing with it, we wanted to start testing *curlybot* with children. First, we wanted to conduct an informal observation of usage and play styles. The observation of the usage would tell us if children could understand the interface or if something needed to be changed in our design. The play styles would help us understand how children used *curlybot* and if the system afforded different play styles. This test also allowed us to determine for what age groups *curlybot* is best suited.

After concluding these studies, we considered conducing more quantitative test to determine if and what children were learning with *curlybot*. We consulted child developmental psychologists at MIT and Interval Research Corporation, who confirmed that a quantitative study was beyond the scope of a Master's thesis for two reasons. One, it is very difficult to construct a quantitative test to show whether or not *curlybot* teaches something without a control, namely a different tool teaching the same concept. Two, it is very difficult to prove that children learn something (beyond memorizing) without showing that they can transfer that knowledge to another task. This would require a longitudinal study and would still not be conclusive because there can always be other external factors that allow them to understand a new task.

So we opted for something simpler. We conducted a second study that was more focused on the educational value of *curlybot*. We were interested in posing questions and having children come to an understanding of the problem using *curlybot*. This was not a quantitative study and there is no proof that children will transfer this knowledge, but it was a quick way to gauge some progress in the children's thought processes.

Next, after some discussion with people from the Learning Company, we thought it might be fruitful to get feedback from teachers about uses for *curlybot*. Because of their real-life experience conveying ideas to children everyday, we felt they would have a different perspective on *curlybot* as a tool. By seeing it, they might come up with new ways to communicate concepts they already teach to their students.

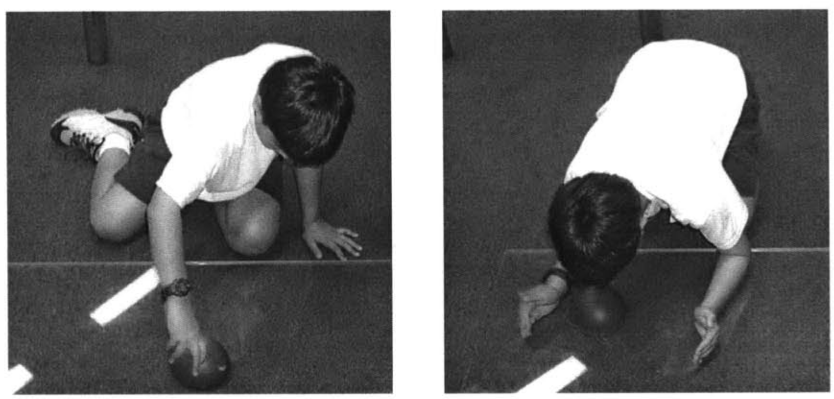
6.1 first study with children

The first study was conducted at the Science Museum in Boston, Massachusetts over several days in August 1999. Though this did not allow for a completely random cross section of children, it easily provided us with a large group (81) of children for initial tests. The Science Museum seemed like a effective environment for making observations, since the children are prepared to play with new things and generally do not notice when someone is observing them.

In the entrance to the Discovery Center of the Museum, we set up a 3'x 4' piece of acrylic to clearly demarcate the play space. This was also done to observe if the children would learn how to keep *curlybot* in that space. The play area was constrained to the Plexiglas, since we used a version of *curlybot* that was not designed to run on the surrounding carpet. If *curlybot* fell off the platform, it did not move and was no longer engaging.

Figure 6-1

Child playing with *curlybot* on Plexiglas platform



In order to learn how effective the interface was from the start, very little instruction was given to the children. We then were interested in monitoring what children did with *curlybot*. Did children figure out how to keep *curlybot* from running outside of the demarcated area? Were they more interested in geometric designs, gestures, or narratives? How long did it take them to figure it out? Can we generalize the responses of different age groups? Is there an age where children cannot interact with the device at all? It should be noted that our results are based on qualitative observations, and subjective categorization. These results are nonetheless interesting, because they provide us with a rough guide for further study.

Most of the children knew what to do with *curlybot* by observing how others had used it. If they did not, we would ask one of the other children to explain how it worked. From these explanations, we were able to observe what the previous participants had learned beyond the basic functionality of how to record and play. Out of the twenty-two children who were asked to explain how to use the toy to someone else, three of them also described how to keep *curlybot* on the platform in addition to explaining the basic functionality.

About a quarter of the children (21 out of 81), explicitly created geometric shapes. Four children did what we considered to be explicitly gestural recordings, while the rest did narrative recordings. It was difficult to draw lines between the different interactions, since there was some overlap between the categories. One ten-year-old girl, for example, recorded a beautiful geometric piece after observing four boys of her age record strictly geometric shapes. However, unlike the boys, her geometric shapes had accelerations and pauses, which created a more gestural pattern. This made us categorize her actions as gestural rather than geometric, even though she was also very successful at keeping *curlybot* on the platform through a geometric pattern. It is interesting to note that the boys were impressed and tried to create some more gestural patterns after her performance. This also shows that a child can easily be affected by another child's interaction with *curlybot*. Our results are heavily affected by this fact, since we were not working in a controlled environment where children were isolated from one another while playing with *curlybot*.

The sharing of knowledge between children is very encouraging. Through this process children push themselves to be more creative and are eager to show their friends their findings. The findings are then used to push their creativity further.

We hoped to see trends in play between the different age groups, however the main finding was that children under the age of four generally could not meaningfully interact with *curlybot*. We also thought that older children might not learn much from the interaction, but that did not seem to be the case. Older children spent just as much time as younger ones trying to figure out how to design a pattern that would stay on the platform.

It was interesting to observe that the children had a tendency to make large and fast gestures with *curlybot*. This caused two problems. One, because there was a constrained play area, large motions that did not end exactly where they began made *curlybot* fall off the platform. Two, this version of *curlybot* was not designed to reproduce fast motions as accurately as slow ones and, as a result, *curlybot* did not repeat geometric shapes perfectly. Overall, the children were not concerned with these problems and continued to play with *curlybot* anyway. For future tests, though, the control algorithm should be adjusted.

It usually was not possible to have children perform specific tasks given the informal environment of the study. However, there was one seven-year-old girl who played with *curlybot* for an extended period of time and accepted our challenge to create a few geometric shapes out of their most basic elements. We found that she only needed us to provide an example before being able to create the shapes herself. We showed her how to create a square and let her try it on her own. When we asked her to create a circle, she started by designing it with very large arcs. She needed additional help to understand that a circle could be created from a very small repeated segment. Later on, the same girl came back, and asked if she could try a shape she had been thinking about. We were pleased to see that she continued to process her new knowledge about shapes even outside the play area. *curlybot* appears to have become an object-to-think-with for her.

Though this user test was not conclusive, it confirmed that *curlybot* is fun for children and that our research goals and questions were indeed relevant in view of the children's interactions with the toy.

6.2 second study with children

The second user study happened at the Media Lab during the Mindfest conference October 23rd 1999 [Min99]. The goal of this study was to obtain more specific information about what children could learn and how they could solve problems with *curlybot*. The idea was to present them with specific design challenges and observe how they tried to create solutions.

We had three groups of children between the ages of five and ten. In order to keep the group focused, we limited the number of children per group to eight and we did not allow their parents or any other adults to be present. The sessions were recorded with their parents' permission to allow us to focus on the interaction with the children at the time and to help us be consistent in our protocol among groups.

