Topobo:
A Gestural Design Tool with Kinetic Memory

Amanda J. Parkes

B.S.E. Product Design Engineering
B.A. Art History
Stanford University, 1996

Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning,
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Abstract

The modeling of kinetic systems, both in physical materials and virtual simulations, provides a methodology to better understand and explore the forces and dynamics of our physical environment. The need to experiment, prototype and model with programmable kinetic forms is becoming increasingly important as digital technology becomes more readily embedded in physical structures and provides real-time variable data the capacity to transform the structures themselves. This thesis introduces Topobo, a gestural design tool embedded with kinetic memory- the ability to record, playback, and transform physical motion in three dimensional space. As a set of kinetic building blocks, Topobo records and repeats the body's gesture while the system's peer-to-peer networking scheme provides the capability to pass and transform q gesture. This creates a means to represent and understand algorithmic simulations in a physical material, providing a physical demonstration of how a simple set of rules can lead to complex form and behavior. Topobo takes advantage of the editability of computer data combined with the physical immediacy of a tangible model to provide a means for expression and investigation of kinetic patterns and processes not possible with existing materials.

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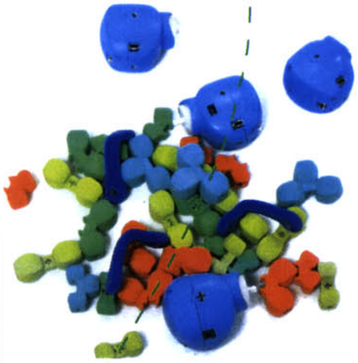
Chapter 1
Introduction

The Tangible Media Group at the MIT Media Lab is pursuing a research vision called “Tangible Bits” with the goal of extending access to computation beyond a traditional graphical user interface (GUI), consisting of a keyboard, mouse and screen, to interfaces that use physical objects as tangible embodiments of digital information. The concept of “Tangible User Interfaces” seeks to take advantage of people’s existing skills and bodily knowledge for interacting with the physical world and provide interfaces which allow users direct control of computation through the manipulation of physical objects. Transparency to the intangible world of digital information thus becomes possible through familiar tools and actions of the hand and body.

The development of Tangible Interfaces builds on the premise that hands have long been considered an important player in the human creative, thinking, and learning process, as Malcolm McCullough comments, “Human beings like to make things: they like to use their hands at least as much as their brains;...If we are to tap the increasing visuality and dynamics of computing in order to open new realms of abstraction, we should depend very much on these human traits to do so” [McCullough 1996]. The relationship of hands and computation



has been more formally addressed by the concept of Direct Manipulation, first coined in 1983 by software engineer Ben Shneiderman and later researched in depth by George Fitzmaurice. He argues that "improving the 'directness' and 'manipulability' of the interface can be achieved by improving the input mechanisms for graphical user interfaces" [Fitzmaurice 1995]. The principles of Direct Manipulation have greatly informed the development of Tangible User Interfaces as they work to achieve such manipulability by integrating the input and output spaces, implying a physical manipulation of the digital data itself.

The application of Tangible Interfaces to computational simulations of complex systems has emerged as an important area in Tangible Media research. They provide an appropriate application for modeling system behavior because using tangible representations (objects) as parameters in a complex system creates a bridge to the physical world and can allow the interaction between complex parameters in a simulation to be more easily manipulated and understood. This ability to provide better understanding relies on the coincident input and output space of information and control, and often times, the synchronous input and output timing as afforded by Tangible Interfaces.

1.1 Why Kinetic Modeling?

As a methodology for learning and design, model-making in both physical materials as well as computer simulations can be seen as systems to understand and represent the world. Model making is a prevalent activity in education that ranges from kindergartners' experimentation with wooden blocks to college physics students' computer simulation of material stress and strain as well as design for professionals. Model making employs the hands and body in the creative process and allows rapid experimentation with a system to understand its limitations.

For the most part, however, the modeling of kinetic systems has been constrained to on-screen simulations. The need to experiment, prototype, and model with programmable kinetic forms is becoming increasingly important as digital technology becomes more readily embedded in physical structures and provides real-time variable data the capacity to transform physical structures themselves. From biologically inspired simulations on the micro-scale to the understanding of dynamic systems on a human scale to the emerging idea of architecture as programmable construction machines, [Snoonian 2002] the creation of a computationally augmented physical design tool which captures motion and gesture brings kinetic simulation into the physical world and increase our capacity to learn and design through the model-making process.

The development of a fundamental kinetic building block embedded with computation and networking capabilities functions as a material extension to physically mimic the body, building on these dissections of gestural movement into a static medium, to create a three-dimensional dynamic mechanization. Such a system takes advantage of the combination of the editability of computer data and the physical immediacy of a tangible model and provides a means for expression and investigation of patterns and processes not possible with existing materials.

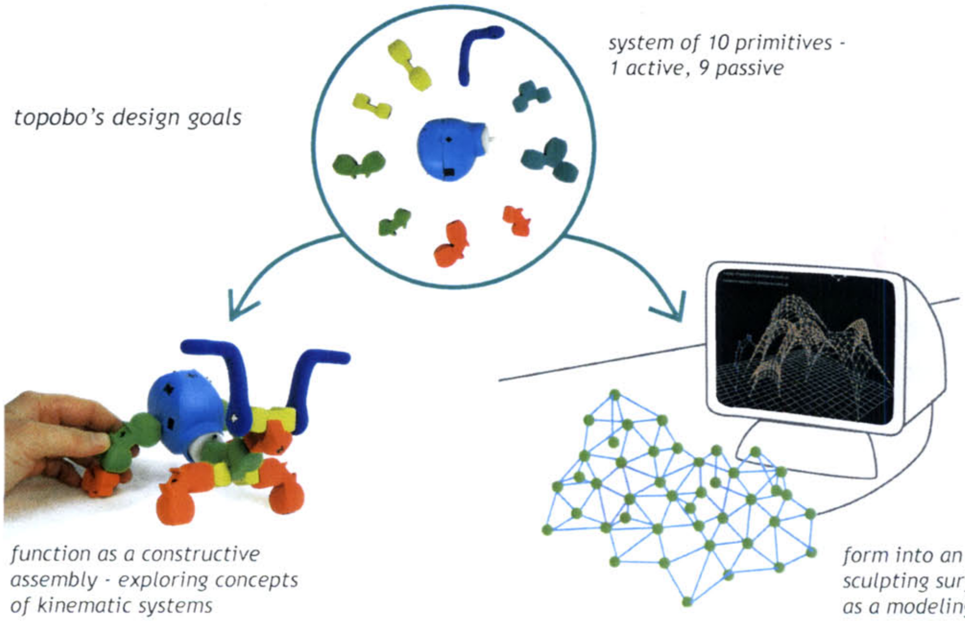
1.2 The Topobo System

The Topobo system presented in this thesis is an actuated 3D modeling system that can configured in a variety of formations and then physically programmed to move. The name Topobo is derived from topology, botanical, and robot and the system functions like a set of motorized building blocks with the ability to record and playback physical motion. It is comprised of ten different primitives which connect to each other in multiple orientations. Nine of these primitives are called "Passive" because they form static connections (four of the geometries occur in two different scales). One "Active" primitive is built with a motor and embedded electronics and when joined together, the Actives create a decentralized peer-to-peer network.

Special orange Actives called "Queens" provide a means for centralized control by commanding other Actives to copy their motion. In addition, special pieces called "backpacks" can be attached to an Active to modify its motion. The combined functionality of Queens and backpacks creates the capability to pass a behavior with a transforming variable through the system, presenting a means to represent and understand mathematical based simulations in a physical material. This can demonstrate physically how a simple set of rules can lead to complex form and behavior. In addition, the system has been developed to function autonomously (as a constructive digital manipulative), or as connected to a PC with a variety of applications as a kinetic interface.

