Sculpting Behavior

Tangible languages for composition, communication and learning

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Abstract

For over a century, educators and constructivist theorists have argued that children learn by actively forming and testing – constructing – theories about how the world works. Recent efforts in the design of "tangible user interfaces" (TUIs) for learning have sought to bring together interaction models like direct manipulation and pedagogical frameworks like constructivism to make new, often complex, ideas salient for young children. Tangible interfaces attempt to eliminate the distance between the computational and physical world by making behavior directly manipulable with one's hands. In the past, systems for children to model behavior have been either intuitive-but-simple, e.g. curlybot or complex-but-abstract, e.g. LEGO Mindstorms. In order to develop a system that supports a user's transition from intuitive-but-simple constructions to constructions that are complex-but-abstract, I draw upon constructivist educational theories, particularly Bruner's theories of how learning progresses through enactive then iconic and then symbolic representations.

We present a set of design guidelines to create a class of tools that helps people transition from simple-but-intuitive exploration to abstract-and-flexible exploration. The Topobo system is designed to facilitate mental transitions between different representations of ideas, and between different tools. A modular approach, with an inherent grammar, helps people make such transitions. With Topobo, children use enactive knowledge, e.g. knowing how to walk, as the intellectual basis to understand a scientific domain, e.g. engineering and robot locomotion. Queens, backpacks, Remix and Robo add various abstractions to the system, and extend the tangible interface. Children use Topobo to transition from hands-on knowledge to theories that can be tested and reformulated, employing a combination of enactive, iconic and symbolic representations of ideas.

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1. Introduction

1.1 Learning by doing

For over a century, educators and constructivist theorists have argued that children learn by actively forming and testing – constructing – theories about how the world works. In many cases, this kind of learning has been facilitated by providing specialized toys (manipulatives) for children to build specific kinds of models [Pia52; Bru04]. With the introduction of computers, researchers were inspired to introduce certain complex and dynamic ideas (like feedback and emergency) to children by creating systems for children to author dynamic systems, and systems with behavior by creating computer programs. In combining physical manipulatives with programming languages that enable embedded physical (robotic) and information behavior, "digital manipulatives" enabled children to create physical models with embedded physical (robotic) and information behavior [Res98]. The most popular of such systems rely on a separate screen-based programming interface that use iconic procedural (block based) programming systems that permits abstract and extensible program structures, e.g. Lego Mindstorms. However, decoupling the tangible manipulative from the programming activity has made many systems concepts inaccessible to younger children.

1.2 Tangible Interfaces for learning

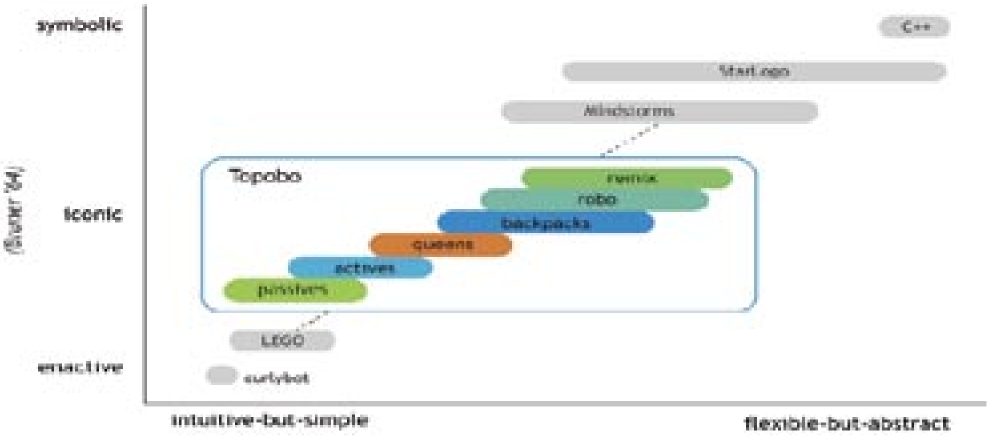
Recent efforts in the design of "tangible user interfaces" (TUIs) for learning have sought to bring together interaction models like direct manipulation and pedagogical frameworks like constructivism to make new, often complex, ideas salient for young children [O'Ma05]. My work extends the breadth of interaction techniques in tangible interfaces so that children may more intuitively explore new ideas through the creation of dynamic compositions. Although there is value in a variety of computational media for children (both screen-based and tangible), research has suggested several areas where tangibles may provide advantages over screen-based computational educational media:

- in collocated, collaborative learning exercises
- for tasks emphasizing motor skills and kinesthetic development
- in situations involving spatial problem solving
- in situations where a GUI may be overly complex, distracting or aesthetically inappropriate
- in applications where the user controls many things simultaneously

Tangible interfaces attempt to eliminate the distance between the computational and physical world by making behavior directly manipulable with one's hands. Tangibles have the potential to enable a new class of digital manipulative that is accessible to younger children. Many tangibles have been argued to make computing concepts more intuitive [O'Ma05], allowing people to create simple dynamic constructions. However, the challenge has been to create a tangible system that is both accessible to young children and can remain engaging for children as they develop and grow. Or, in the educator's words, how can a digital manipulative have both a "low floor" (easy to get started) and a "high ceiling" (be flexible and extensible). Such a system must have the benefits of both hands-on design and programming, and be able to support more abstract representation and manipulation of computational behavior.

In the past, systems for children to model behavior have been either intuitive-but-simple, e.g. curlybot [Fre00] or complex-but-abstract, e.g. LEGO Mindstorms. In general, Tangibles have been criticized for being intuitive, but too simple, and programming languages have been criticized for being sophisticated, but (especially for younger children) hard to learn. In order to develop a system that supports a user's transition from intuitive-but-simple constructions to constructions that are complex-but-abstract, I look to foundation theory from the learning sciences.

1.3 Theoretical foundation: an epistemological framework for HCI



Previous work was either intuitive-but-simple or flexible-but-abstract. Topobo tries to span a range of complexity with a modular system.

Constructivist educational theorists such as Piaget, Bruner, and Pestalozzi have profoundly influenced HCI researchers such as Seymour Papert [Pap80] and Alan Kay [Kay89]. Both of these visionaries regarded the computer as a "tool to think with" and sought a framework to guide the invention of a computational machine that is a creative medium.

Bruner [Bru04] and Piaget [Pia52, Col01] described a rather linear sequence of stages all people seem to progress through as they represent and acquire knowledge. I will use Bruner's terminology because it is more descriptive. Knowledge is first represented and acquired through doing things. *Enactive* representations describe how physical things are done. Some knowledge, such as learning to ride a bike, can not be adequately described in any other way, and must be learned through action. Later, most knowledge can be abstracted, represented and manipulated with symbols. *Iconic* representation is characterized by using and manipulating images to identify and represent ideas. Later, language and grammatical rules can be used to play with relationships of ideas, allowing people to fluidly reformulate and test concepts. *Symbolic* representations are characterized by an abstract mapping of a word to an idea, and a grammar with rules that allows flexible manipulations of ideas through symbolic manipulations. It is the hallmark of language, either natural or invented, e.g. the English language, math, music, a computer language. Piaget demonstrated that children seem to progress through these various stages of acquiring and representing knowledge through predictable stages of development, and Bruner argued that much new knowledge must be acquired according to this order.

Papert, who worked with Piaget prior to developing LOGO, incorporated these theories of epistemology in his activities [Pap80]. Papert anthropomorphized a programming language, by making one that is programmed from a first-person perspective and can be related to a child's personal, concrete experiences. LOGO presented children with linguistic programming tools, and teacher-guided design projects introduced abstract concepts to children. For example, children would "walk the turtle" to understand through bodily movement and thinking how a computer controlled turtle could be programmed to behave.

When Alan Kay developed the Dynabook (with smalltalk, the gui icons and iconic programming) in the 1970's, he also looked to Bruner's ideas to reformulate how ordinary people could leverage computational power [Kay89]. Kay's great insight to replace a computer's linguistic representations (e.g. command line text) with iconic ones (e.g. icons) led to the development of the modern GUI, which made computers more directly understandable and usable by a larger, non-expert audience.

Bruner's framework also provides a means to understand how tangibles can make certain domains of knowledge — especially ones which can not be exclusively captured through iconic and symbolic representations — more accessible by leveraging people's enactive modes of learning. The HCI researcher generally deals with balancing the flexibility of a programming language, and the accessibility of simple, single-use tools. According to constructivist theories of learning, a combination of UI's would best serve users to tackle a domain of knowledge. As Pestalozzi taught, "things before words, concrete before abstract."