The test happened on the same platform as the previous study, namely a large acrylic sheet on the floor. Each group received a quick demonstration of *curlybot's* capabilities. We showed them how to record and playback a motion, gave them a few sample gestures, and showed them that *curlybot* repeats the motions over and over again. Then, we showed them how a repeated motion, if just moved forward and stop, would make *curlybot* fall off the platform. We then asked them the first question: "How do you create a gesture that does not fall of the table?"

Figure 6-2

Child recording a pattern to stay on the platform (clips from video)

After the introduction, I helped the children stay on track by coaxing them along, if they appear become lost or distracted. They would try things out and I would hint to them if they were moving in the right direction. At times, if they were moving off track or maybe did not understand what they were doing, I would take *curlybot* back from them and show them something with *curlybot* that would put them on track again. In the end, the first two sessions were successful, with the second one being particularly successful. In the last one we had trouble keeping the children focused. There were two children that could not stay focused and distracted the whole group with a hand-held video game they had just received at another event in Mindfest. Once those two had seen *curlybot* and played with it, they went back to figuring out the new video game. This unfortunately distracted the entire session and humbled our expectations of *curlybot* in the real world next to video games.

Each session started with children raising their hands wanting to create a gesture after our initial presentation. In general, the first thing they would try would be a gesture that ended in a different place from where they started. Unless the orientation is favorable, which it usually is not, this makes *curlybot* fall off the table. Through questions we try to make children think about what may have gone wrong. Then, usually, children call out to try something they think is going to work. Invariably, it also does not work. In general, we pursue this for some time until they understand the importance of where they start and end, as well as their orientation at the beginning and end.

The second group of children, tried to make geometric shapes immediately, like a rectangle that followed the perimeter of the platform to keep it on the platform. This was close to working, but the shape was very large and because it was slightly off in orientation when *curlybot* was returned to the starting point it fell off the table. We then prompted the children to try smaller shapes. After some experimentation, they created a triangle that did not fall off the table. They then concluded, "Triangles don't fall off." We asked them to try a few other things and see if they could generalize that statement. After a few attempts they made a square that did the same thing and concluded, "Geometric shapes don't fall off." I asked them again, if they are sure only geometric shapes work.

After more exploration of geometric shapes, we intervened. We showed them a shape that did not end where it started and asked them to extrapolate where it was going to go. It was an exaggerated difference in position, and most of them seemed to guess correctly where it was going to go. We then asked them to elaborate on their thoughts, and one of them made a very insightful comment, saying "It drifts over time." This is correct; after every move it drifts over more by the difference between the start and end position. After this, they played more with geometric shapes and were able grasp the concept that they had to bring it back to the same position and orientation.

Although the same position and orientation will guarantee that it stays on the platform, both are not required. For example, if one moves *curlybot* forward a little and then turns a little, a circle is created that does not fall off the platform, even though the position and orientation are not the same. It just has to move around a central point. If one moves back to the same position and changes the orientation, *curlybot* will do the gesture, rotate and not fall off as long as the gesture starts close to the center of the platform. We tried to explain some of these ideas to the children, but we were running out of time, so we moved forward with the next problem.

Next, we wanted to see if the children could understand differential geometry. We asked them to create a circle. They all tried, but always made it out of a complete circle gesture. Then we asked them if they could make their gesture smaller and still create a circle. They then drew a half circle that would repeat to make a full circle. We asked them again if they could make it even smaller and they made something close to a quarter. Then we asked them what the smallest gesture they could make that would still create a circle. They still made things that were fairly large, which was somewhat disappointing. Since we were close to running out of time, we finally showed them a very small motion forward and small turn that resulted in a very good circle.

Figure 6-3

Children explaining a recorded path and working together to solve the problem

We wanted to give them one more challenge before they left. In everything they recorded so far there had been a pause as the gesture was repeated by *curlybot*. We showed the children the pause one more time by recording a forward movement that repeated over and over again. We pressed the button to record, moved *curlybot* and pressed the button to stop. We then asked them how to get rid of the pause and received many "Oh, oh, oh, I know" responses. Even though they thought they knew, it still took them a little while to discover that they had to start and stop the recording while *curlybot* was moving. Even if you don't pause for a split second when you start and stop, the change in acceleration gives *curlybot* a abrupt movement that looks like a pause.

The first group was similar, but one child had a very interesting solution to my question of how to keep it on the table, namely to put sensors on *curlybot* to sense the edges and stop. That response took us by surprise, but clearly this child was thinking beyond the current device (and probably playing with LEGO Minstorms). This forced us to redefine the problem keeping *curlybot* in its current form on this platform. The first child in this group to solve the problem made *curlybot* spin in place, which also took me by surprise. It was an elegant solution.

This user study gave us a qualitative sense that children were indeed starting to learn something from the experience. Given more time to play with *curlybot*, these children would probably start absorbing some of the ideas. This could probably be observed by watching how they play with *curlybot* in the future. Children may learn to produce gestures that never fall off the table, because they can start predicting where *curlybot* is going. And if they understand this system, perhaps some of that knowledge will be transferred to understanding vector or differential geometry later in their studies.

6.3 feedback from teachers

After a suggestion from people at the Learning Company to meet with teachers to broaden the potential uses for *curlybot*, I met with a total of fourteen teachers. For the most part these were small meetings with three or four teachers, where I would demonstrate *curlybot*, talk about its potential educational uses would be and give an overview of children's responses from the user test.

Because the teacher's pratical experience in trying to convey ideas to children every day, they were able to identify a few new ideas and important considerations. Some of these ideas have been incorporated into other parts of this thesis.

My first presentation was at the Learning Company, where the teachers quickly saw the potential for *curlybot*, but wanted to see more structured activity. Their suggestion was to design educational mats, which have prescribed activities on them that the children could follow. This could include designing a path for *curlybot* through a series of obstacles. The mat would restrict the recording to part of the mat forcing the child to design a pattern that would repeat forward around the obstacles. The mat could be pop-up style to have more interesting and convincing terrain.

It was very important for the teachers to have *curlybot* in an educational context. Even though it is fun on its own, for the child to truly learn, they felt the toy needed direction and guidance.

In the end, we concluded that it would be interesting to add measuring tools to *curlybot* that would indicate the angle it had turned, for example. In the right context, children with no knowledge of the abstract concept of "degrees," could start exploring them concretely.

After my second presentation with three teachers from different schools, one of them told me that *curlybot* could be useful for reinforcing ideas they are teaching in a different way. She told me that teachers in early grades try to combine different ways of looking at material to make it more accessible to the whole class. This is particularly effective when the teacher wants the children to memorize something. Instead of just memorizing the text, the teacher would sing a song with the text. The children practice by seeing it, writing it, and now also singing it (and as a by product listening to it). The singing also invokes a different intelligence of Gardner's Multiple Intelligences Theory.

In all my presentation, the teachers were very interested in the Logo-like applications I had introduced and the problems I had posed to children. As a result, it was difficult to invent new uses for *curlybot*, but they all shared my enthusiasm for the idea and the educational potential.

My last presentation was at the Trotter School in Boston, where I met with seven teachers. One of the most interesting suggestions I received was to have children complete mirror images of a path with *curlybot*. Completing mirror images is an activity that they do at school and the teachers felt the tactile feedback and movements would make the activity more compelling.