The Topobo system was originally conceived of with two design goals which on first consideration from may appear somewhat divergent in nature - designing a constructive assembly that could be used to model and experiment with dynamic motion and form, and designing an actuated surface which could serve as a modeling tool and interface to an on-screen 3D modeling environment. These two approaches overlap, however, in a basic functionality of supplying the ability to sculpt and replicate motion in three dimensional space. The system

topobo's design goals



system of 10 primitives - 1 active, 9 passive

function as a constructive assembly - exploring concepts of kinematic systems

form into an actuated sculpting surface - used as a modeling tool derives its strength and versatility in the development of a fundamental unit of kinetic memory which could serve both purposes. In the pursuit of these two goals, we were naturally influenced by diverse fields - research in human computer interaction; the design process (and design tools); materials and methods for artistic expression; and educational and learning theories. We believe the convergence of these influences has placed Topobo in a unique application space within the realm of digital technology.

1.3 Specificity vs. Generality of computational tools

Although building on the Tangible Interface tradition of creating tools for modeling simulations, as a project Topobo marks a shift in form of the tools created. Many of the past Tangible Interface projects which modeled simulations utilized a more generalized 2D platform, such as the Sensetable [Patten 2001]. The Sensetable provides a non-specific table top with 3D objects (pucks) in a generalized/abstracted forms which could represent any variety of specific digital data. This is certainly an appropriate approach for simulations of systems involving complex abstract data structures. The three dimensional design of Topobo, however, is distinctly linked to its functionality as a kinetic recording tool, and thus is very specific in form. Because Topobo attempts to mimic and respond to natural physical systems, its form is also modeled on biological yet regular structures. As an autonomous object embedded with computation, Topobo seeks to represent its specific digital functionality through its form as well as its behavior.

Designer and HCI visionary Bill Buxton comments on the designer's role in choosing the appropriate form for a computational tool just as they would choose the form of any other tools through a metaphor comparing desktop computers to multi-functional "super-appliances." "It is as inappropriate to channel all of one's computational activities though a single "workstation" as it is to try to build a desk with a Swiss army knife. Even if all of the needed tools were collected in the knife, they are still more effective when they are not integrated into a single package" [Buxton 2001]. In the design of Topobo, we have chosen a single specific function, gestural recording, embodied in a very specifically defined form, with the intention of creating a clearly defined tool whose ergonomics and aesthetics serves to compliment and delineate its functionality.

1.4 Thesis Structure

This thesis is divided into six remaining chapters:

Chapter 2 **Background and Related Work**
describes related background work from a variety of disciplines, both conceptual and technical, which have influenced the development of Topobo.

Chapter 3 **System Design**
provides a detailed description of the Topobo system design from initial guiding design principles to prototyping phases through to its current state being manufactured in a small run.

Chapter 4 **Topobo in Action - Evaluation in the Classroom**
discusses our studies with children in classrooms using Topobo as a physics teaching tool.

Chapter 5 **Virtual System Extensions and Applications**
describes connecting Topobo to a GUI and its potential applications to expand the learning process with Topobo

Chapter 6 **From Constructive Assembly to Meshed Surface**
describes initial investigation and potential applications of constructing the Topobo primitives into an actuated meshed surface

Chapter 7 **Conclusion**
offers concluding thoughts and presents Topobo contributions in three contextual frameworks.

The term "we" in this thesis refers to Hayes Raffle, another research assistant in the Tangible Media Group, and myself, as the process of designing and building Topobo has been truly collaborative throughout.

Chapter 2

Background & Related Work

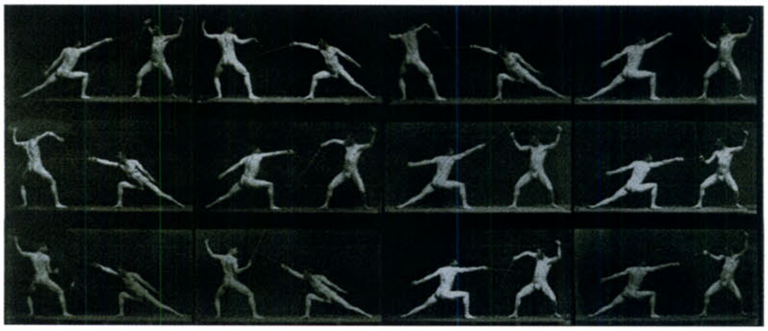
Designed to be a flexible tool, Topobo naturally draws inspiration from a broad combination of disciplines- Tangible Interfaces, education and learning theory, robotics, haptics, biology, and kinetic art and architecture. Conceptually, it builds on a range of twentieth century investigations into the visualization and mechanization of motion and gesture, both artistic and industrial. Its physical form and dynamic behavior derive from forms and growth patterns in nature. As an educational tool, it draws on the development of educational manipulatives and the learning theories behind them to emerge as part of a new class of digital manipulatives- a blending of the tradition of educational manipulatives [Brosterman 1997] and tangible interfaces [Ishii 1997], which bring access to the complex and temporal processes which computers describe well.

The formulation of Topobo to function as a GUI peripheral or actuated surface, draws on several existing systems which have investigated the concept of using a physical gesture or surface as a input or output device to a virtual environment. Technologically, Topobo's distributed electronics design and actuation draws inspiration from modular robotic systems and existing haptic and tangible interface projects.

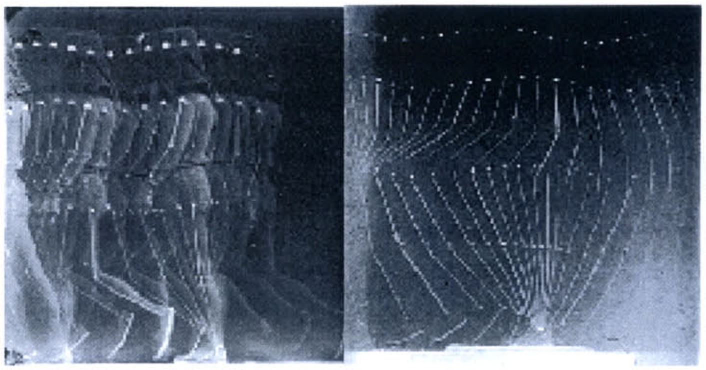
2.1 Kinetic memory - Representation and Mechanization

Kinetic memory, the notion of capturing and recording gestures, has been examined historically by experiments in late nineteenth and early twentieth century art, photography and studies of industry efficiency. With the dawning of the industrial age of the twentieth century, artists sought to incorporate many of the characteristics of the highly mechanized society around them, using and celebrating the visual language of the engineer. These experiments provide examples of a mechanized deconstruction of natural motion through translation into two-dimensional or three-dimensional static visualizations. Topobo draws on these studies in examining methods to represent kinetic data as recorded by the human body.

Early two-dimensional studies which reflect the notion of kinetic memory began with the photographs of Eadweard Muybridge in the late nineteenth century. For the first time, Muybridge was able to divide a segment of time into numerous consecutive stop action photographs, recording the motion of an animal or human in a series of images. Soon after, French physiologist Etienne-Jules Marey developed chronophotography, "inscription of time by light" in which consecutive images of a figure in action were superimposed, showing different states of movement in one image [Mandel 1989]. He performed many studies by photographing humans in motion clothed all in black except for metallic strips outlining the arms and legs. The effect was an illusion of overlapping stick figures in successive phases all in one picture, abstracting the human form into a mechanical model.