Constructivist theories are used here to help guide a UI design that balances ease-of-use (the educator's "low floor) with abstraction and flexibility ("high ceiling"). Tangibles were conceived as physical embodiments of data, or special-purpose controllers that create the illusion that data is directly manipulable with one's hands. There is evidence that people often "think with their hands" [Joh87] and we can interpret from Bruner that tangibles are intuitive precisely because they allow novices to access new ideas through enactive representations of those ideas, by exploring and representing those ideas through action. In this work, we specifically address how a domain of knowledge that is *enactive* in nature — knowing how to walk — can be leveraged via tangibles for people to learn about how principles of robotic locomotion.

In trying to reach a broad range of users and complexity, we find that where tangibles are intuitive, abstraction permits a certain flexibility of use. We theorize that a class of related tools and UI approaches may allow users to approach ideas first through concrete, enactive representations (e.g. tangibles), later through iconic representations (e.g. tangible+visual representations) and last through manipulations characteristic of language. While some ideas may generally only be expressible through one domain or the other, tools can be designed to ease the transition from enactive to iconic to linguistic representation of ideas.

2. Topobo Concept

2.1 The problem

Educators know that allowing children to construct physical models can help them evaluate mental models (theories) — and by constructing models with computational behavior, children can begin to understand dynamic and complex ideas. But a major problem in introducing computing (and embedded computing in particular) to kids stems from the disconnect between the physical and computational realms, or the "layers of abstraction" that separate them. This thesis proposal presents a new tangible robotic construction system for children to learn about principles of ambulatory locomotion, as they collaborate, create, and bring their ideas to life. The Topobo System eliminates the distance between computation and the "real" world while providing possibilities for truly sophisticated activities — intellectual, playful and physical.

2.2 Hypothesis: Spanning a range of complexity

We hypothesize that a tangible constructive assembly system can support children to learn a domain of sophisticated ideas related to robotics and locomotion, and can span concepts from simple to complex by supporting users to engage and transition ideas through a range of representations — enactive, iconic, and symbolic — as they construct physical models. A system grammar will reveal many layers of complexity to users as they become more fluent with the system.

2.3 The approach

Topobo is a 3d constructive assembly system with *kinetic memory*, the ability to record and playback physical motion. Children use Topobo to design and animate playful robotic creations. A child may build a moose with Topobo, twist the moose in her hands to animate the creature, and then watch the moose replay these motions by itself.

The same way stacking blocks helps children learn how stone buildings stand up, animating Topobo helps children learn how animals walk. Topobo helps people transition from simple-but-intuitive exploration to abstract-and-flexible exploration with a system of modular tools. With Topobo, children use enactive knowledge, e.g. knowing how to walk, as the intellectual basis to understand a scientific domain, e.g. engineering and robot locomotion. Components called Queens, backpacks, Remix and Robo add various abstractions and computer-relation functions to the system, and extend the tangible interface so that children can transition from hands-on knowledge to theories that can be tested and reformulated through a combination of enactive, iconic and symbolic representations of ideas. The idea is to grow from simple constructions (and simple ideas) to complex ones, through a constructive, collaborative and social process.

2.3 A scenario

Dave and Mike, two sixth graders, come together on a rainy Saturday to play "battle bots" with Topobo. They pull a box of parts from under Dave's bed and start snapping parts together to create a robotic lion. They have played with Topobo before, and quickly assemble a four-legged creature with a long tail. "One, two three!" Mike says, as he pressed they button on an Active to set the creature in recording mode. Dave grabs two legs and Mike grabs the other two as they begin to make the Lion's legs walk back and forth. Mike presses the button again to set the Lion in looping playback mode, and they set it down to watch it walk on its own. They suddenly realized the creation didn't work as planned. Dave broke his focus, stopped his ongoing activity and then asked: Why? What happened? Why it is not walking?

This breakdown in the ongoing activity of building a Topobo model may produce a certain conceptualization in Dave's mind [Bød91; Flo86]: he may start thinking and manipulating Topobo in new ways in order to produce movement, feedback, global-local interaction and walking. The process of physically debugging his creation may give Dave new insights to kinematic systems.

Dave and Mike continue playing with Topobo for the next 45 minutes. They add a heavier tail to the lion, and see that it still does not work. The legs are moving, but they do not produce walking. Mike gets on the floor and begins to crawl very slowly, noticing the sequence his hands and knees touch the floor when he is moving forward. Mike and Dave study this motion, trying to conceptualize a pattern of movement they can recreate with Topobo. They make the lion's left shorter, and experiment with different patterns of movement. Finally, after many attempts to mimic a crawling sequence, their Lion walks forward.

Dave works to
program a Lion.

In working to refine this walking motion, Dave and Mike learn how their Lion can be made to walk forwards, backwards and even walk in an arc, turning as it moves. Now that they understand how to make their Lion move as they imagine, Dave grabs the *Remix* sampler/sequencer and plug it in to an Active on the Lion. Dave and Mike collaborate to create a new, longer walking sequence, and Dave uses the red Remix token to capture and save four perfect lion-steps. Next, they record a backwards walking motion and Dave captures it with the blue Remix token. Last, they pose the lion in a position low to the ground, and with the yellow Remix token, Dave saves the pose to use later.

Dave unplugs Remix and attaches Robo, which is like a video game controller, to the Lion. Pressing the buttons on Robo will spontaneously playback the motions Dave just recorded with Remix. With Robo, Dave can also make the motions playback bigger, smaller, faster, slower or backwards with button presses and subtle movements of two joysticks. The Lion is ready to perform.

Dave and Mike recreate the Lion’s design, this time making an orange and blue “Tiger.” Once the Tiger is built, programmed and connected to a separate Robo controller, Dave and Mike are ready to compete. Each boy is convinced he can outwit his opponent, flipping his opponent’s creature upside down. But it’s been three hours of work already! First, they need a break for lunch.

3. Topobo System Design

Topobo has been designed to support seamless transition up a mountain of ideas related to morphology, dynamic physics, locomotion, and robotics control. A number of principles help address the core hypothesis.

3.1 Design Principles

Reveal knowledge about the natural world by capturing core relationships common to animals and machines

A tangible construction kit can allow even very young children to play with complex ideas. Topobo captures a body of knowledge that exists at the intersection of biology and robotics, and presents it as a family of modular, reconfigurable components that children can use to explore their own ideas.

Support creative expression, collaboration and communication — in the tradition of art media

Art media (paints, clay, pens and paper) are said to enable children to invent their own "languages" for expression, collaboration and communication [Giu00]. This work builds tangible media in an art-making tradition, to support collaboration, personal expression and communication. We observe children's patterns of usage of such media, and activities that children specifically identify as motivating them, e.g. model-making, animation, competition, and performance.

Be meaningful even if the power is turned off

The system builds on a history of successful manipulatives, without abandoning their inherently good qualities. As such, the system succeeds in a traditional manner (as biologically-inspired building blocks) even when the computational technology is absent.

Leverage aesthetics — motivate learning by helping users emotionally connect with their work

Aesthetics — of form, of behavior — have the valuable and motivating effect of making people care about their work. Emotional connection to one's work makes one a more caring (and focused) learner.

Build on, and provide means to externalize, users' existing knowledge

A central design goal of this thesis is to create a system with which a user may create a physical model that is both an externalization of an idea (a mental model), so that a user can identify and experiment with their ideas. The model provides a playground for the learner to discover relationships and new ideas that would not be discovered without the manipulative; new ideas, discovered through play with the tangible media, are then internalized by the user.

Be accessible, yet sophisticated

A focus of this work is to demonstrate a system that can coevolve with children as their interests and abilities develop, helping children climb a mountain of ideas. Put another way, how can a single system appeal to the broad age and developmental range of a growing child? In order to reach across ages, I had to create tools that spanned enactive to symbolic representations of knowledge, and support simple to complex constructions and investigations.

Support conceptual abstraction by embodying abstract concepts in tangible media

System components begin simple and introduce increasingly complex ideas. Complexity is layered: I will explain how even young (4 year old) children can play with the passive blocks. Five year olds can use one Active, and older children begin to explore multiple degrees of freedom by connecting many Active blocks together. Queens introduce centralized control and the abstract idea of repetition. Backpacks further introduce abstract concepts like conditional and feedback behaviors, and Remix and Robo provide tangible tools to represent abstract ideas related to sampling, sequencing, nesting and reorganization of records.

Leverage a system grammar

The system is developed as a dynamic spatial language, where both the structural and behavioral aspects of the system are formulated according to a reconfigurable grammar. Children are the best learners of new language, and a clear grammar supports users to transition from simple to complex patterns of use, as their concrete experiences evolve into abstract ideas.