They thought it might also be interesting to use *curlybot* to help teach children the difference between left and right. They were also very interested in using *curlybot* to help teach children learn how to draw letters, in particular lower case printed letters. This seems to be growing problem that the schools have trouble addressing.

The teachers were also very fascinated by the different pen positions. They thought asking children to think about what pattern would be created with the different pen position on a basic geometric shape would be a great test problem. Of course, the point would be to have children solve the problem without the aid of *curlybot*. The discussion of pens on *curlybot* and the drawings it created led to a discussion on the recent lack of drawing children do and have done when they enter school. They felt that a tool like *curlybot* could help increase that again, or at least the sensitivity to it.

When the teachers heard about the mats that were previously suggested, they thought it would be great to create mazes of letters that children could follow to understand how to create the letter and turn the activity into a game.

Overall the experience with teachers was very fruitful and provided much new insight.

7 conclusion

This thesis introduced *curlybot*, the basis for a new class of computational toys programmed by demonstration that are expressive, creative and educational. I presented the basic system, whose interaction and interface design make it easy to use while remaining open-ended and expressive. The variety of interaction scenarios showed the different educational and creative possibilities with the current system and future augmentations.

I have discussed some of the educational potential and implications of *curlybot*. This includes using *curlybot* as a thing-to-think-with that make new domains of knowledge accessible or old domains of knowledge approachable in new ways, support multiple learning and play styles, support multiple intelligences, and allow children to create an affective and intellectual relationship with it.

The thesis also explores some of the design issues and principles encountered during the process, like transparency, coupling, and the coincidence of input and output space. The implementation is discussed in detail and describes many of the technical issues that were encountered during development and the solutions we found.

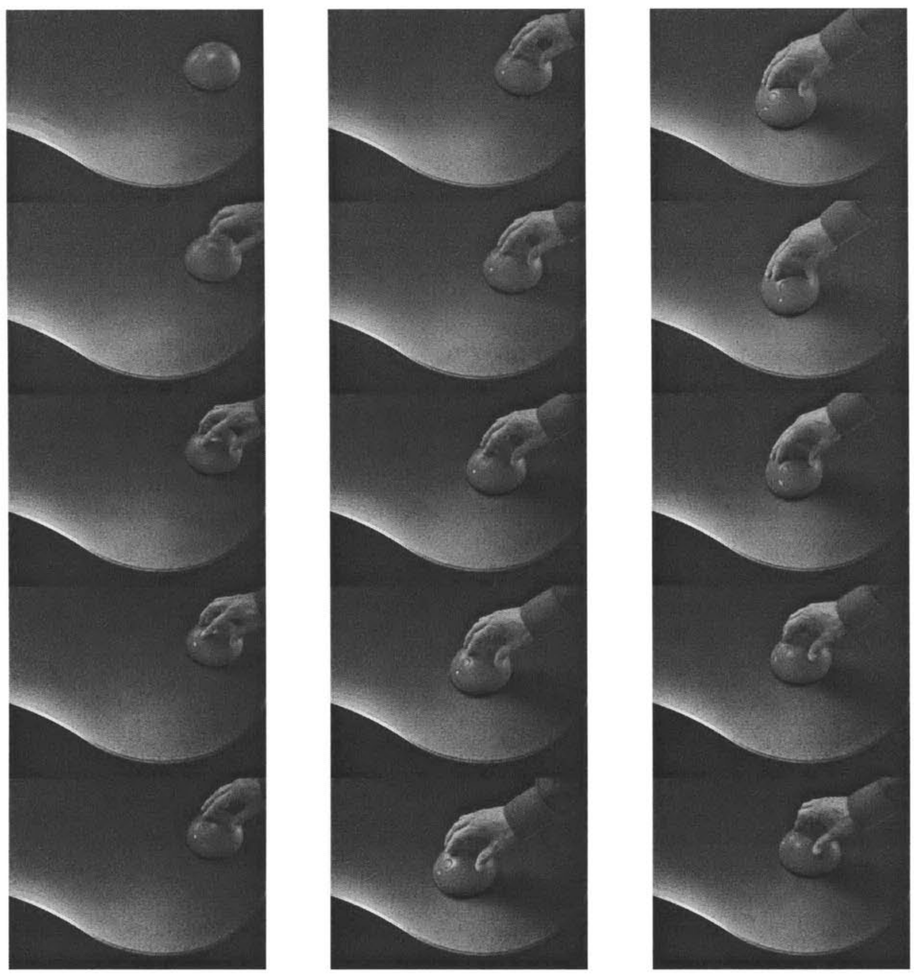
The results for our preliminary user studies show that *curlybot* succeeds in engaging children ages four and above to play with advanced mathematical and computational concepts (previously learned at a later age and often with the aid of a traditional computer) in a fluid and expressive fashion. The combination of expression and learning in *curlybot* is a powerful way to connect with children and keep them engaged in the learning activity.

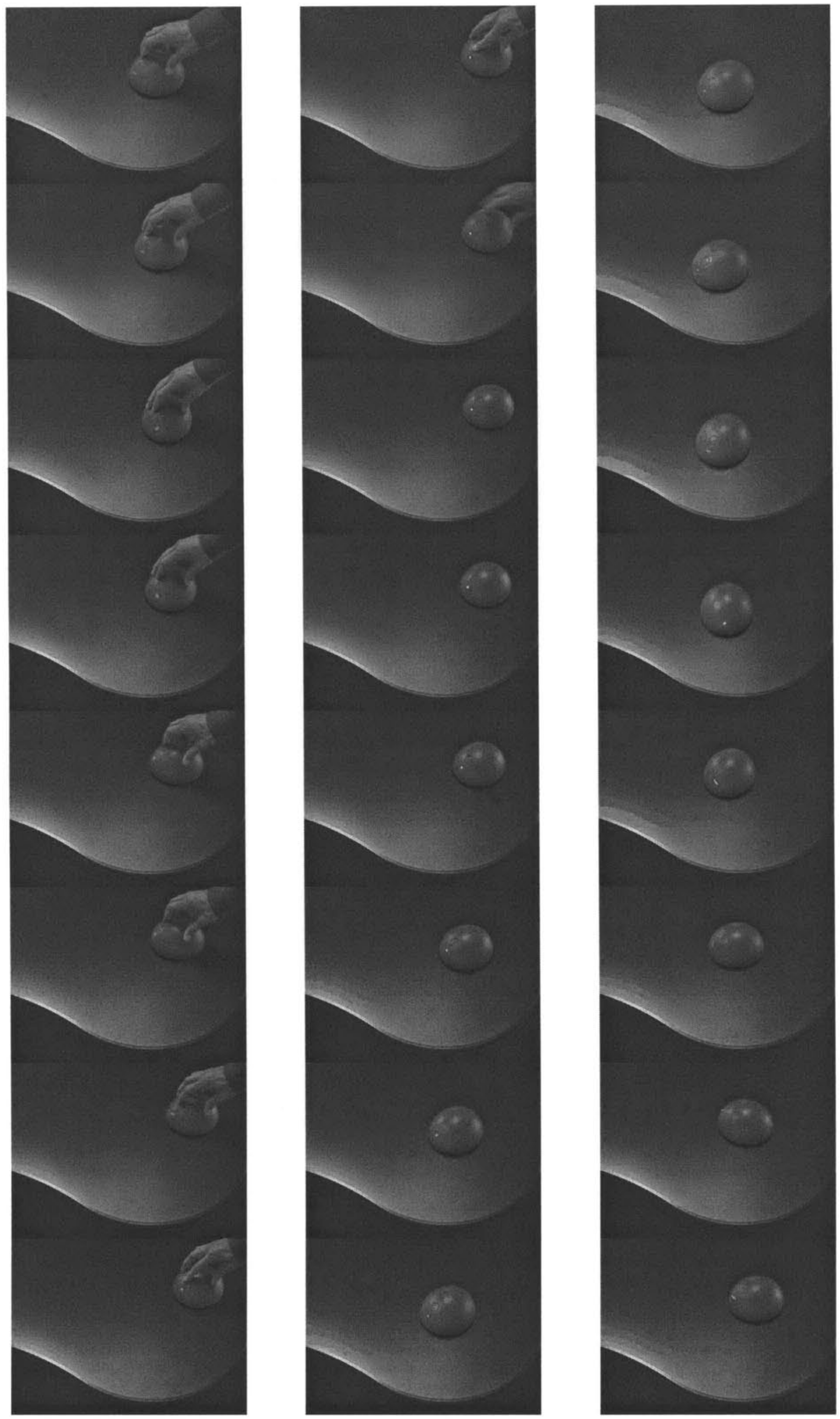
In the future, a longer term study would be needed to reveal if and to what extent interacting with *curlybot* prepares children for working in text-based or graphical programming environments, such as Logo. These types of studies are much more challenging, since it is difficult to isolate the contributions from a specific source to a child's future abilities.