Eadweard Muybridge, Fencing. 1887

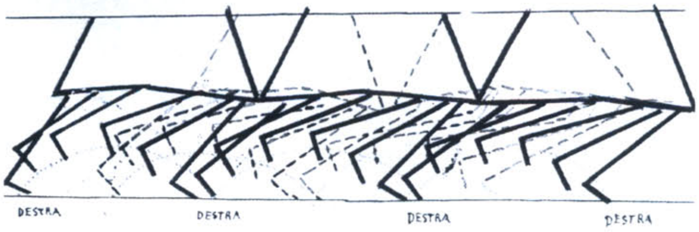


Etienne-Jules Marey, Man in a black costume with white lines and dots, 1886.

Marey's chronophotographs influenced the work of artists that followed as they explored dynamic representation. In 1912, Marcel Duchamp painted *Nude Descending a Staircase* which he described as "not a painting but an organization of kinetic elements --an expression of time and space through the abstract presentation of movement," [Popper 1968] reflecting simultaneous views of a figure in space.

The Italian Futurist Movement also investigated multiple representations of a moving figure both in two dimensional drawing and paintings as well as three dimensional sculpture. Conceptually, the Futurists were searching for a representational strategy to symbolize power, progress and mechanization and they produced an artistic vocabulary charged with motion and speed, as Balla stated, "All things move, all things run, all things are rapidly changing. A profile is never motionless before our eyes, it constantly appears and disappears. On account of the persistency of the image on the retina, moving objects constantly multiply themselves: their form changes, like rapid vibrations in their mad career.

Marcel Duchamp, Nude Descending a Staircase No.2, 1912

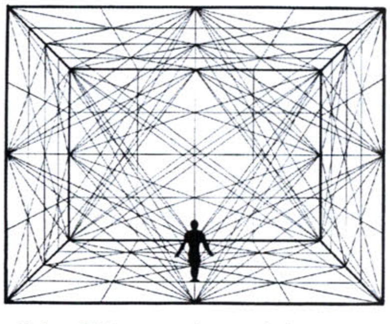


Giacomo Balla, Girl Running on a Balcony, study, 1912

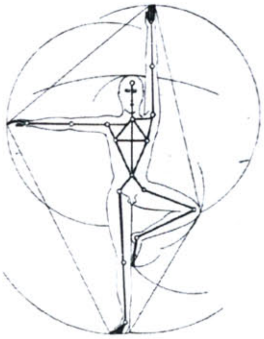
Giacomo Balla, Abstracted Speed, 1913

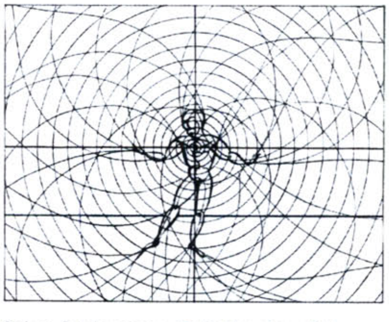
Thus, a running horse has not four legs, but twenty, and their movements are triangular" [Tisdall 1977]. The Futurists drew no aesthetic distinction between representations of human or animal motion and those of machines or mechanized motion. Every object moving in space could be defined by its "force lines," the tracings of physical presence which reflect the objects emotive dynamism.

A different approach to gesture and mechanization was investigated by Oskar Schlemmer in the 1920's at the Bauhaus. The German design school sought a new synthesis between art and modern technology by employing an industrialized aesthetic based on the study of the biological facts of human form [Gropius 1961]. As director of the Bauhaus Stage shop, Schlemmer expanded his work as a sculptor to design for the theatre - design for movement of intercommunicating parts in three dimensional space. In the process he created a new understanding and delineation of human motion and gesture. Schlemmer sought to deconstruct the motion of the body in three dimensional space by each gesture or motion being dissected into a unique "sphere of activity" to create the laws of motion of the human body in space. This serves to abstract the human body into what he refers to as a "technical organism" [Gropius 1961]. The technical organism can then be rationally defined by its relationship to the space around it, its environment, "The laws of cubical space are the invisible linear network of planimetric and stereometric relationships. This

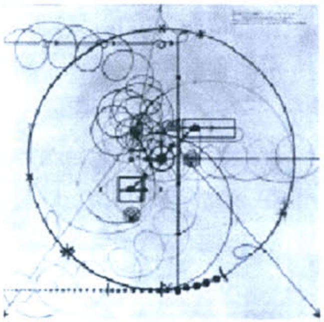


Oskar Schlemmer, Laws of the human body in cubical space

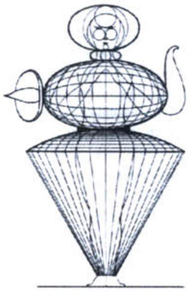




Oskar Schlemmer, Calisthenics of the human body



Oskar Schlemmer, Diagram of a Gesture Dance - giving a linear indication of the paths of motion



Oskar Schlemmer, The laws of motion of the human body in space with the various aspects of rotation, direction, and intersection of space: the spinning top, snail, spiral, disk. Result: a technical organism.

mathematic corresponds to the inherent mathematic of the human body and creates its balance by means of movements, which by their very nature are determined mechanically and rationally." [Gropius 1961]. Dissecting the range of motion of each limb can be seen as corollary to dissecting the range of motion on each individual Active in a Topobo creation. Together they represent a unified fluid motion, individually a mechanically abstracted one.

Outside of the realm of the arts, Frank and Lillian Gilbreth studied human motion for the purpose of increasing industrial efficiency. They created photographic and three dimensional models of the paths of human motion from which they derived the principles of human economy [Mandel 1989]. For their studies, they developed the process of stereo chronocyclegraph (time-motion-writing) in which small electric lights, blinking twenty times a second were attached to a subject and one cycle of the worker's motions were photographed in a darkened

Frank Gilbreth, Stretched Chronocyclegraph of the Motions of a Girl Folding Handkerchiefs, n.d.

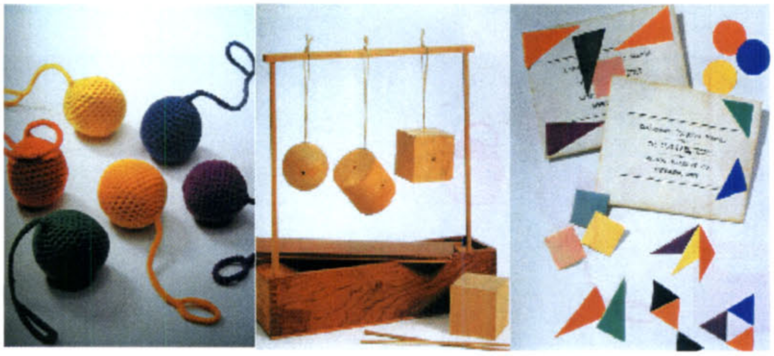
Frank Gilbreth, Making a Wire Model of Motion, n.d.

studio. The distance between the light tracings revealed changes in speed and hesitations and a type of two dimensional motion portrait was produced. The Gilbreths also sculpted wire motion models based on the form of the chronocyclegraph so that the correct movements could be more easily visualized.

2.2 Educational Manipulatives

As an educational tool, Topobo can be viewed in the context of an emerging new class of "Digital Manipulatives" [Resnick 1999] which embeds computation into familiar physical systems to enhance learning and thinking. Digital manipulatives are intended to be easy to use and to improve access to many of the complex and temporal processes that computers describe well, seeking to make accessible concepts that are currently considered too advanced for children at a certain age [Resnick 1999]. The development of digital manipulatives builds on the idea of using manipulative materials in education, a tradition started in 1837 by Friedrich Froebel, inventor of the "kindergarten gifts," a set of objects which were designed to facilitate learning by helping children appreciate common patterns and forms found in nature [Brosterman 1997].