Topobo's structural grammar is based on the static growth of crystals and the kinetic movement of mammalian skeletons and regular crystal meshes. Information behavior is structured with a syntax that can be described in comparison to a linguistic framework:

alphabet: system components, e.g. passives, actives, queens, backpacks, remix, robo
noun: a built object with an identity, e.g. Dave and Mike's "Lion"
verb: recorded movement recreated by a noun, e.g. the Lion's walking motion
adverb: local and global modifications to parameters of verbs, e.g. faster-slower Backpack
sentence, story: combine actions for performance or narrative, e.g. with Remix and Robo

This grammar allows users to apply abstract, symbolic procedures to enactive representations of knowledge. That is, children who know how to crawl can mimic crawling using their kinesthetic sense (moving Topobo in their hands) and can leverage abstract principles such as repetition (using a Queen to duplicate that knowledge across many Actives) or variable control (via backpacks).

One implication of this grammar is that modules introduce complexity and abstraction in a seamless manner, that is, without interfering with the function and patters-of-use of other modules. The Backpacks introduce modulation, variables, and sensors without altering the ways people will engage with Actives.

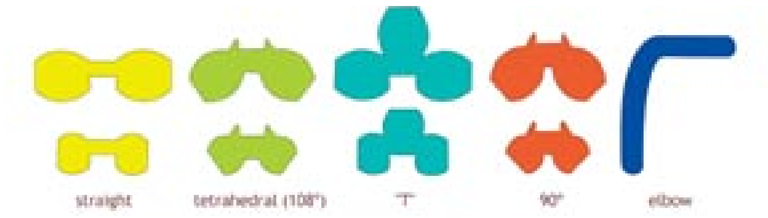
More generally, the grammar can support complexity that arises from relationships between parts, including properties common to natural language such as recursion, where patterns (whether structural or behavioral) can be reconfigured, copied and nested within one another.

To meet these design goals, various elements of the system have been designed, built and evaluated independently over the course of four and a half years. The basic system components follow.

3.2 System Components

Passives

We designed nine different Passives to allow a variety of physical structures to be built. Since Topobo is intended to model various natural forms like skeletons and interlacing meshes, the system allows branching and spatial looping. The Topobo geometry (Figure 4) is based on cubic and tetrahedral crystals.

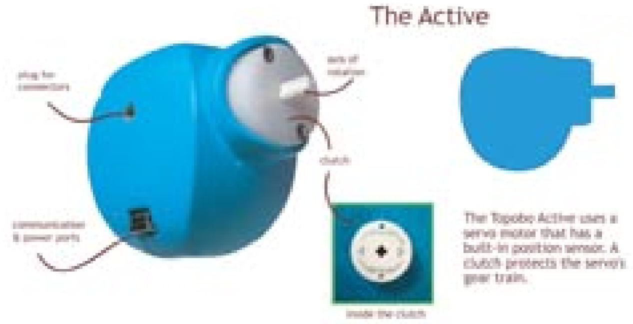


The passives come in two sizes with a 3:2 scale ratio that is based on the fibonacci ratio found in natural structures like plants and skeletons.

The "elbow" (offset 90°) comes in one size. The "straight," "T," "L" (90°), and "tetra" (108°) shapes come in two sizes with a scale ratio 2:3, based on the Fibonacci ratio that describes scaling in growing systems like mammalian skeletons. These latter 8 pieces are bisected by hermaphroditic notches, allowing any two pieces to connect and branch at a right angle. For example, two straight pieces will form a "+" shape, or two tetras will form a tetrahedron. This arrangement allows the formation of regular meshes like a silicon tetrahedral lattice or simple forms like a pentagon or square (Figure 4). Children notice this regularity quickly because when a child tries to build large, interconnected forms, pieces often fit together.

Actives

The Actives are motorized, networkable, egg-shaped plastic objects with a button and an LED for indicating whether the system is in record (red) or playback (green) mode. To record a movement, the user presses a button on an Active, twists and moves the Active to program a sequence of behaviors, and then presses the button again. The Active immediately goes into playback mode, which repeatedly replays the user's input until the button is pressed a third time, which makes the active stop moving.



The Topobo Active uses a servo motor that has a built-in position sensor. A clutch protects the servo's gear train.

The Active design accommodates multiple electrical and mechanical connections. A clutch protects the motor from excessive torque.

In a creation with many Actives, all of the Actives will record and playback at the same time. For example, if a child makes a circular ring of Actives, pressing a button on one of the Actives then sets all of the Actives in the structure to be in recording mode. The child may then move the circular structure of actives in the manner of a tank tread rolling across the floor, and then press any one of the Actives' buttons to set the structure into playback mode. At that moment, the motion that each of the Actives remembers is their local motion, despite the fact that the child has manipulated the global structure. In playback mode, the Actives mimic their local behaviors inspiring the whole system to take on the global motion imparted to it by the child.

The Active is made of a servo motor and electronics in a plastic housing. The housing has 6 points of mechanical connection, three sockets to connect power/communication cables and a button that is backlit by a red-green LED. One of the mechanical connectors is connected to the output shaft of the servo motor and rotates 170°. On board custom electronics handle power distribution, memory and processing, and peer-to-peer, multichannel serial communications. Each Active is identical and autonomous, and only needs power to function.

The one-button interface was inspired by Curlybot [Fre00] and chosen because it is extremely easy to use. While the one-button interface is limited, 3D motion concepts are complex and the immediacy of the interface design encourages rapid experimentation with motion. Physical programming by example also results in natural looking, emotionally engaging motions because they are the reflection of the user's own body movements [Fre00].

Queens — centralized control

In recording mode, a user will grasp and wiggle an individual Active component in a creation. In playback mode, that same Active component will mimic the motion that was made to it. The other Actives in the structure have no motion to mimic. In some situations, it may be desirable for all Actives in a structure to mimic the motions made to one individual Active in the structure. To accommodate this complexity, we introduced the Queen. In both recording and playback modes, all motions of the Queen are imparted directly to all Actives connected to the Queen.

Programming with a Queen: In both record and playback modes, all motions of the Queen are imparted directly to all Actives connected to the Queen.

For example, suppose that one constructs a linear structure of actives with a Queen at one end. When the Queen is recording, all of the other Actives will mimic its angular position. Thus, increasing rotations to the Queen cause the entire structure to begin to curl into a circular form. Eventually, the ends will touch (figure 5).

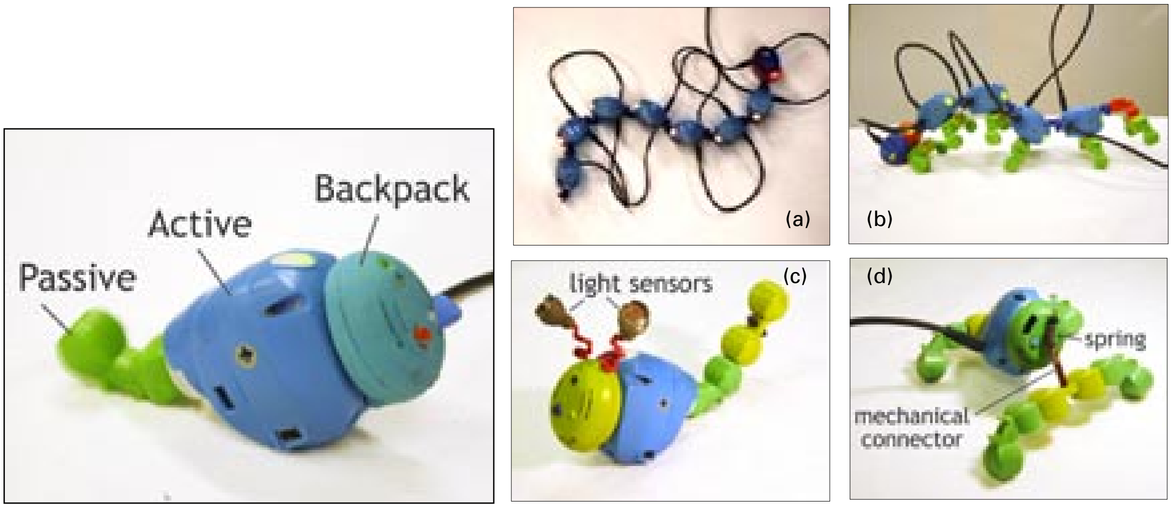
Topobo Queens can be used to provide tangible examples of spatial translation. For example, two facing Actives that have identical motions will appear to have mirrored motions if their output shafts are facing each other. This can be used to construct scissor-like motions in a walking animal.

A Queen does not need to be mechanically attached to the creation it is programming, so it can also be used as a remote controller. Remote programming with a Queen gives a child synchronous input and output feedback during programming, allowing the child to observe their creation's motion while they are composing it.