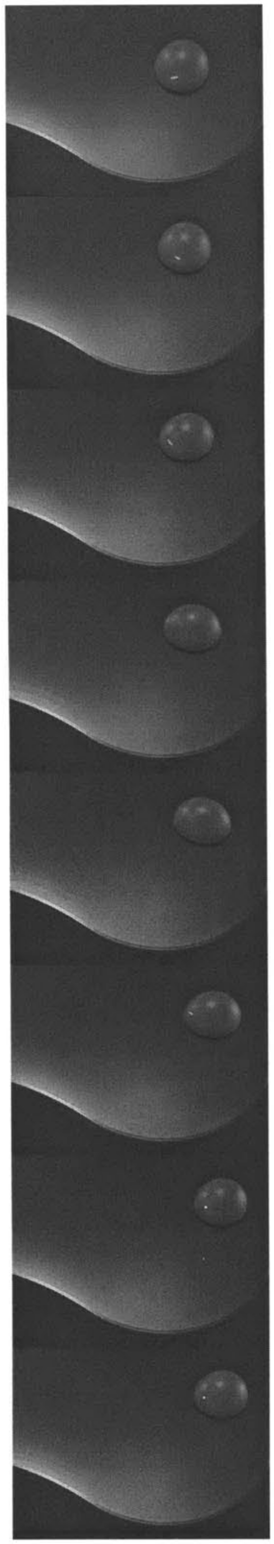
This thesis demonstrates that by being engaging and not overtly pedagogical, *curlybot* can be a powerful tool for education and self-guided exploration. *curlybot* encourages children to have a dialog with the toy, reflect upon their actions, and share these ideas with their peers. This thesis also illustrates the range of possibilities that grow from combining a simple conceptual idea and simple physical components with deeper educational implications.

appendix a: *curlybot* in motion

The following are still images from a video that show both the recording and playback of a gesture. In this case, the gesture is moving straight forward and wiggling back to the start. The images are viewed from top to bottom and left to right. (And, yes, I did think of turning my thesis into a flipbook).







appendix b: fröbel's gifts and occupations

This appendix shows a few more samples of Fröbel's Gifts and Occupations with some images taken from the book *Inventing Kindergarten* [Bro97]. Below is an overview of all the 20 Gifts and Occupations.

Gift 1	Balls
Gift 2	Sphere, Cylinder, and Cube
Gift 3-6	Blocks
Gift 7	Parquetry
Gift 8	Sticks
Gift 9	Rings
Gift 10	Grid Drawing
Gift 11	Pricking
Gift 12	Sewing
Gift 13	Cutting
Gift 14	Weaving
Gift 15	Slats
Gift 16	Jointed Slats
Gift 17	Interlacing
Gift 18	Folding
Gift 19	Peas Work
Gift 20	Modeling Clay

Figure B-1

Using Blocks (Gift 7) to explore geometric principles like Pythagoras Theorem

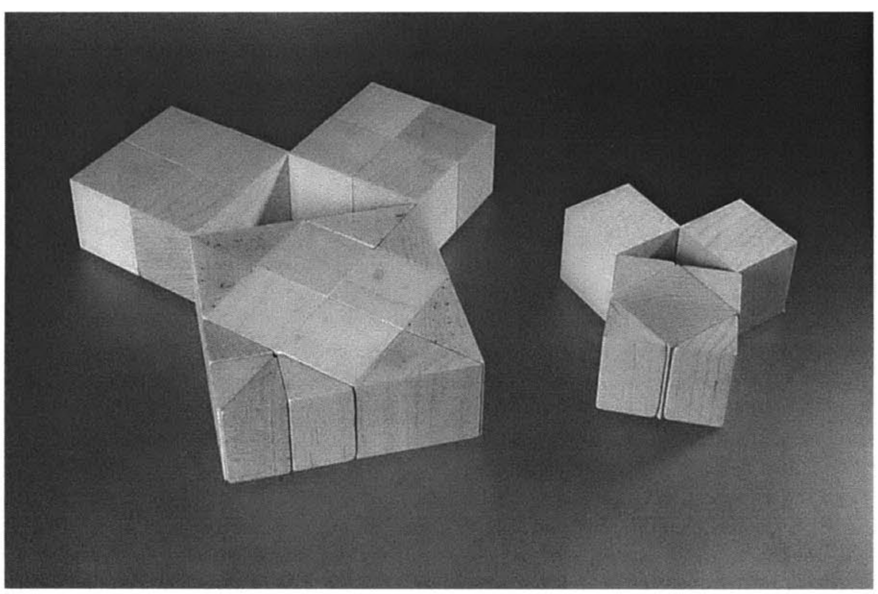


Figure B-2

Using Sticks (Gift 8), Rings (Gift 9), and Jointed Slats (Gift 16)