Froebel was influenced by Swiss educator Johann Heinrich Pestalozzi who argued that the best way to learn was through senses and physical activity. This idea was later built on by Jean Piaget who developed the "child's stages of knowledge," an epistemological framework which posited that children must first construct knowledge from "concrete operations" which can then lead to an understanding of the abstract [Piaget



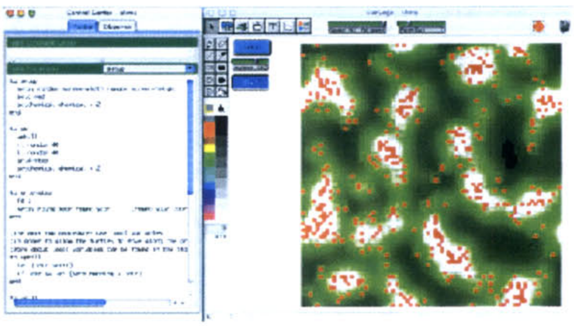
Friedrich Froebel's kindergarten gifts - using physical objects to teach children about forms and process of the natural world

1976]. At MIT, Seymour Papert, who had studied with Piaget, began to experiment with using computational tools like the programming language Logo to expand upon Piaget's theory of how concrete operations could advance thinking and learning for young children, a concept he coined "body syntonic learning" [Papert 1980].

Mitchel Resnick and the Lifelong Kindergarten Group at the MIT Media Lab have been instigators in the development of digital manipulatives by combining the flexible computational language LOGO, into the LEGO building system, creating the "Progammable Brick." Resnick describes how digital manipulatives can enable children to explore a new set of concepts, "children, by playing and building with these new manipulatives, can gain a deeper understanding of how dynamic systems behave...computation and communication capabilities play a critical role: they enable physical objects to move, sense and interact with one another - and, as a result, make systems-related concepts more salient to (and manipulable by) children" [Resnick 1999]. Their work became the basis for the commercially available toy LEGO MIndstorms, which allows users to build robotic creations out of LEGO bricks which can be programmed with LOGO in a GUI environment.

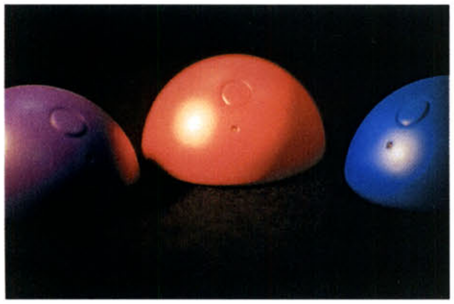
Mitch Resnick, Programmable Brick - an early digital manipulative

Dynamic system simulation was also investigated at length by Resnick with the StarLogo modeling environment [Resnick 1998]. StarLogo was created to give children a tool to easily model distributed systems like ant colonies that exhibit feedback and emergence, and thus learn about why such systems behave as they do. StarLogo also encourages an understanding of system dynamics by constructing and observing the behavior of distributed networks, an objective we aimed to do physically with Topobo.



StarLogo screen based modeling environment for dynamic system simulation

All the work done by Resnick and the Lifelong Kindergarten Group requires programming of behaviors to be done with a GUI interface. With the development of Topobo we sought to move



Phil Frei, curlybot, 2000 - inspired Topobo's single button tactile programming interface

away from this paradigm. The idea of tactile programming, providing Topobo with coincident input/output space, derives from the educational toy, curlybot [Frei 2000]. We chose to mimic curlybot's technique of physical programming-by-example because it is intuitive for young children to use. Physical programming also results in natural looking, emotionally engaging motions because they are the reflection of the user's own body movements. A coincident input/output space is also a computationally simple approach to composing motion for complex multiple degrees of freedom structures compared to traditional inverse kinematics techniques.

Another important influence in the realm of educational manipulatives comes from my own past experience developing interactive exhibits at the San Francisco Exploratorium, the museum of science, art and human perception. The Exploratorium has built a reputation for innovation in exhibit interactivity and for its ability to teach through stimulating visitors' curiosity about the world around them and using the concept of familiarity to facilitate an understanding of difficult scientific concepts. Yet this innovation has been primarily in the mechanical realm. In many cases, I encountered concepts which could have been enhanced by incorporating computational elements, however was frustrated by the lack of available tools to link digital data to an exhibit's physicality, so crucial to successfully conveying its content. As an exhibit developer, I came to understand the importance of the relationship of the physical/mechanical form as an intermediary between our bodies (and body syntonic learning) and the concept being demonstrated. The Exploratorium's many examples of using simple models and machines to teach children complex kinematics concepts has helped guide the design of Topobo.

the ZOOB® system - for modeling biological growth and movement

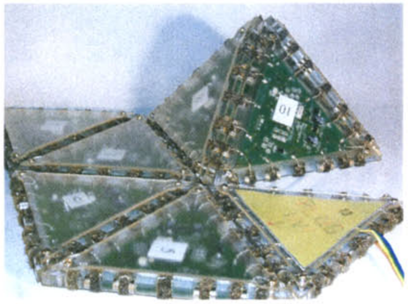
The mechanical design of Topobo is inspired by the design and dynamics of the ZOOB® building toy, which is based on the movement of skeletons and the folding of proteins. Topobo complements this type of building activity by also modeling a structure's dynamic motion.

2.3 Physical /Virtual tools

Sensing Geometries

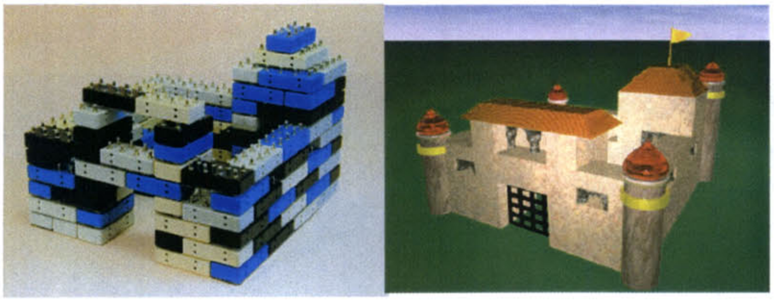
In addition to serving as a digital manipulative for learning about kinematic systems, Topobo was also planned to function as an input/output device to a GUI interface. Our system design choices were informed by several existing physical/ virtual systems which have investigated the concept of sensing the geometry of 3D forms, or using a physical gesture or surface as a input or output device to a virtual environment.

The project Triangles [Gorbet 1998] developed by Matt Gorbet and Maggie Orth at the Media Lab in 1998 is a physical computer interface in the form of a construction kit of identical, flat, plastic triangles, each with a microprocessor inside. The Triangles connect together both physically and digitally with magnetic, conducting connectors. When the pieces contact one another, specific connection information is sent back to a computer that keeps track of the configuration of the system. Users can build both two and three dimensional structures and patterns. The Triangles system provides a model of physical embodiment of digital information topography, informing the physical networking criteria of Topobo.



Triangles, Gorbet and Orth, 1998 - 3D physical arrangement of the pieces is sensed and appears on-screen

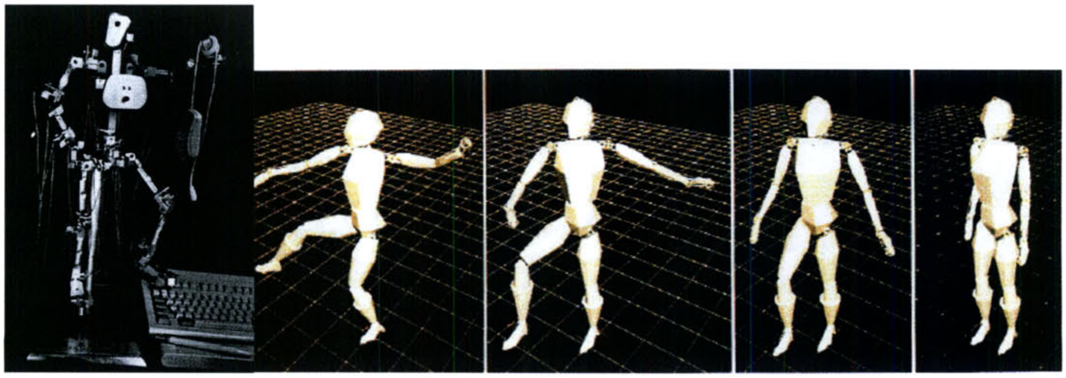
A project executed at the Mitsubishi Electric Research Lab entitled *Tangible Interactions and Graphical Interpretation* [Anderson 2000] investigates many of the issues addressed in Triangles, but functions as a more representational



MERL Tangible Interactions and Graphical Interpretation, Anderson, 2000 - structure built of bricks (left) is sensed and interpreted on-screen as image on right approach to 3D modeling. The system uses building blocks embedded with computation whose geometry can be sensed to appear as a virtual model in a GUI. The system employs simple mechanical/electrical connectors modeled on LEGO connections which allows for an asynchronous, distributed communication system (a common bus linking all the blocks). The computation of the overall structure, however, is parallel and distributed to allow for a reasonable time of computation of a model including up to five hundred blocks. The block structure is then interpreted by the system to be represented on screen as a building where different elements-- walls, roofs, windows-- have been identified and graphically detailed.