Backpacks

Backpacks introduce parameterized transformations, sensors and feedback to a modular robotic building system with specialized modular components. The challenge backpacks address is to create a tangible interface that can retain the immediacy and emotional engagement of "record and play" and incorporate a mechanism for real time and direct modulation of behavior during program execution.

Backpacks are modular physical components that children can incorporate into robotic creations to modulate frequency, amplitude, phase and orientation of motion recordings. Using Backpacks, children can investigate basic kinematic principles that underlie why their specific creations exhibit the specific behaviors they observe. Backpacks make tangible some of the benefits of symbolic abstraction, and introduce sensors, feedback and behavior modulation to the record and play paradigm. User studies with children ages 6-15 indicate that Backpacks extend the conceptual limits of record and play with an interface that is consistent with both the physicality of educational manipulatives and the local-global systems dynamics that are characteristic of complex robots.



Left: Backpack. Right: (a) Time Delay causes queen motions to produce a sinusoidal wave, used (b) to mimic the locomotion of a caterpillar. (c) light sensors replace the knob in Offset Backpack (left). (d) Bigger-Smaller backpack exhibits mechanical feedback (right).

When using Topobo, a child will make a model, record a motion, and watch it play back. If he would like to change the movement of his creation, he will start over and record a new motion. Although a child can flexibly edit the shape of his physical model, he cannot edit the "shape" of his recording (the program). Backpacks allow children to modulate recorded Topobo motions. They are physical components with a button and a knob that can be snapped onto an Active to modulate the phase, amplitude, frequency, or orientation of playback motions. These effects are described using familiar words, where phase is called *Time Delay*, frequency is called *Faster-Slower*, amplitude is called *Bigger-Smaller*, and orientation is called *Offset*. If we think of Topobo in terms of grammar, a child's physical creation is a "noun," its recorded motion is a "verb," and Backpacks are "adverbs."

Scenario

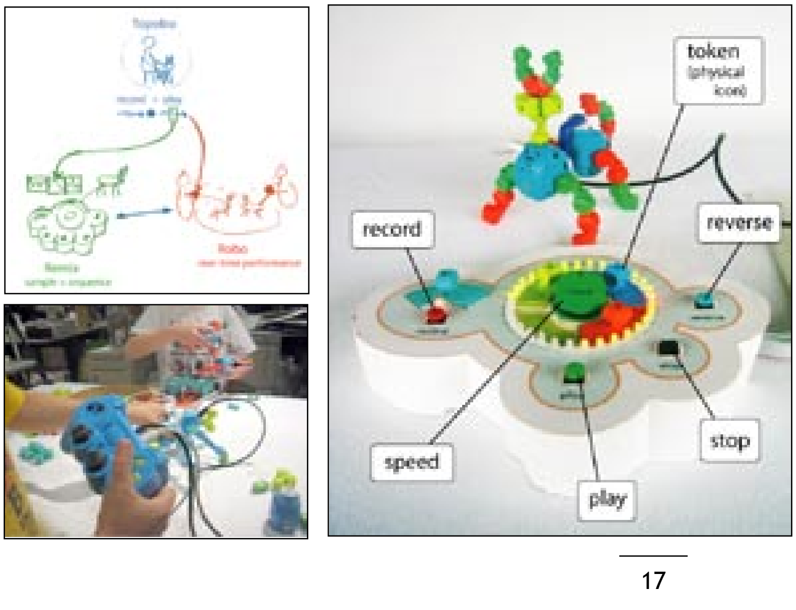
Jack, age ten, has been working on a Topobo ant for a half hour, struggling to make it reliably walk forwards and then backwards. Jack's structure walks sometimes, but Jack is having trouble predicting the direction the ant walks. Jack wonders if the ant would walk better if its back legs took a slightly larger step than they do currently. He attaches a *bigger-smaller* Backpack to the Active that controls the back legs, and turns its knob to slightly amplify the motion. It has no effect, so he tries making the motion *much* larger. This doesn't work either, so Jack tries attaching the Backpack to the front legs instead. By experimenting turning the knob from smaller to bigger and back again, Jack discovers that his ant walks forward perfectly when the front legs make a smaller motion, and actually walks backwards when the motion is made larger. Jack is so surprised that he can control the direction by changing the scale of the motion! He's not sure why it works, but Jack knows how he can use his discovery: he replaces the bigger-smaller Backpack with another one that has light-sensor eyes (instead of a knob). He grabs the antennae on the eyes, pointing one eye forward and other one backwards, and uses a flashlight to make his ant follow the light around his room.

Implications

Although parameterized control, sensors and feedback are typically part of a traditional programming paradigm, Backpacks are not pursuing a path to replace symbolic programming with tangible direct manipulation. There is still a big divide between symbolic descriptions of dynamics and simple record and play systems, and giving people tools to manipulate parameters is not the same as a mathematical approach. Our intention is to maintain the immediacy of record and play, and the analog data sets that result, and introduce some of the manipulation that is traditionally done with programming. I believe the strength of such a system lies not on its high degree of abstraction, but rather in an interaction model that makes certain complex ideas accessible and salient to children. My intention is to "raise the ceiling" of complexity in record and play paradigms by making fundamental aspects of kinematic systems manipulable, without sacrificing any of the immediacy and playfulness that has been appreciated in record and play interfaces.

Remix and Robo

Remix and *Robo* are composition and performance based tools for robotics control. Remix is a tangible interface used to sample, organize and manipulate gesturally-recorded robotic motions. Robo is a modified game controller used to capture robotic motions, adjust global motion parameters and execute motion recordings in real-time. Children use Remix and Robo to engage in (1) character design and (2) competitive endeavors with Topobo.



Top left: Topobo, Remix and Robo. Right: Remix. Bottom left: Jonathan reaches in to a battle to redesign his robot.

My objective is to provide new entry paths into robotics learning. Users age 7-adult use Remix and Robo to engage in different kinds of performative activities. Whereas robotic design is typically rooted in engineering paradigms, with Remix and Robo users pursue cooperative and competitive social performances. Activities like character design and robot competitions introduce a social context that motivates learners to focus and reflect upon their understanding of the robotic manipulative itself.

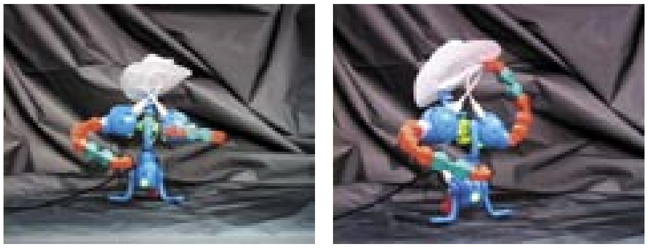
Topobo, Remix to Robo can be compared to video performance tools: in video performance, a camera will be used for pure data capture (Topobo), an editing suite will be used to sample, sequence and organize a library of video clips (Remix), and video-jockey tools will be used to perform video mixing spontaneously (Robo). Such tools are designed to be used interchangeably, have some functional overlap (e.g. one could conceivably video-jockey with raw unedited video data), and are tailored to support different usage patterns.

Scenario

"This is walking. This is anger. And this is respect... With a few moves, you have enough expression to do a whole movie." — Bob, 12 years old

Bob has recently developed a fascination with creating his own animations. Although he usually is making animated flipbook drawings, today he realized that he can animate and control Topobo for an animated video he imagines. Bob uses paper to decorate his cowboy creature and experiments both with continuous animation and with "keyframe" recording using Robo, by recording still gestures. "[Keyframes are] a little more 'real time.' I was constantly pushing buttons to do everything, which was satisfying."

Robo and Remix allow Bob to create a character with a wide range of expressive range. "You couldn't do character animation without these controllers. This is a different problem than getting something to walk.... It would be interesting to work from a script, because I bet I could get something rapidly across." .



Bob uses Robo to direct his cowboy to show anger (left) and respect (right).

3.7 Beyond Tangibles — Explorations and Experiments

This investigation pursues the limits of a tangible system for design and learning about principles of physics and biology via play with robotic technology. Explorations and experiments test the limits of hands-on programming and control. How can hands-on programming converge with more traditional robotic and technology developments?

TeleTopobo — modular telerobotics

TeleTopobo abandons the design principle of collocated collaboration and investigates how a modular telerobotic system can support remote collaboration and communication. For children and adults, TeleTopobo opens an opportunity for users to design their own telerobotic interfaces for haptic communication. It permits remote sharing of gestural Topobo programs and expert tutoring among communities of Topobo users. For educators, TeleTopobo enables remote teaching and learning of educational robotics, a research initiative currently pursued with other educational robotic systems, e.g. LEGO Robolab.