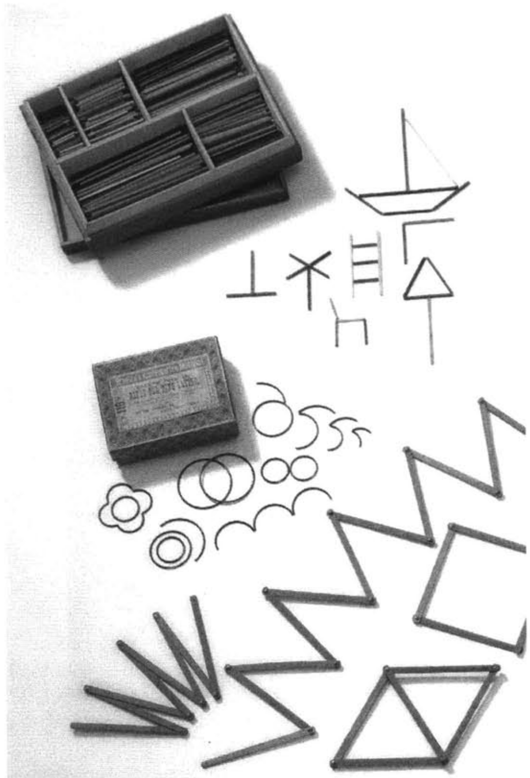
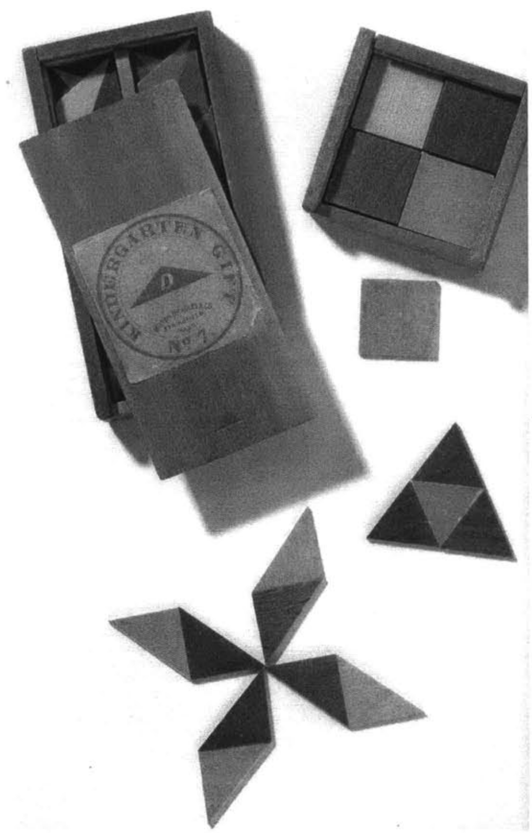


Figure B-3

Parquetry (Gift 7)



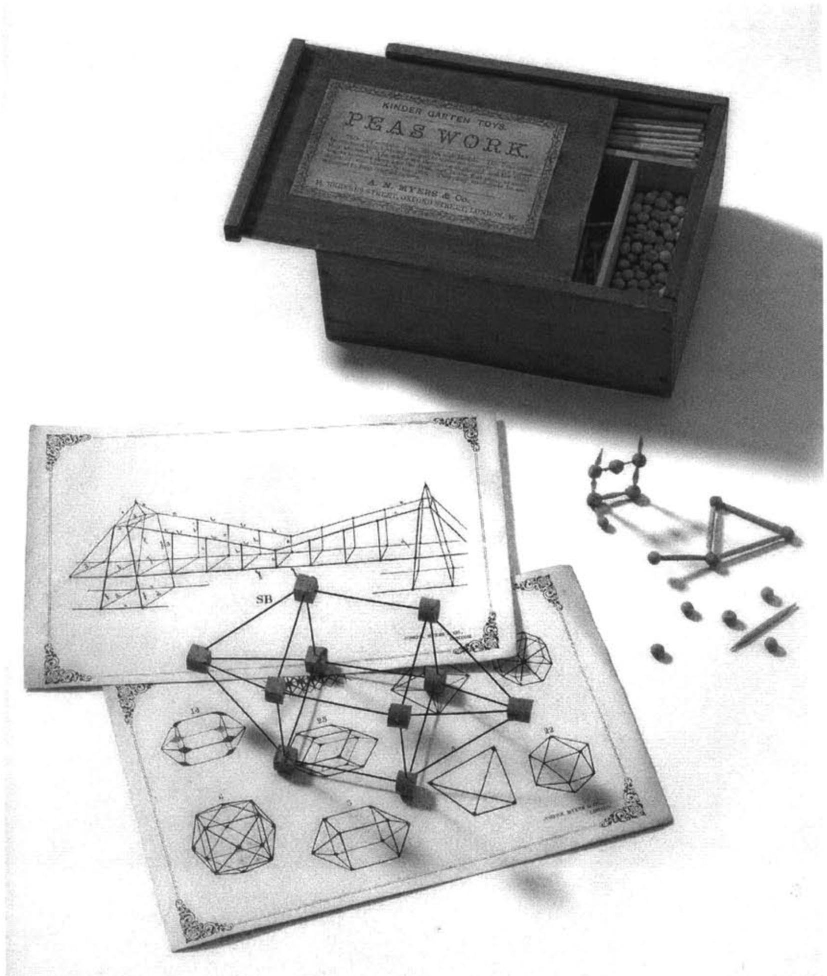


Figure B-4

Peas Work (Gift 19) uses soft peas and sticks to create three-dimenstional objects

appendix c: other *curlybot* design possibilities

This appendix has a series of sketches that illustrate other design possibilities for *curlybot*. The sketches show some of the ideas discussed in the thesis, like adding pens, removable memory, and characters. They also help to illustrate the usability issues one is going to encounter with different form factors. For example, where does one put the record button or how does one hold and move *curlybot* when it has antennas or pens.

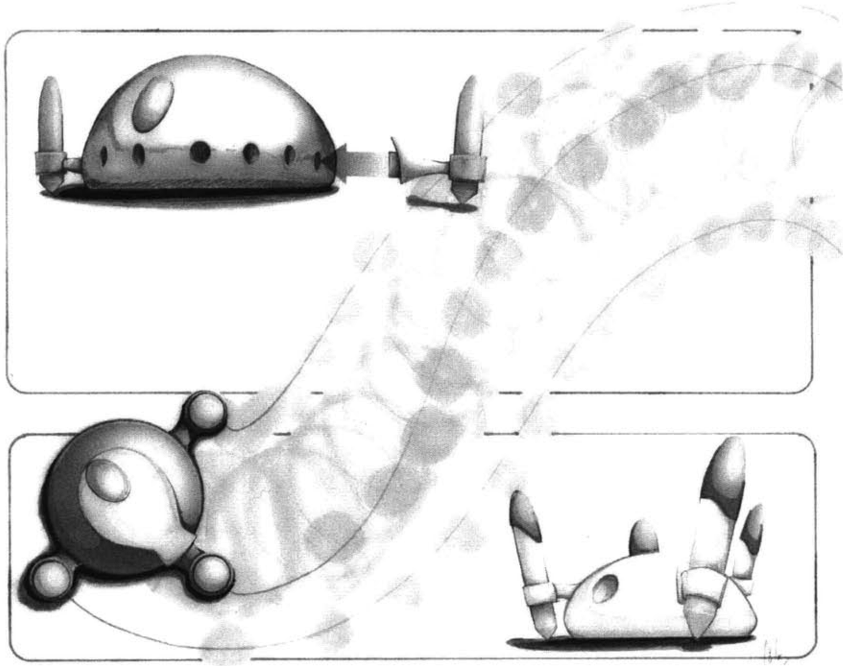


Figure C-1

A few designs of different pen attachments for *curlybot*, including adjustable pen positions