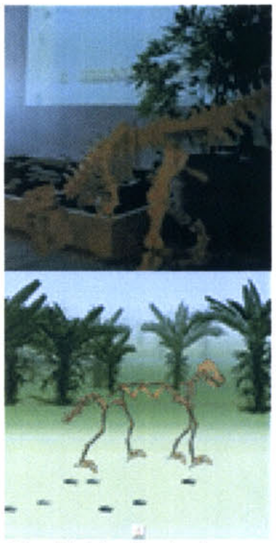
Sensing Gesture

Projects such as Triangles or the MERL Bricks involve sensing the geometry of statically rigid structures however lack a real time physical interface for detecting moving pieces. A separate class of projects, track the movements of physical input devices based on animal models to generate animations. The Monkey [Esposito 1995] is a specialized input device for virtual body animation. It resembles a mechanical mannequin with articulated limbs and joints. Instead of constructing a simulation of human animation and locomotion using a screen interface, the user poses and moves the Monkey to define a character's animation. The Monkey itself does not have actuated elements, but is manually manipulated to position the body into key frames for a sequence.



The Monkey, Esposito, 1995 - physical model for manipulation (left) and on-screen representation (right)

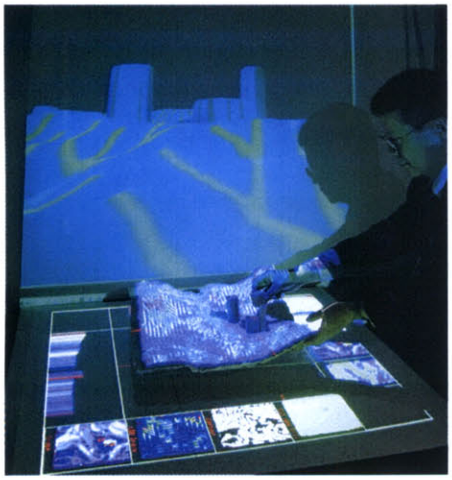
Dino Stable, a project conducted by Carol Strohecker in the Everyday Learning Group at Media Lab Europe also utilizes a physical skeletal model to construct a virtual model on screen for animation. Dino Stable is a learning environment for experimenting with principles of motion, in particular the role of center of mass in balancing. Players unearth skeletal parts tagged with radio-frequency ID tags for assembly of animistic creatures which are then sensed as on-screen creations. Based on a constructed creature's number of legs, the location and mass of its center, and a selected speed of movement, the software analyzes whether the creature can balance as it moves - either it goes forth to frolic or collapses. Animations include a rich set of gait patterns deriving from literature on biomechanics and animal locomotion.



Dino Stable, Strohecker, 2003 - physical model (top) is tagged to be sensed as part of on-screen creation (bottom)

Surfaces

Beyond its usage as an actuated constructive assembly, one of the original conceptions of Topobo is to construct the elements into an actuated meshed surface. We examined several systems which investigate physical/virtual surface modeling tools, both with and without actuation. Illuminating Clay, [Piper 2002] a project designed by Ben Piper and Carlo Ratti at the MIT Media Lab as a landscape design tool. It uses inert clay as the interface and external sensors and a projector to create a coincident input/output space. Users of the system alter the topography of a clay landscape model while the changing geometry is captured in real-time by a laser scanner. The geometry is then analyzed by a library of landscape functions and results are projected back in

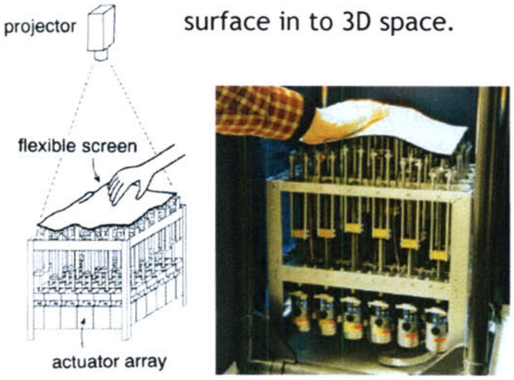


Illuminating Clay, Piper, 2002 - real-time computational feedback is projected onto a clay surface as it is manipulated real-time onto the surface model. Illuminating clay provides the physical affordances of real clay, but does not contain a mechanism for the computer to change the physical interface based on the data, the interaction loop is one-directional. Topobo aims to provide a physical sculpting medium that is bi-directional: a user can manipulate a form, and a computer can give computational feedback by manipulating the form.

While Illuminating Clay provides visual computational feedback to three dimensional surface topology but with no means to physically change the output surface, the Actuated Workbench [Pangaro 2002] investigates planar actuation in a two dimensional surface. The Actuated Workbench uses an array of electromagnets embedded in a table to physically manipulate the input devices (pucks on a table top) to express computational output. The addition of actuation to an interface allows the computer to maintain consistency between the physical and digital states of data objects.

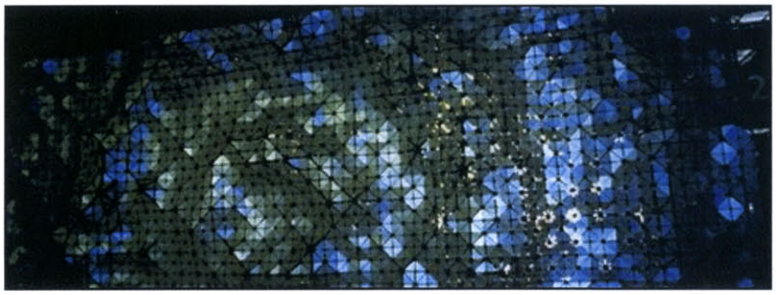
A combination of actuation and three dimensional topology is investigated in the project Feelex [Iwata 2001] an interface device which provides haptic feedback to animated graphics through a deformable surface. An animated image is projected onto a flexible membrane (screen) and the Feelex system manipulates the membrane with a sort of "actuated pinscreen" that can change the height of the membrane at discreet points on its surface. The user can then touch the image directly and feel its shape and rigidity. This allows manipulation of a 2D surface in to 3D space.

two actuated surfaces



Feelex, Iwata, 2001 - uses an array of mechanical actuators to change the topography of the flexible membrane surface

Actuated Workbench, Pangaro, 2002 - uses an array of electromagnets to move objects on a table top