Protobo — a distributed programming language for robotic motion

Backpacks, Remix and Robo begin to suggest that tangible programming might converge with dataflow programming paradigms like Max or PD. However, linguistic programming models may be more extensible for programming massively scaled and distributed systems like Topobo. Protobo is a lisp-based language for a distributed modular robotic system. Protobo will offer the expert Topobo user an opportunity to test — and extend — her ideas by scripting Topobo behaviors with global, high level commands that are executed as distributed algorithms. A Topobo user's transition from hands-on programming to protobo will allow the learning theorist an opportunity to investigate how children may transfer ideas from a tangible to a linguistic mode of representation.

Protobo will allow for globalized, central programming of a decentralized tangible system.

4. Evaluations

This thesis is about designing a system to support playful learning across a span of age and complexity. Evaluations address the hypothesis and design principles, by investigating people's usage and interpretations of the various system components. We begin with *functional* questions, i.e. were people able to understand and use the system to play with certain ideas, as a means to address *structural* questions, i.e. how did people relate to the system, and how does people's use of the tools indicate certain patterns of growth and internalization of ideas.

Example Functional questions:
Is the system easy to use, understand, and experiment with? Do people's creations reflect a range of complexity of constructions? Do we find both simple and complex models being built? Does the system appeal to a wide range of users? Is Topobo emotionally and intellectually interesting for children adept with symbolic representations?

Example Structural questions:
Do we see evidence that the system supports users to transition from enactive to iconic to symbolic representations of their ideas? Are users' theories about animals and machines developing and becoming more sophisticated as they use the system?

A series of studies have focused on users' experiences with the various system components. I will illustrate our methodology by reviewing an example study in which early adolescents used a Topobo system of Passive, Active and Queen components.

4.1 Example Study with Early Adolescents

Evaluations with two eighth grade "Physics by Design" classes focused on Topobo's role supporting design, experimentation and conceptual abstraction. This study followed classroom work with kindergartners and second graders, and we sought to evaluate several core functional questions related to the design principles:

- Is Topobo emotionally and intellectually interesting for children adept with symbolic representations?
- Is the system easy to use, understand, and experiment with? Does the "grammar" work to support experimentation and iteration?
- Can children leverage their enactive knowledge about walking to help them create walking robots? Will this lead to successful designs?
- What appear to be the benefits of a tangible interface for investigating principles of locomotion? What are its limitations?

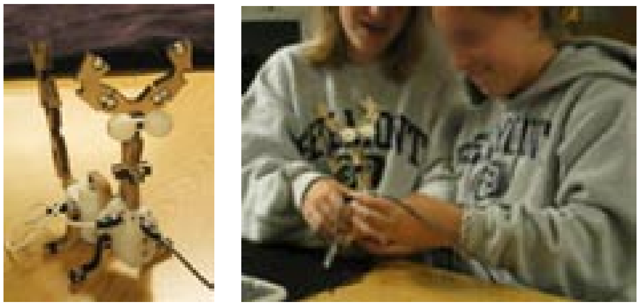
Our students normally engaged in group projects using manipulatives like LEGO Robolab, so the evaluation was designed to be like familiar classroom activities. We met with four groups of 8 students twice over two weeks, and students worked in pairs or groups of three. These sessions included three homework worksheets and interviews with students.

Our first evaluation session introduced the system. Using a preliminary worksheet, students described different types of motion related to their bodies based on both their pre-existing conceptual models of motion and then based on activities we designed. The next day, we explained how to use Topobo with demonstrations and examples.

Students began by freely exploring the system. Many students built anthropomorphic creations, programming them to tell stories or wiggle around. Their creations often did not move as they expected. Falling creations elicited exclamations like "add more legs" and "make it lower, like a baby." For most of these students, Topobo quickly became a tool to experiment with center of gravity and dynamic balance.

A week later children focused on a task to construct a "walking creature." Students first planned and drew their creature and then tried to build it and make it walk. We observed two different methods of design. The first method involved "active iteration" during the creative process. Students built a small part of a creation, programmed it repeatedly until the desired motion was found and then added components, testing how the new components changed the dynamic balance of the creation. This process continued until they had their desired creation. The second method involved students who would "compartmentalize" the processes of structural building and programming motion. Students who compartmentalized would build a creation in its entirety and then program its movement only at the end of their process.

A second grader built this static scorpion, left; he identified with the building system at its most basic passive level. Eighth grade girls, below, collaborate to program their 2-DOF moose.



Students who employed active iteration were more successful at building creations which walked and balanced. These students' creations tended to be very different from their original designs on paper and the students were generally able to explain how physical constraints had influenced their designs. In comparison, students who compartmentalized building and programming usually ended up deconstructing their creation and trying to rebuild it using a more iterative process. Children's success reconfiguring both active and passive structures supports our hypothesis that a system with a clear grammar can make interrelated concepts manipulable.

These findings show that an interface design should support active iteration by allowing users to switch between interdependent processes. Users often need to test many ideas to incrementally develop a successful design. Students who initially compartmentalized the design of form and motion eventually adopted active iteration, suggesting that Topobo supports rapid experimentation with these interdependent processes. These findings also suggest that Topobo would benefit from an ability to save and reuse motions, so that forms can be edited and motion can be kept consistent; this observation led to Backpacks, Remix and Robo interfaces.

4.2 Summarized Findings

Age Range Findings

In classroom studies with 25 kindergartners (5-6 years old), 22 second graders, and 32 eighth graders we evaluated Topobo's effectiveness as a educational tool for children at various educational levels. It appeared that all groups of kids had similar initial experiences of discovery. The children worked first to understand this unknown toy (or system or machine or thing, depending on the different vocabularies kids used to refer to Topobo). Children then worked to put together and assemble parts in a coherent way, and finally tried to program their constructions and test their movement.

Kindergartners generally built static structures, or programmed only one Active. Some kindergartners puzzled over cause and effect with the programming and playback, while others understood the interface and playfully experimented with creations and storytelling. Kindergartners engagement with simple structures suggests that the system indeed has a "low floor," but the second graders were much more deeply curious about the system, at times spending their entire recess working to refine a creation. This leads us to believe that the kinetic possibilities Topobo presents may be best suited for children ages 7 and older.

Compared to the second graders, 8th graders were much more adept at programming subtle physical manipulations and were more successful at controlling movement. However, many students did not discover how to use more than one Active to create a single 2 DOF motion, and as a group, 8th graders seemed less comfortable experimenting with irregular arrangements of Actives than the younger children were. This suggests that children ages 8-11 who are in the process of developing abstract mental models, but still experiment very freely, may benefit most from Topobo.

We tested Topobo with a wide age range to evaluate its capacity to be both accessible and complex to children at widely varying educational levels. Eighth graders compared it to LEGO Mindstorms as a programming tool, and several students suggested that the addition of sensors and environmental feedback would improve the system. Both the second graders and the eighth graders concluded that Topobo was probably designed for their age range. This supports our hypothesis that Topobo can support learners at multiple levels. Vygotsky refers to the "zone of proximal development" [Vyg78] as the optimal learning stage where children are exploring concepts beyond those they would be able to understand independently, but are not dependent on adult support for learning. Our observations that students at multiple developmental levels effectively collaborate with Topobo encourages us that the system may support rich learning experiences during such cognitive transitions. Our findings support our hypothesis that a tangible system can provide both a "low floor" and a "high ceiling."

Topobo Passives and Actives

Our evaluations suggest that children develop affective relationships with Topobo creations and that their experimentation with Topobo allows them to learn about movement and animal locomotion through comparisons of their creations to their own bodies. Eighth grade science students' abilities to quickly develop various types of walking robots suggests that a tangible interface can support understanding how balance, leverage and gravity affect moving structures because the interface itself responds to the forces of nature that constrain such systems.

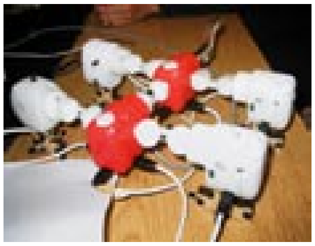
Kindergartners, second graders and eighth graders all related to Topobo models with their "familiar knowledge" about animals and machines. Metaphoric allusions to machines (robotics) and especially to animals ("the elephant," "the ant," "the scorpion," "the horse," "the no-walking man") were descriptive and salient. Many 8th grade students changed their creations based on their ideas about how animals and people move. "We tried to make it walk, but it couldn't balance so we made it crawl. You know, like a baby." One group experimented with creating a "frog" with scalloped legs. Another referenced the coordinated motion of a horse's legs, and another the crawling of a six legged insect. One of the groups explained that when their creation did not work as planned, they thought more deeply and specifically about the animal motion they were attempting to imitate than during the initial drawing of their design. This suggests that the system is meeting the goal to help children use physical models to reflect on their mental models. It also shows how the system has met its goal to help children explore concepts common to the domains of engineering and biology.