Figure C-2

A variety somewhat abstract designs, including and example of removable memory

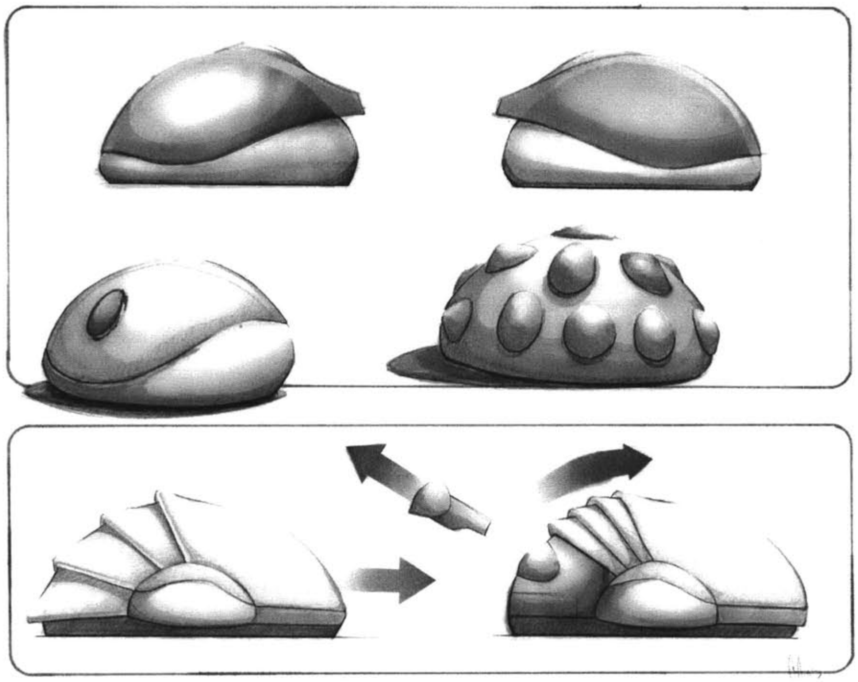
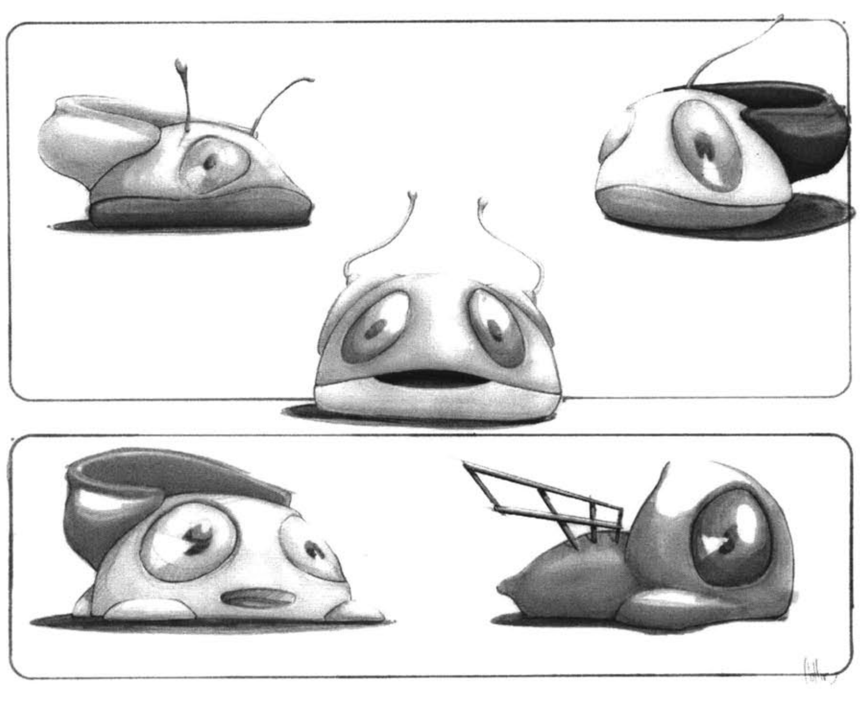


Figure C-3

curlybot characters with pouches in the back and antennas that indicate if it is in record or playback mode



appendix d: new creative tools

Creative toys, like Fröbel's Gifts or LEGO blocks, shape the way we think about the world at a very young age. We have seen the influence of these toys in modern design and art, like Bauhaus, Frank Lloyd Wright, and Piet Mondrian [Bro97].

New creative toys can help expand our view of the world. If one only plays with LEGO blocks as a child, one can be constrained to think about rectangular, mechanical, up-and-down construction. With toys that approach things differently, children may be able to understand and address problems and designs in different ways.

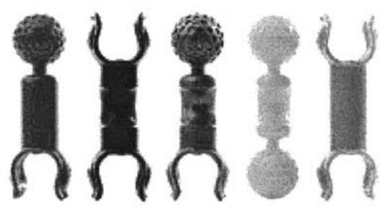


Figure D-1

Five basic ZOOB units

Recently, are becoming more organic and kinetic, in part, because of technological advances. One good example is Michael Joaquin Grey's ZOOB building set, which consists of five basic units that can connect in over 20 different ways. The five basic units, like basic units in chemical or biological systems, have certain properties and affordances when connected. One can start building organic structures that can move and represent biological and chemical constructions and connections. Through this one can have a broader understanding of these system developed through play. This in turn can give people a better intuition, and facilitate their play with more advanced ideas, so that they are not struggling to learn or understand but rather advancing the field or transferring knowledge and understanding to other fields, like art and design.

curlybot has been designed to provide a different perspective on tools that explore organic physical movement and the repetition of patterns. Like ZOOB, *curlybot* tries to break away from the traditional toys that afford mechanical and industrial play, like LEGO and toy trains, to toys that are more organic and expressive.