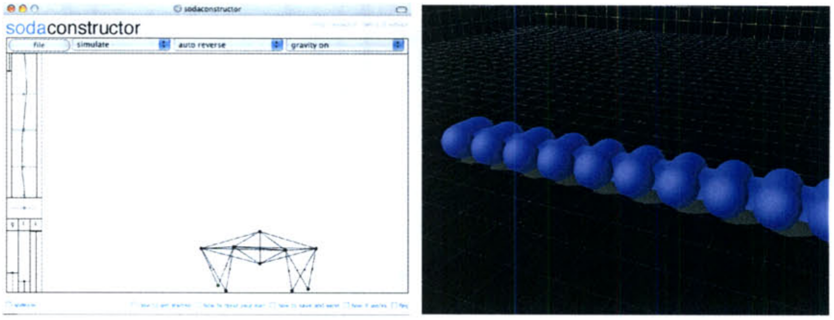
Mark Goulthorpe, Aegis Hyposurface, 2001 - facetted deformable surface which moves in response to sensed environmental stimuli or a controlled mathematical function

Actuated surfaces in a larger architecture scale have also been investigated. Mark Goulthorpe's Aegis Hyposurface [Leach 2002] is a facetted metallic surface that has potential to deform physically in response to electronic stimuli from the environment (movement, sound, light, etc.) or to be controlled by a centralized mathematical function. The system is driven by a bed of 896 pneumatic pistons while the dynamic 'terrains' are generated as real-time calculations. While the actuation method is different, using Topobo as a meshed surface would provide a scaled down modeling system for testing patterns and sequences for kinetic architecture applications such as this.

A Topobo meshing system would serve to build on projects such as these by combining elements of a deformable surface, input as well as output, haptic feedback, and virtual representation and simulation in one system.

2.4 Virtual tools for motion play

Several virtual environments for experimenting with moving structures in a simulated physics environment have served as models and influenced the development of a virtual extension for Topobo. Soda Constructor is an web based applet developed by Ed Burton at SodaPlay (www.sodayplay.com). Soda Constructor allows a user to build creations out of simple balls and sticks in a virtual environment of selectable stiffness, friction and gravity. The motion of the creatures is controlled by varying the amplitude and phase of a sinusoidal rhythm wave. The interface is black and white, with a minimalist



two virtual tools for motion play - in both environments the creations motion is manipulated in response to changing environmental conditions

screen shot from soda constructor

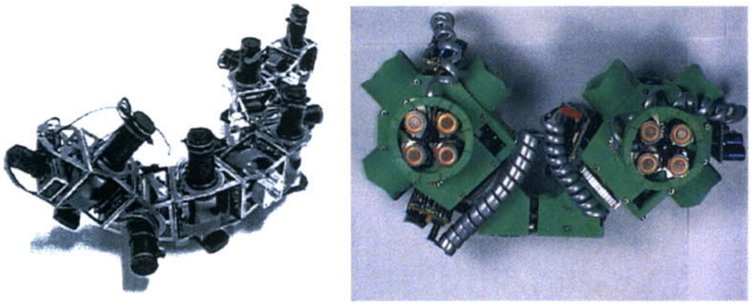
screen shot of a caterpillar-like creature modeled in Juice

aesthetic which creates an intuitive interaction by putting the emphasis on sculpting the motion of the figures, not on the rendering of the model.

Much like Soda Constructor, the application Juice [www.natew.com/juice] functions like a dynamic virtual erector set with realistic physics. Juice utilizes the physics simulator "Open Dynamics Engine" [http://ode.org] developed by Russell Smith. To build a creation in Juice, a user chooses from a set of geometric primitives (cubes, cylinders etc.) and attaches them together to move using virtual oscillating motors which function like hinges that open and close to an angle which can be set by the user. In this way it mimics very closely how Topobo's motion is determined by the repetition of the range of real servo motors, however the rendering style proves to be very computational intensive which can interrupt the rhythm of the motion. The physics engine behind Juice is more powerful and "correct" than Soda Constructor's but the interface is very cumbersome and non-intuitive, taking multiple operations to determine one repeating motion.

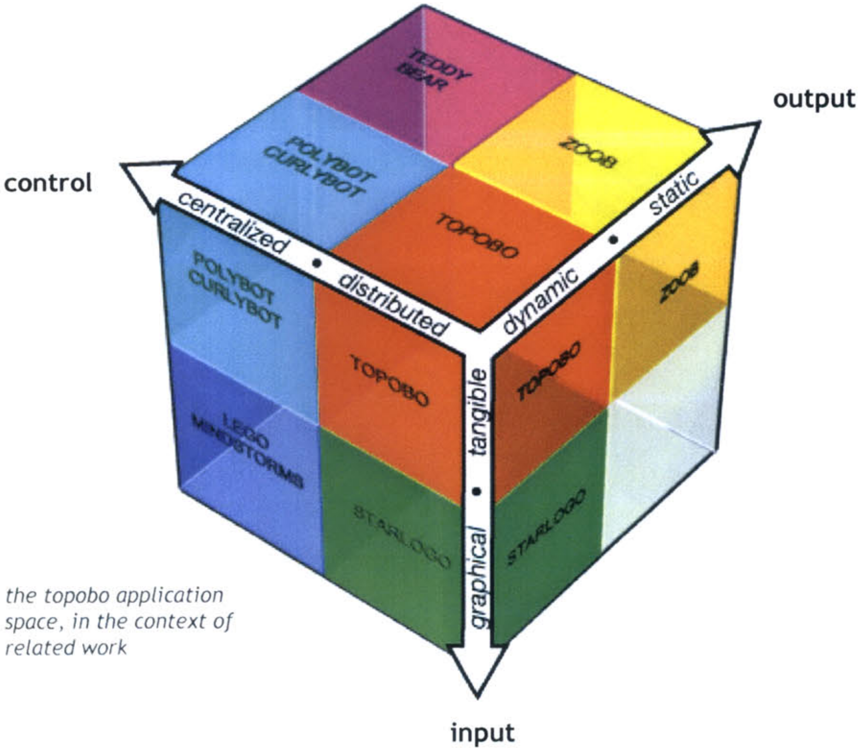
2.5 Electronics Design

Technical inspiration for Topobo's actuation and distributed computation system comes from the distributed electronics based on natural systems in projects like "Real Molecule" [Kotay 1999] and "PolyBot" [Yim 2000] although their conceptual intention differs significantly. These researchers in modular robotics have been working to make a generalized



modular electronics systems- Polybot, left, (Yim 2000) and Real Molecule, right, (Kotay 1999) provided technical inspiration for topobo

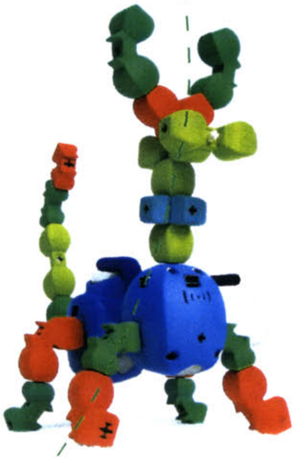
robotic node that can be used to configure robots of varying forms and behaviors. Preconfigurable robots, however, generally aim to be completely autonomous "smart" machines capable of doing tasks that people can not do, or do not want to do. Topobo is designed to be a user interface that encourages creativity, discovery and learning through active experimentation with the system.



the topobo application space, in the context of related work

Chapter 3
System Design

The Topobo system was originally conceived of with two design goals which on first consideration may appear somewhat divergent in nature - to create a constructive assembly that could be used to model and experiment with dynamic motion and form, and to create an actuated surface which could serve as a modeling tool to interface to an on-screen 3D modeling environment. These two approaches overlap, however, in a basic functionality of supplying the ability to sculpt and replicate motion in three dimensional space. The system as planned to derive its strength and versatility by developing a fundamental unit of kinetic memory which could serve both purposes. The addition of static pieces in differing geometries would serve to augment the dynamic pieces by providing greater versatility in the types of forms and structures which could be created.



We began with a more concentrated approach toward applications of the constructive assembly as it allowed us to focus the scope on the physical system and experiment more easily with proof of concept sketches involving fewer parts. We believed that by carefully designing each individual component of the physical system and their relationships to each other, this set of geometric primitives would naturally provide a means to explore the structure for the meshed surface later.