The fact that children can learn about the mechanical world through play with Topobo suggests, to a certain extent, the potential for body and ego syntonic learning as described by Papert [Pap80]. We believe that programming Topobo is a body syntonic activity because Topobo's kinematic motion, feedback, and global-local interactions are firmly related to children's sense and knowledge about their own bodies. Topobo my also be somewhat ego syntonic because it is coherent with children's' sense of themselves a people with intentions, goals, desire, likes and dislikes. Evidence that two eighth grade girls, who were among the most skilled Topobo users, wanted to take name their creature, take it home, and keep it like a doll or a pet supports the goal that the system is supporting users' motivation via emotional connection to their work.

Queens

Some students had success using the Queens, while others experienced a level of frustration with them. We believe some students became frustrated with them because using the Queens requires a different cognitive model than using Topobo with direct manipulation. In direct record mode, children focus on relative movement of the Actives, e.g. "how far did the leg move from its static position." However, this conceptual model does not work well with a Queen. Students would often begin by carefully positioning their creation before programming it. But as soon as the student pressed Record on the Queen, the creation would kick wildly out of position as the Actives mimicked the Queen's absolute angular position.

Many students quickly grasped certain abstract systems concepts tangible with the Topobo Queens. One group of 8th graders discovered that they could create two separate networks of legs on either side of an animal, each governed by a Queen. Using this concept, they would be able to program each pair of legs with different motions but the legs in each network would have the same repeated motion. This supports our goal to support conceptual abstraction by embodying abstract concepts in the tangible media.



Backpacks

Our evaluation of the Backpacks took place in a variety of settings with children aged 6-15. We sought to understand how variable control of motion parameters could support children to step back and reflect upon their understanding of their creations' behaviors. We also sought to determine if users could quickly grasp complex ideas related to sensors, control and conditional behaviors.

Studies offered evidence that children as young as seven could understand Backpacks as a conceptual modeling tool for motion. In general, Backpacks describing more concrete observable concepts (Faster-Slower or Bigger-Smaller) were more quickly understood and utilized. Children twelve years and older began to understand the conceptual roles of Backpacks, but needed to deconstruct build creations involving Backpacks in order to successfully decipher and apprehend their effects.

K-3rd graders suggest new backpacks.

Because the Backpacks are more conceptually abstract than the original Topobo system, we found our evaluation results would have been richer and more conclusive if we would have conducted more sessions with the same children, giving them more time to develop a thorough understanding of the Backpacks' potential and complexity. In general, users with more Topobo experience used Backpacks more often and more successfully.

In an interview with Jack, a six year old who had played with Topobo in several sessions over two years, he described that he would like to make his own backpack: one that randomized the motion, making topobo "go crazy." In being able to envision his own backpack, Jack demonstrates that he has conceptually understood the principles behind the Backpacks, as manipulators of parameters of motion that have an adverbial relationship to Active components.

Remix & Robo

Evaluations with 16 users from age 4-adult addressed how Remix and Robo could support (1) more sophisticated functional and social applications of Topobo, (2) support active design iteration and (3) encourage users to reflect upon their ideas by providing global controls and enforcing a physical "stepping back" from one's work. These observations contribute more generally to the goals to support higher degrees of complexity and to provide modular tools that build on the strengths of — rather than interfere with — the less abstract system components.

Users who had developed successful characters employed the controllers in various ways—competition, performance, global controls for investigating physics dynamics—depending on users' personal interests. Some people used Remix and Robo to refine their gestural designs, for instance to create more successful locomotion. Others used the controllers to apply their work to a secondary application domain, such as narrative performance. For most users, the controllers played into people's existing hands-on design process, allowing people to adjust and understand abstract variables for motion, and to reflect on their own design and thinking.

Our evaluation confirmed the design principle that providing tools to control robotic behavior can support children to analyze and refine their designs. All users related to the system first as a building toy and secondly as a robotic vehicle, a character, or a puppet for narrative performance. The introduction of Robo and Remix did not alter the basic character or play pattern with Topobo, evidenced by all users' intense interactions with Topobo prior to employing the controllers.

We observed users physical step back and reflect on their creations, which may indicate that the higher degree of abstraction afforded by the interfaces supported a transition from concrete to abstract representation of knowledge [Ack96]. Users ages 7-adult found Remix and Robo to be an important part of their mastery of new ideas. According to one adult who rapidly learned how to achieve his goals with Topobo, "Robo and Remix show that the system does actually develop with you. Even as you get smarter, you can still learn something with Topobo. [Remix and Robo] are something you use in different ways as you get better at it."

4.3 Informal evaluations via Exhibitions, Workshops and Courses:

We have conducted a series of public exhibitions, workshops and courses with Topobo to roughly gauge children's teachers' and researchers' reactions and interpretations of the system. Although not intended to be formal evaluations, these workshops have refined our understanding of the system, helped guide and inspire its development, and have sparked much of the work outlined in this proposal. The following workshops and courses have been completed:

Courses, workshops and exhibitions
Ars Electronica Gallery installation, OK Centrum, 2005. IVREA workshop, 2005. Cooper Hewitt educator's workshop, 2005. SIGGRAPH etech and educator's forum 2006. MIT teacher education program, workshop of lesson plan writing for new technology, 2006.

4.4 Continuing Studies

I continue to conduct collaborative longitudinal evaluations in 4th grade science classes, high school science and engineering classes, teacher training programs, and after school programs with at-risk and elderly users. In addition, we continue public exhibitions in the U.S., Japan and Austria to evaluate children's and adults' initial responses and uses of the system. These longitudinal studies and exhibitions are intended to evaluate several questions:

Elementary and High School studies

- Will other researchers come to similar conclusions about what children learn with Topobo?
- How is Topobo experienced and used in the absence of trained researchers?
- How do various teachers envision using a system like Topobo for formal education? What does a Topobo lesson plan look like, and how does it compare to lessons from existing educational robotics platforms, e.g. LEGO?
- Can a play-based system like Topobo (as opposed to an engineering-based system like LEGO) be a successful tool in formal education / school environments?

University of Joensuu study

- Will other researchers come to similar conclusions about what children learn with Topobo?
- Is Topobo appropriate for at-risk and elderly users' learning?
- How does Topobo compare to LEGO Mindstorms in an informal, after-school robotics learning environment?

Public Exhibitions in the U.S., Japan and Austria

- How is Topobo experienced and used in the absence of trained researchers?
- How is Topobo experienced in an informal, self-guided educational setting like a science museum?
- Do cultural differences in the U.S., Austria and Japan lead to obvious differences in usage patterns?

SIGGRAPH Educator Programs, 2006-2007:

- How do various teachers and teacher-trainers envision using a system like Topobo for formal education?

Tufts CEEO

- Will other researchers come to similar conclusions about what children learn with Topobo?
- How do various teachers and teacher-trainers envision using a system like Topobo for formal education? What does a Topobo lesson plan look like, and how does it compare to lessons from existing educational robotics platforms, e.g. LEGO?
- Can a play-based system like Topobo (as opposed to an engineering-based system like LEGO) be a successful tool in formal education / school environments?

5. Background and Related Work

Topobo was designed to help both children and adults learn complex ideas about motion in the natural and mechanical world, and explore how a system can span a wide age range of users and complexity of use, thought, and social interaction. To satisfy the design principles of the system, we build a foundation with work from fields of education, toy design, HCI, and robotics.

I begin by placing Topobo in an educational context, considering the educational implications for physical interactivity and historical trends in educational manipulatives. This educational overview will conclude by looking in more detail at how Topobo contributes to recent work in educational toy design. A review of related robotics research will support the technical conception of the project and the functional aspects of the system design.

5.1 An Educational Basis for Tangible Media

Physical manipulatives have an influential role in children's education, and experiences working with physical objects have been shown to be central to a child's emotional and cognitive development [Bro97; Pia76]. Children are already exploring the nature and behavior of the world by interacting with physical tools, and are thus receptive to an open-ended tool like Topobo with which to create metaphors of the natural world.

Topobo can be viewed, in part, as a synthesis of the educational toy curlybot, which records and plays back physical motion [Fre00], the biological building toy ZOOB [Zoo04] and the educational software StarLogo that allows children to create software models of distributed systems [Res94]. All of these systems aim to help children learn by building playful models within constraints specific to different processes. They stem from a rich history of educational toys made famous by Frederick Froebel, who invented Kindergarten and a variety of "gifts" (manipulative toys) with which children can learn through play. Although manipulatives are not ubiquitous in formal education, they have a tradition that can be traced back to the 19th century, pioneered by educators such as Pestalozzi, Froebel, Montessori, and Piaget.