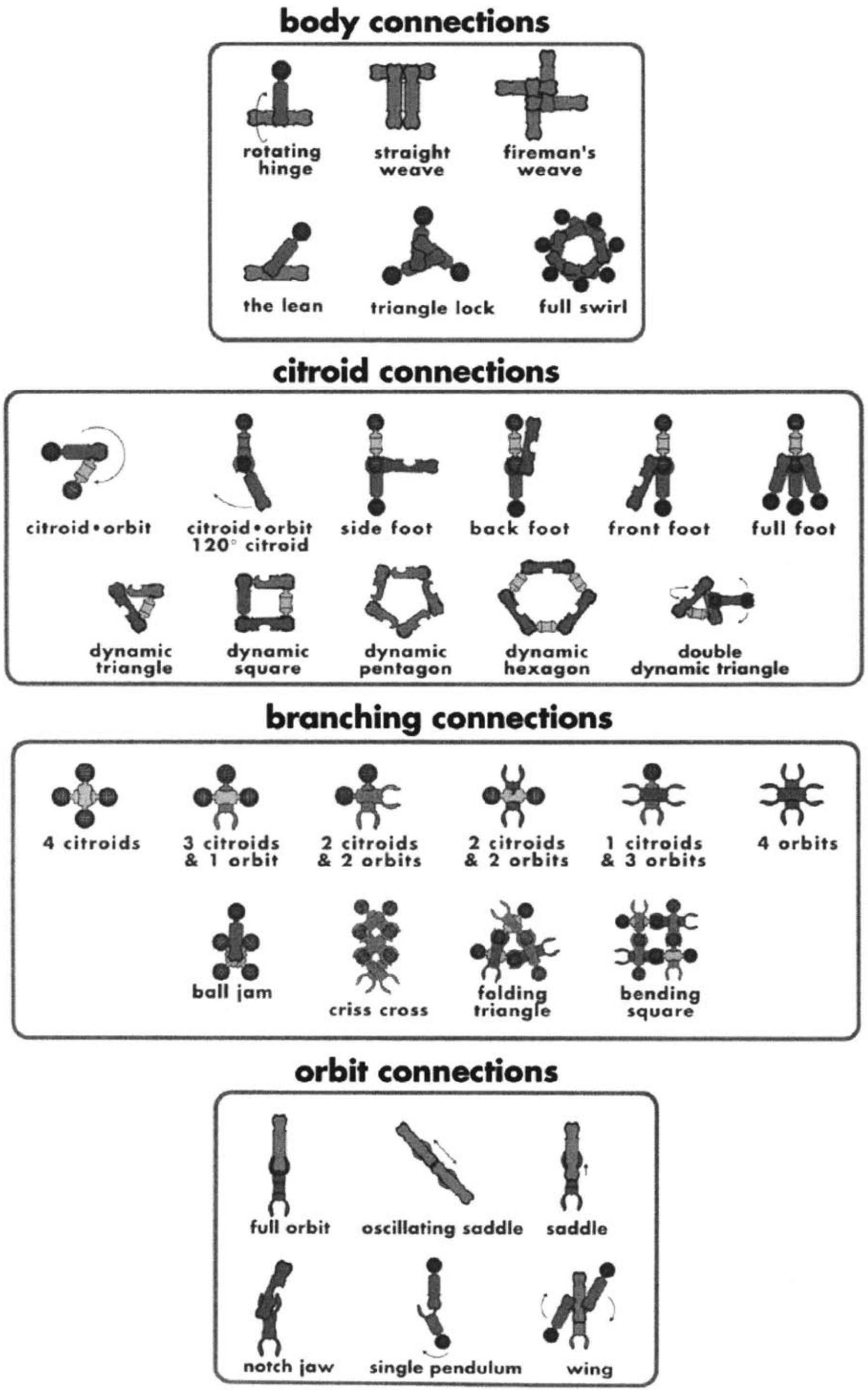


Figure D-2

Different connections possible with ZOOB system

Figure D-3

A cube construction deformed into a sphere or collapsed onto itself

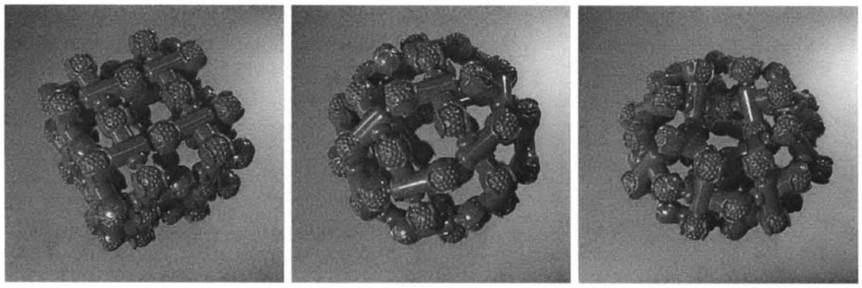


Figure D-4

Fireman's weave is an example of a rigid weave, but more flexible ones are also possible

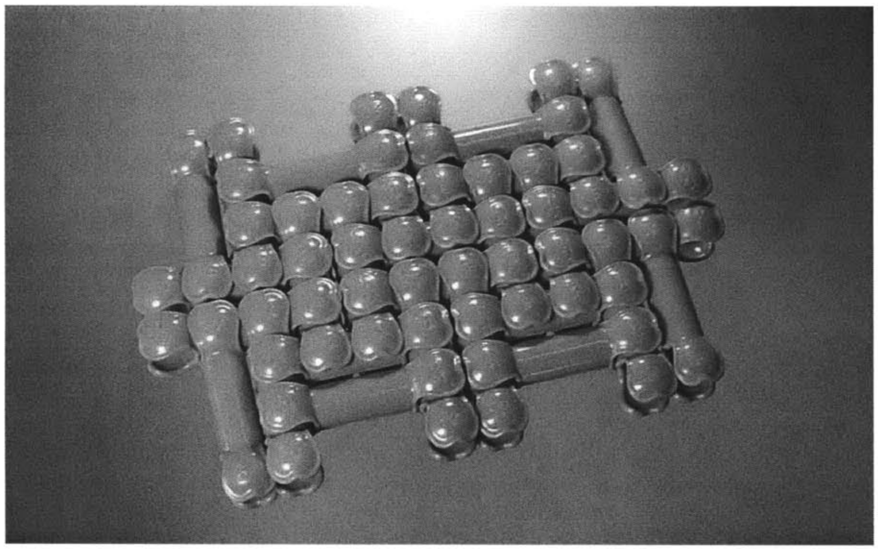
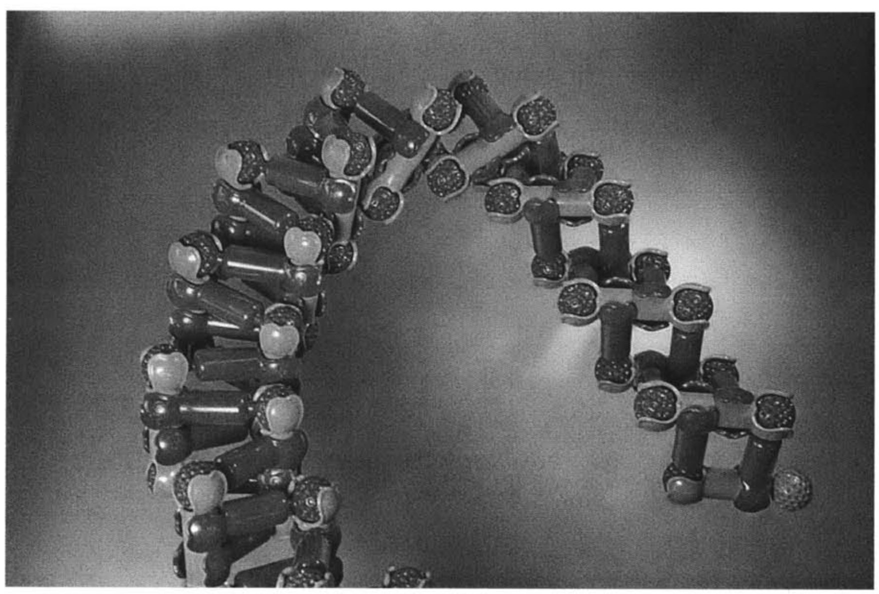


Figure D-5

The accordion structure is an example of a hindging mechanism



8 references

[Abe81] Abelson H., and diSessa A. (1981). *Turtle Geometry.* Cambridge:MIT Press.

[Bor98a] Borovoy R., Martin F., Vemuri S., Resnick M., Silverman B., and Hancock C. (1998). Meme Tags and Community Mirrors: Moving from Conferences to Collaboration. *Proceedings CSCW '98,* ACM Press, 159-168.

[Bor98b] Borovoy, R. and Martin F. (1998). Dance Craze Buggies. <http://el.www.media.mit.edu/people/borovoy/cars/>.

[Bor99] Borovoy R., and Martin F. (1999). Tradable Bits. <http://el.www.media.mit.edu/people/borovoy/>.

[Bra97] Brave, S., and Dahley, D. (1997). inTouch: a medium for haptic interpersonal communication. *Extended Abstracts of CHI'97,* ACM Press, 363-364.