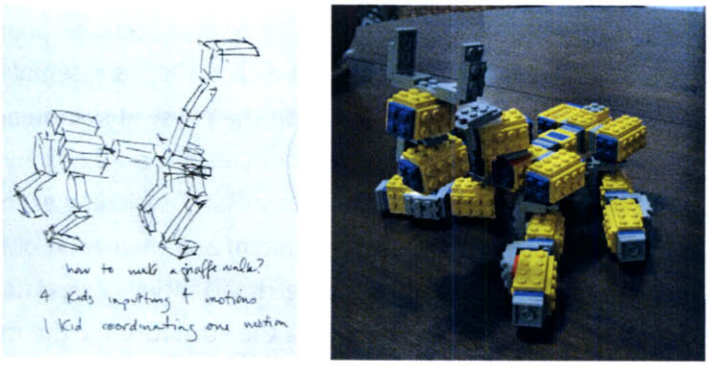
3.1 Design Principles

Topobo was designed to retain the best qualities of existing manipulative materials while giving the material a new identity - an identity that can both reveal new patterns and processes, and that allows users to creatively express patterns and processes that can not be expressed with existing materials. To achieve this goal, we established a set of design principles:

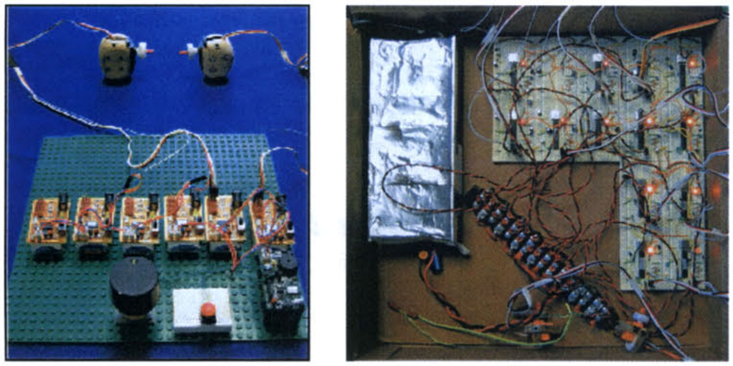
> ***Be accessible, yet Sophisticated*** - have an interface that is ergonomic, intuitive and easy for even very young children, but supports growth across multiple cognitive levels.
>
> ***Be robust*** - have a design that would not break or malfunction in any way.
>
> ***Be meaningful even if the power is turned off*** - technology should add to a toy, without sacrificing the good qualities inherent to its class of toys.
>
> ***Be expressive*** - encourage exploration of a topic without prescribing "right" and "wrong" activities.
>
> ***Engage multiple senses*** - engage sight, sound, and touch to provide rich, memorable interactions.
>
> ***Be scalable*** - In the spirit of a modular system, we designed every individual computational component to be complete and extensible

3.2 Early Design Studies

We began our development by surveying many different types of actuation technologies including magnetic and motorized, both rotary and linear. Due to the high quality and affordability



early design sketches - a drawing and model made with LEGOs and rotating joints

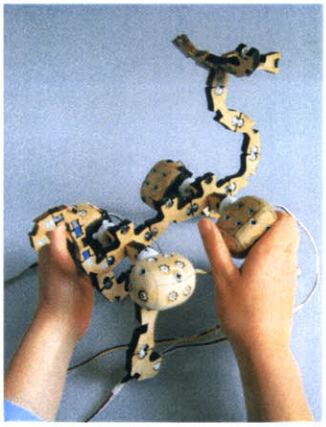


the first system prototypes - a cricket prototype (left) with servos encased in wood and our first scalable prototype (right) custom breadboarded electronics with daisy-chained power

of miniature motors compared to other actuators we chose rotary motion as a kinetic constraint, and initially built dozens of physical prototypes out of plastic and cardboard to study spatial geometries with rotary motion. This led to the development of the current system geometry and a proof of concept using Cricket microcontrollers and servo motors. The Cricket prototype was extremely fast to implement and allowed us to experiment with the capabilities of the system design. Our first scalable prototype followed, made with wood, hobby servos and breadboarded electronics. Evaluations of this system with kindergartners and second graders helped guide the design of the current system.

3.3 System Overview

The basic Topobo system consists of one active (motorized) component and nine passive (static) components which can be combined mechanically to produce a variety of structures. The active component consists of a servo motor and custom on-board circuitry to handle power distribution, memory and processing, and multi-channel serial communications contained in a plastic housing with a single button interface. The passive components consist of five geometries (four in two different scales) based on cubic and tetrahedral crystal structure, allowing the creation of biologically inspired structures. Both the Passives and the Actives are embedded with "+" shaped LEGO technics plugs and are mechanically attached using LEGO Technics pins. To directly program a motion into the system, a user pressing a button on an active, twists the



topobo is programmed by twisting and moving a creation

creation, presses a button again and the motion is played back repeatedly. Special actives called "Queens" and a "backpack" addition provide a means for centralized control and behavioral transformation.

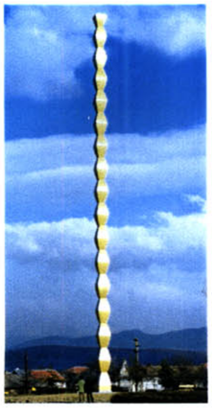
the Topobo parts

3.4 The System Aesthetic

All the components of the system are intended to be aesthetically consistent both visually and formally. The pieces should individually feel "complete" but be able to combine with other pieces to create unified-looking creations.

Form

We studied examples of sculpture, patterning in nature, as well as existing constructive assembly systems to inform our design decisions. Brancusi's "Endless Column" provided particular inspiration on how to give the system an organic yet geometrically regular feel. The relationship between the Active and Passives became particularly important, they needed to be aesthetically cohesive while functionally diverse, giving users the ability to easily recognize where and how to program the system. We also faced a challenge with regards to scale, we needed to create a system that fit comfortably in the hands of children and allowed for small detailed creations while working within the constraint that the minimum size of the Active was determined by the spacial needs of the embedded electronics and motor.



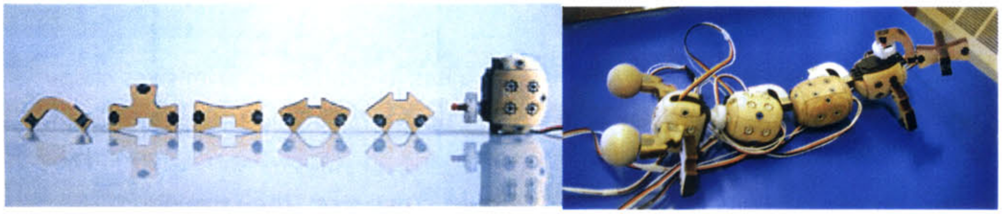
Constantin Brancusi, Endless Column, 1938 - provided inspiration for the form of topobo

Color

The color palette of Topobo consists of secondary and tertiary colors which were chosen to lend visual sophistication but with a fun and playful edge. We wanted the colors to retain a relationship to nature although imbued with greater saturation. We developed a palette of cool colors (blues and greens) with one accent color (a deep orange) to give characters a visual "pop." These colors are all tonally consistent so that none is much brighter or darker than another. The system specifically avoids the traditional primary palette (red, yellow, blue) of many children's toys and the colors were intended to appeal equally to both genders. The parts are color coded by shape to be able to easily distinguish between forms and to lend themselves to playful, unified looking creations.