Kinesthesia and Learning

Touch is a central aspect of learning, and the study of kinesthesia focuses on the individual's movement and interaction with physical objects as a means of learning. Researchers in education, developmental psychological and cognitive sciences have found that movement occupies a central position in human activity [Lab75] and it is a central feature of early learning [Pia52]. According to Piaget, sensorimotor experience comprises the principal focus of the infant's early knowledge of the world. The advent of symbolic thought occurs when children internalize sensorimotor experience in mental representation. For example, children build speech on prior sensorimotor knowledge [Pia52]. Similarly, scientists who study the brain have shown that physical experience creates especially strong neural pathways in the brain. When people participate in tactile/kinesthetic activity, the two hemispheres of the brain are simultaneously engaged. This type of learning experience helps assure that new information will be retained in long-term memory [Fur75].

Recent evidence supports the further idea of a separate bodily intelligence [Gar83; Joh87]. Children consolidate their development of bodily-gestural skills through play and games [Bru73], and one can think of children's orchestration of a set of motor skills as bodily problem-solving (i.e. skill connotes knowledge). Bodily-kinesthetic intelligence is comprised of two components: masterful coordination of one's body movements and the ability to manipulate objects in a skilled manner [Gar83]. Kinesthetic knowledge provides conscious appreciation of resistance, position and weight of objects. Kinesthetic memory enables a person think about movement by mentally reconstructing muscular effort, movement and position in space. Since the Topobo system — which couples movement, memory and dynamic balance — is a reflection of the child's own kinesthetic knowledge, play with Topobo may support bodily-kinesthetic learning.

Building Toys

Building toys allow children to explore a certain physical "vocabulary" through physical construction and play and to make certain discoveries through building and experimentation. The popularity of systems like LEGO©, K'Nex©, Lincoln Logs© and ZOOB© in toys stores and in classrooms is evidence of our culture's appreciation for educational manipulatives.

From one perspective, Topobo is a new member of the building toy heritage. The topology of Topobo's physical modeling system as well as some of its conceptual foundation is inspired by the design and dynamics of the ZOOB building toy, which is based on the movement of skeletons and the folding of proteins [Zoo04]. Zoob addressed how modeling and reflexive investigation with a non-computational toy can help people understand dynamic systems. Zoob is very easy to use, and with only five different shaped parts, the system can scale to represent thousands of different kinds of creations. This dual simplicity and complexity helped inspire the physical and interaction design for Topobo. While Topobo lacks the spatial flexibility of Zoob, the system complements a "biological building" activity by also modeling a structure's dynamic motion.

Topobo also facilitates explorations in topology in a different manner than Zoob. While ZOOB was intended to convey some aspects of the nonlinear nature of information behavior, it does not make information behavior manipulable. Topobo is designed to make certain systems concepts more clear with the Queens and Backpacks. These components give children a tool to explore how information can change in a nonlinear system and how simple changes can lead to familiar results (in this case, familiar forms and movements).

Educational Manipulatives

Until the 19th century, the core of the educational process was based upon lectures and recitations. At that time, few people believed that young children were capable of being formally educated. One of the first supporters for "hands-on learning" and the education of children was the Swiss educator Johann Heinrich Pestalozzi who claimed that students need to learn through their senses and through physical activity, arguing for "things before words, concrete before abstract" [Pes03].

Pestalozzi influenced Friedrich Froebel who created the first kindergarten by the year 1837. Froebel's kindergarten was filled with objects—"the Kindergarten gifts"—for children to use and play. These objects were designed to help children recognize and appreciate the common patterns, shapes and forms found in nature [Bro97].

Maria Montessori received and extended Froebel's practices, and later inspired networks of schools in which manipulative materials play a key role. Montessori tried to develop a framework for an "education of the senses," i.e. materials, objects and learning experiences that help children develop their sensory capabilities, control their own learning process and learn through personal exploration [Mon12].

Piaget continued some of this trend by providing an epistemological foundation for these educational ideas. He developed his famous "child's stages of knowledge development" by constructing a particular progression from the concrete to the abstract: children must first construct knowledge through "concrete operations" before moving on to "formal operations" [Pia76]. Piaget showed that the physical environment and objects in it have central roles in a child's cognitive development, being a basis for thought and growth.

LOGO

Seymour Papert, who studied with Piaget before coming to MIT, took Piaget's research into a new direction by using computational tools such as LOGO to reevaluate how concrete operations can open new ways of thinking and learning for children at early stages of development. This perspective gave birth to the constructionist theory of the "child as an epistemologist" who can build his/her own knowledge, and explore the nature of that knowledge, by playing with certain programmable environments [Pap80].

The principles underlying LOGO led to other digital environments and manipulatives designed to engage children in different types of thinking, such as understanding the dynamics of leaderless, rule-based systems. For example, the StarLogo modeling environment was created to give children a tool to model distributed systems like ant colonies that exhibit feedback and emergence, and thus learn about why such systems behave as they do [Res94]. It also encourages an understanding of system dynamics by constructing and observing the behavior of distributed networks. While Topobo does not have the abstraction (and thus conceptual flexibility) of StarLogo, certain types of dynamics and systems concepts are made tangible with Topobo Queens and Backpacks that take advantage of Topobo's physically and digitally embodied parallel processes.

Digital Manipulatives

In an effort to reintroduce tangibility to Papert's vision, Resnick proposed "Digital Manipulatives" that couple digital construction (e.g. programming tools) with physical construction (e.g. blocks). Where wooden blocks allow kids to make towers that fall over, and thus understand static structures and gravity, programmable blocks may allow kids to understand certain systems concepts. As Resnick argues, "children, by playing and building with these new manipulatives, can gain a deeper understanding of how dynamic systems behave... We expect that digital manipulatives will make [feedback and emergence] accessible to even younger students, enabling students to explore these ideas through direct manipulation of familiar physical objects" [Res98].

Tangible Interfaces for learning

Digital manipulatives sought to bring hands-on learning closer to the design of computational behavior. Many examples represented core computational concepts in a way similar to Papert's approach with LOGO. One limitation of this approach is that symbolic (language-based) manipulations are often not the most intuitive way to learn new ideas, and tend to be inaccessible to younger children (under age ten).

A tangible approach can eliminate the distance between physical and computational modeling, and encapsulate physical activities in the tools themselves; children's primary experiences with the computational design process begins as hands-on explorations.

Curlybot coupled input (program) and output (execution) space via programming-by-demonstration [Fre00]. Whereas projects like Logo have successfully allowed children to explore advanced mathematical concepts related to differential geometry, curlybot's physical programming and looping playback were shown to help much younger children (as young as four) experiment with some of these same ideas through a form of "gestural programming." Curlybot lacks the physical "construction" activities that are so common and valuable with educational manipulatives. One of Topobo's contributions to digital manipulatives is its integration of physical and program construction activities, presenting them both as tangible, constructive processes.

5.3 Related robotics research

Various robotics technology allowed us to couple tangible programming and physical output.

Modular, Self-reconfigurable Robots

In order to embed and distribute Topobo's computation and control into the physical building system, we drew from state of the art robotics research and development. Researchers in modular robotics have been working to make a generalized robotic node that can be used to configure robots of varying forms and behaviors. Projects like "Real Molecule" [Kot99] and "PolyBot" [Yim00] draw inspiration from natural systems and provided valuable examples for Topobo's distributed electronics design. While Topobo is not intended to be self-reconfiguring, it is a modular robotic system and thus requires specific design approaches that support modularity such as distributed, scalable sensing and control. However, it is important to note that modular robotic precedents differ markedly from Topobo in intent: reconfigurable robots generally aim to be completely autonomous "smart" machines capable of doing tasks that people can not do, or do not want to do. Topobo is designed to be a medium for thinking that encourages creativity, discovery and learning through active experimentation with the system. This difference is evident in analyzing the design criteria of the systems. For instance, Topobo does not need to have the high degrees of accuracy necessary to create a self reconfiguring robot, nor does the system need to be aware of its own geometry. Conversely, modular robots do not need to be ergonomic nor do they need an intuitive interface for users of the system.

The creators of PolyBot patented several modular toy robot designs that use programming by demonstration for data input [Duf98]. These patents describe several similar systems to Topobo, but the prototypes were never fully designed and implemented as a toy nor were they formally evaluated [Raffle, personal communication]. Furthermore, these systems use centralized control even when they function independently of a PC [Duf98]. Decentralized control — and thus, both physical and computational modularity — was an important design criteria for Topobo and is a unique contribution to a modular robotic toy.