[Bro97] Brosterman, N. (1997). *Inventing Kindergarten.* New York: Harry N. Adams Inc.

[Cyp93] Cypher Allen (1993). *Watch What I Do: Programming by Demonstration.* Cambridge: MIT Press.

[Dah98] Dahley, Andrew (1998). Designing Kinetic Objects for Digital Information Display. Master's thesis, Massachusetts Institute of Technology, Department of Architecture.

[Dru87] Druin, Alison (1987). Building an alternative to the traditional computer terminal. Master's thesis, Massachusetts Institute of Technology, Department of Architecture.

[Dru00] Druin, A. and Hendler J. (2000). *Robots for Kids: Exploring New Technologies for Learning.* Morgan Kaufmann Publishers. "Chapter 1: To Mindstorms and Beyond: Evolution of a Construction Kit for Magical Machines." Martin F., Mikhak, B. Resnick M., Silverman B., and Berg R.

[Eis84] Eisenberg N., Tryon K., and Cameron E. (1984). The Relation of Preschoolers' Peer Interaction to Their Sex-Typed Toy Choices. *Child Development* 55, 1044-1050.

[Fog98] Fogg, B.J., Cutler, L., Arnold, P., and Eisback, C. (1998). HandJive: A device for interpersonal haptic entertainment. *Proceedings of CHI'98,* ACM Press, 57-64.

[Fro04] Froebel, F. (1904). Pedagogics of the kindergarten (J. Jarvis, Trans.). New York: D. Appleton & Company.

[Fre00] Frei, P., Su, V., Mikhak, B., and Ishii, H. (2000). curlybot: Designing a New Class of Computational Toys. *Proceedings of CHI '00,* ACM Press, 129-136

[Gar83] Gardner, H. (1983). *Frames of mind: The theory of multiple intelligences.* New York: Basic Books.

[Gar93] Gardner, H. (1993). *Multiple Intelligences: The theory in practice.* New York: Basic Books.

[Gor98] Gorbet, M., Orth, M. and Ishii, H. (1998). Triangles: Tangible Interface for Manipulation and Exploration of Digital Information. *Proceedings of CHI '98,* ACM Press, 49-56.

[Ish97] Ishii, H. and Ullmer, B. (1997). Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms. *Proceedings of CHI'97,* ACM Press, 234-241.

[Lev98] Levin, Golan (1998). Curly. <http://acg.media.mit.edu/people/golan/curly/>.

[Kaf96] Kafai Y., and Resnick, M., eds. (1996). C*onstructionism in Practice:* Designing, Thinking, and Learning in a Digital World. Mahwah, NJ: Lawrence Erlbaum.

[Mar88] Martin, Fred (1988). Children, Cybernetics, and Programmable Turtles. Master's thesis, Massachusetts Institute of Technology, Department of Architecture

[Mar99] Martin F., Mikhak B., Resnick M., Silverman B., and Berg R. (1999). To Mindstorms and Beyond: Evolution of a Construction Kit for Magical Machines. *Robots for Kids* edited by Alison Druin and James Hendler. Morgan Kaufmann Publishers, Inc.

[Min99] Mindfest '99. MIT Media Lab. <http://www.media.mit.edu/mindfest/>.

[Pap80] Papert, Seymour (1980). *Mindstorms*: Children Computers and Powerful Ideas. BasicBooks.

[Pia62] Piaget, J. (1962). *Play, Dreams, and Imitation in Childhood.* New York: Norton.

[Pul73] Pulaski, Mary Ann (1973). Toys and Imaginative Play. *The Child's World of Make-Believe.* Ed. Jerome Singer. Academic Press. 73-103.

[Res98a] Resnick, M. (1998). Technologies for Lifelong Kindergarten. *Educational Technology Research and Development*, vol. 46, no. 4.

[Res98b] Resnick M., Martin F., Berg R., Borovoy R., Colella V., Kramer K., Silverman B (1998). Digital Manipulatives: New Toys to Think With. *Proceedings of CHI'98*, ACM Press, 281-287.

[Res99] Resnick, M., Eisenberg, M., Berg, R., and Martin, F. (1999). Learning with Digital Manipulatives: A New Generation of Froebel Gifts for Exploring "Advanced" Mathematical and Scientific Concepts. Research proposal, May 1999.

[Ryo99] Ryokai K., and Cassell J. (1999). StoryMat: A Play Space for Collaborative Storytelling. *Extended Abstracts of CHI'99*, ACM, 201.

[Sho79] Shotwell, J., Wolf, D., and Gardner, H. (1979). Exploring Early Symbolization. In B. Sutton-Smith (ed.), *Play and Learning*.

[Sil91] Silverman B., and Tempel M. (1991). Fuzzy Logo. Logo Foundation Memo. <http://el.www.media.mit.edu/groups/logo-foundation/Publications/Fuzzy-Logo.html>.

[Smi75] Smith D. (1975). Pygmalion: A Creative Programming Environment. Report No. STAN-CS-75-499, Department of Computer Science, Stanford University.

[Smi77] Smith D. (1977). *Pygmalion: A Computer Program to Model and Stimulate Creative Thought*. Basel: Birkhauser.

[Sni95] Snibbe, Scott (1995). Motion Phone. Interactive Communities, SIGGRAPH '95.

[Str99] Strommen, Eric (1999). When the Interface is a Talking Dinosaur: Learning Across Media with ActiMates Barney. *Proceedings of CHI'99*, ACM Press, 288-295.

[Tur90] Turkle, S., and Papert, S. (1990). Epistemological Pluralism. *Signs 16*, 1, 128-157.

[Ull98] Ullmer, B., Ishii, H. and Glas, D. (1998). mediaBlocks: Physical Containers,Transports, and Controls for Online Media. *Proceedings of SIGGRAPH '98*, ACM Press, 379-386.

9 image credits

All of the photographs and illustrations in this document where created by the author except for the following list.

Figure 2-1	Uncle Goose Toys at http://www.unclegoose.com/
Figure 2-2	Instruction for Fröbel's Gifts 2-6, Uncle Goose Toys
Figure 2-3	Lego-Foundation at http://el.www.media.mit.edu/groups/logo-foundation/Logo/Turtle.html
Figure 2-4	Photo © Webb Chappell, Fred Martin and Photo © Webb Chappell
Figure 3-4	Megan Galbraith
Figure 3-5	Photo © Webb Chappell
Figure 3-6	Gary Collins
Figure 3-7	Gary Collins
Figure 3-8	Photo © Webb Chappell and From [Bro99]
Figure 3-9	From [Dah98]
Figure 3-10	Photo © Webb Chappell
Figure 5-2	Photo © Webb Chappell
Figure 5-4	Hiroshi Ishii
Figure 5-5	Gary Collins
Figure B-2	From [Bro97]
Figure B-3	From [Bro97]
Figure B-4	From [Bro97]
Figure D-1	Primordial at http://www.zoob.com/anatomy.html
Figure D-2	Primordial at http://www.zoob.com/tableofconnections.html

Colophon

This document was created by the author using Sony Viao PCG-Z505RX running Windows 98SE. The text and editing was done in Word Office 2000. Since Word cannot handle large documents very well, each of the sections were written as separate files and then later compiled into one for page numbering and to create the table of contents.

The PDF version of the document was created using Adobe Acrobat 4.0. The typeface used throughout the body of the document was Bell Gothic.