Passive Dynamic Robots

Walking robots constructed with Topobo share physical simplicity and local-global dynamics that have been explored by researchers in passive dynamic robots. Researchers in passive dynamic robots aim to deduce the physically elegant designs that can lead to walking robots that require minimal energy input [Col98; Rui04]. Like some Topobo walking creations, these robots combine falling and inverse-pendulum dynamics that are prevalent in ambulatory systems.

Programming by Demonstration: "Record and Play"

Like curlybot, Topobo uses robotic "programming by demonstration" to make the programming activity physical. Other, earlier precedents for robotic programming by demonstration are prevalent in the robotics communities. Researchers in robotic artificial intelligence have for some time used techniques of programming by demonstration to input motions in multiple degrees of freedom. For instance, with the help of a human hand a robot can be taught to pick up a cup [Col98]. Similarly, in manufacturing, an assembly line robot is sometimes physically given endpoints for its trajectory and is then allowed to calculate the optimal path between points. If there are obstacles for the robot to avoid, additional points can be added to obtain the desired trajectory [Tan79]. Like Topobo, these systems use physical input for motion data, sometimes called "physical programming."

Robotic Control Techniques: Beyond Record and Play

Backpacks, Remix and Robo are specially designed to step beyond many limitations of the "record and play" programming model. Systems that employ record and play have been argued to be more experiential in nature and more intuitive for users than other programming paradigms [Ack99, Fre00, Ryo04]. However, since decoupling the physical and symbolic models results in systems that have no clear "handles" to edit the programs, interfaces for manipulating the programs' dynamics are not obvious. This absence of an interface to play with the programs means that children have fewer tools to understand the program's roles in determining the overall system behavior. A question has remained: how can we create digital manipulatives that retain the immediacy and emotional engagement of record and play and incorporate some of the flexibility and sophistication of control structures, feedback and parameterization of data, all concepts that are part of a traditional programming paradigm?

Backpacks introduce the idea of the local and global variable. By playing with Backpacks, children can experiment with conditional behavior, feedback and explore the roles of intangible motion parameters like phase shift, ideas that are usually part of a traditional programming paradigm. Other researchers developing digital manipulatives have built systems that are physical instantiations of mathematical, programming, or dynamic models. For instance, Wyeth's Blocks [Wye02] makes simple conditional behaviors tangible through a series of blocks, and Flow-Blocks [Zuc04] make dynamic systems models tangible and manipulable. Such systems make feedback, conditional and other complex system behavior tangible and are developed primarily to help children manipulate abstract ideas. In contrast to record and play systems, which are broadly described as expressive, the former instances are more abstract representations that follow a more experiential model [Mar03, Zuc04].

Researchers developing more expressive interfaces have conceived of some modular extensions to introduce ideas about conditional behavior to a record and play paradigm. Frei suggested a simple switch for conditional behavior [Fre00] in which a primary motion is recorded, and then a secondary motion is programmed after touching the switch. Subsequent touches to the switch will toggle between primary and secondary motions. This binary state switch is an interesting idea that could be applicable to a system like Topobo, especially because it would result in complex local-global interactions. While this design introduces a hidden state that may be confusing, binary state change may an accessible way to work with multiple recordings.

Other domains have sophisticated tools to manipulate time-sampled data sets. Dataflow models like MAX/msp allow users to design and apply modular filters (small computer programs) to their recordings. Program structures are represented graphically and topologically and the system shares design characteristics with Backpacks, because filters are applied directly to the graphical programs and their effects can be experienced in real time. People have applied MAX/msp to audio, video and robotics, and the "dataflow" programming paradigm suggests interesting GUI extensions to the Topobo system [Dat07, MAX07].

Dataflow models are one approach to linear systems, which are more broadly used by researchers in many domains [Rao04]. Robotics researchers routinely use linear systems to model and understand the dynamics of their creations, and the principles that Backpacks represent tangibly are symbolically manipulated in their mathematical and programmatic models.

Linear systems have also been used in graphical simulation of kinematic structures. Sims' evolved virtual creatures [Sim94] employed directed graphs, a form of dataflow model. Sodaconstructor [Sod07] is a popular online GUI modeler for creating "walking" creatures that respond to a simulated physics environment (figure 12). Thanks in part to its wide distribution over the internet, a large Sodaconstructor community has explored the roles of frequency, amplitude and phase in simulated locomotion of graphical models.

Other GUI learning tools like Starlogo [Res94] have allowed children to explore the ways local and distributed rules can lead to surprising system behaviors. We have made a few of these principles tangible with the Distributed Backpacks, although this conceptual domain is rich and may suggest future work in tangibles.

Many theories about phase shift and oscillations that come from biological systems, such as central pattern generators (CPGs) [Ijs98], are related to the concepts we present here. Specifically, researchers in modular robotics [Kam04, Yim00, Zha03] have explored the roles of phase, amplitude, frequency and orientation in determining their robots' dynamics. In some cases distributed algorithms similar to the Distributed Backpacks have been employed to create wheels, snakes and walking creatures [Zha03]. Our work intends to make these advanced ideas tangible and manipulable by younger students.

From a design perspective, my approach is consistent with Full's argument [Ful98] that "preflexes" play a large role in the locomotion of simple animals like crabs or cockroaches. These creatures, and robots like them, exhibit behavior that may come largely from the interrelationships between an animal's morphology and its control system. In his robotics work, Full places great emphasis on developing the physical and control systems in parallel, which my work also emphasizes.

6. Resources

The majority of the technology and collaborations for this thesis have been either completed or begun. Therefore, no additional resources will be necessary to complete the work outlined herein. This work has been conducted with funds from the following sources:

6.1 Equipment

Basic system design and development
ML / TMG funding (TTT consortium, LEGO Group)

Manufacturing
iCampus student grant, 2005: $42,000 used for production manufacturing stage 1.

Protobo and other experiments
ML and CSAIL funding. KIGS exhibition loan of $20,000 permits manufacturing stage 2.

6.2 Personnel

Ongoing projects rely on the continuing collaboration from researchers or teachers.

Studies at Brookline High
Amanda Parkes, High school teachers Catherine Wolf, Matt Giunta

KIGS show
Amanda Parkes, KIGS staff

Shady Hill School
4th grade science teacher (Jeanne McDermott)

Joensuu study
Marjo Virnes and students

CEEO study
CEEO staff, Elissa Milto

Protopobo
Jonathan Bachrach, CSAIL

7. Timetable

I plan to complete the dissertation defense by December, 2007.

7.1 Summary of proposed research

This work extends the core of my Master's Thesis, for which I developed and tested the basic Topobo system in collaboration with Amanda Parkes. This Ph.D. focuses on reaching beyond the limitations of the original system, so that the tangible interface remains relevant to users as they develop. This investigation includes evaluations of the system's impact to children in a variety of environments. The system components have been evaluated individually and together at periods spanning the past four years. Additionally, Distribution of Topobo system to teachers, scientists and educational researchers at elementary schools and university research labs, and collaborative design of research programs, is complete. All proposed research is scheduled to be completed by September 1, 2007.

7.2 Technical implementations

The following research has already begun (*or has been completed):

Topobo system*
Backpacks*
Remix*
Robo*
TeleTopobo
Protopobo
Mass production of Topobo system, round 1* and round 2.

7.3 Studies

Short term Public exhibitions / evaluations:
ARS Electronica Museum (2 year ongoing installation)
ArtBots (completed) *
NextFest (completed) *
KIGS exhibition (Japan) 3/07-8/07

Short Courses and workshops:
IVREA workshop, 2005 *
SIGGRAPH etech and educator's forum 2006*, 2007
Cooper Hewitt educator's workshop, 2005*
MIT teacher education program, workshop of lesson plan writing for new technology, 2006*

Longitudinal studies:

CEEO — to be completed 8/07
Joensuu study — to be completed 8/07
Brookline High — to be completed 6/07
Shady Hill Elementary School (4th grade science) — to be completed 6/07

7.4 Schedule

July, 2007

Complete production round 2.
Test protopobo with demo applications of distributed algorithms
Thesis chapters 1-3 complete (Intro, Background, System design)
Compile research results from Brookline High and Shady Hill Elementary Schools

August, 2007

Analyze results from Joensuu, KIGS studies, SIGGRAPH 2007
Finish writing chapters 4-10 of thesis (pedagogy, evaluations, technical implementation, computational abstraction of a tangible system (Protopobo), other applications of tangibles for kinetic design and learning, What's Next: applying the "Topobo Approach" to other tangible systems)

September, 2007

Submit Thesis first draft to thesis readers

October, 2007

Address committee comments to first draft
Submit Thesis second draft to committee for review

November, 2007

Thesis defense

December, 2007

Address committee comments on second draft
Address committee comments on thesis defense
Submit final thesis

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