The Topobo color palette

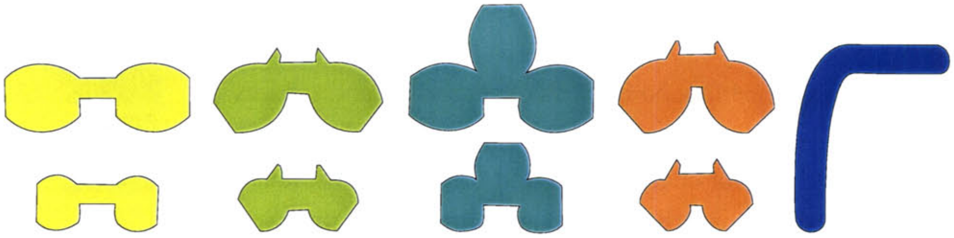
For ease of prototyping, the original pieces, both Active and Passives were lasercut in wood. This proved to be a comfortable homage to old hand-crafted toys while forming a particularly interesting relationship to the embedded electronics. This aesthetic appealed to us although difficulty in molding wood for more three dimensional forms stopped us from continuing with wood as a material. The final pieces are either injection molded in ABS plastic (Passives) or cast in a urethane resin (Actives).

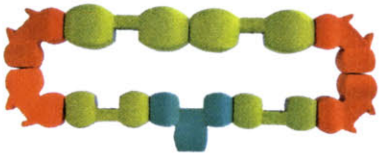


early prototypes lasercut in wood lent the pieces a hand-crafted feel

3.5 Passives

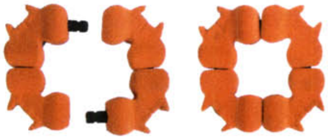
We designed nine different Passives to allow a variety of physical structures to be built. Since Topobo is intended to model various natural forms like anthropomorphic skeletons and regular geometrical meshes, the system allows branching and spatial looping. The Topobo geometry is based on a deconstruction of cubic and tetrahedral crystalline geometries.



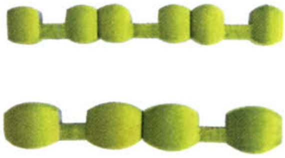


the topobo passives can be connected end to end or with their central notches - the geometry allows for spatial loops

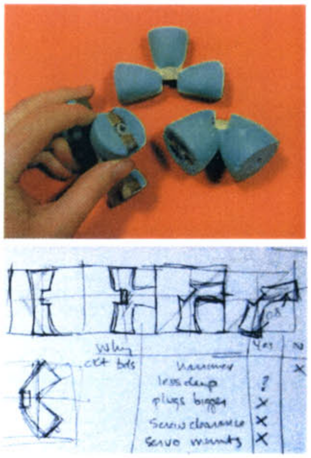
growth patterns and crystal structure inspired the geometry of topobo



scaling 3:2



[Thompson 1942]. Topobo has five different primitives shapes, four of which come in 2 scales: a "straight" piece, a "T", an "L" (90°), a "tetra" (108°), and an "Elbow" (offset 90°). 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. All the pieces except the elbow have a hermaphroditic notch across their center, 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 tetrahedral lattice or simple forms like a pentagon or square and this regularity allows for easier creation of large, interconnected forms.



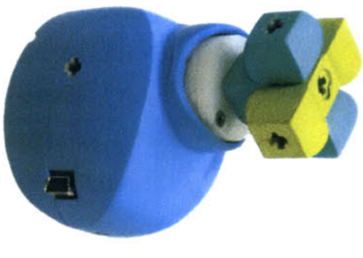
studies for the passives - sketching and in wood and clay

The Passives are also designed to be aesthetically consistent with the system's goals; they should be individually beautiful and assemble to create unified-looking creations. Our early prototypes provided a two dimensional skeletal basis. When moving the products into a more three dimensional form, we wanted to give the silhouette of the pieces a natural soft curve while maintaining a square cross section which intended to imply the possible 90 degree orientations of the notch connections. The biggest challenge of the passive design was considering how the ends of the pieces would meet to give the impression of unified creations. We experimented with different curvatures - extruded cones or bell shaped flares ending in a circle. We decided that we would segment each side of the passives into a "bulb" much like those of Brancusi's "Endless Column," which end in the same square cross section for both scales. From this design, all the parts in both scales could match end-to-end with a consistent silhouette.

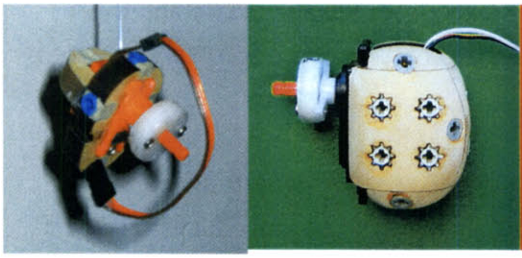
When assigning colors to the Passives, we used the accent color (deep orange) for the 90 degree components because these parts often are most often used to terminate limbs on animals, giving the animal a tonally consistent body with accented feet, ears, or tails. The goal was to avoid "polka dot" creations while keeping the creations visually playful.

3.6 Actives

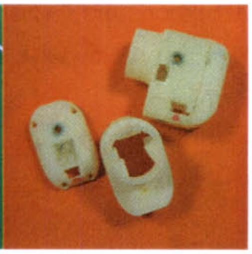
Most basically, the Active consists of a servo motor and electronics in a plastic housing. The housing has six points of mechanical connection, three sockets to connect power/communication cables and one button that is backlit by a red/green LED. One of the mechanical connectors is connected to the output shaft of the servo motor and rotates 170°. On board custom electronics handle power distribution, memory and processing, and peer-to-peer, multichannel serial



the Topobo Active



first Topobo actives were servo motors encased in wood with off-board electronics



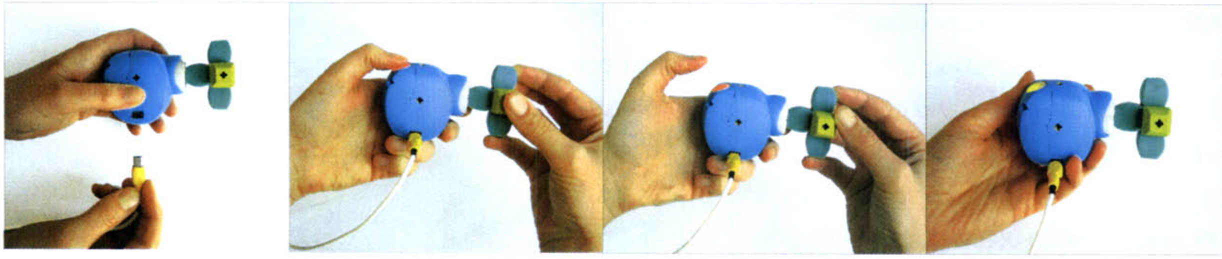
first 3D printed case with embedded electronics - aesthetically too "bulky"

communications. Each Active is identical and autonomous, and only needs power to function.

The original Topobo actives were built by encasing servo motors in wood housings embedded with LEGO plugs for mechanical connections. The electronics were on separate bread boards, attached to each servo by a tangly mess of wires. The electronics were then converted to a PCB and we conducted several design iterations on the Active case, attempting to minimize the size of the Active while incorporating the PCB.

A Topobo Active is programmed by direct manipulation, where each Active synchronously records its own motion. To record a movement, a user presses the button on an Active, twists and moves the creation to program a sequence of behaviors, and then presses the button again. The creation immediately goes into playback mode, which repeatedly replays the motion until the button is pressed a third time for pause. A one-button interface was inspired by curlybot [Frei, 2000] and chosen because it is extremely easy to use. This makes the system

programming an active



plug in the active *press the button to record* *turn the axis with a motion* *press the button for playback* accessible to young children, and it allows older children to focus on structure and kinematics rather than on learning a new programming interface. In a structure with many Actives, the system treats each button identically; a user can start a recording with any button, and stop the recording with any button. While our one-button interface is limited, 3D motion concepts are complex and the immediacy of the interface design encourages rapid experimentation with motion.

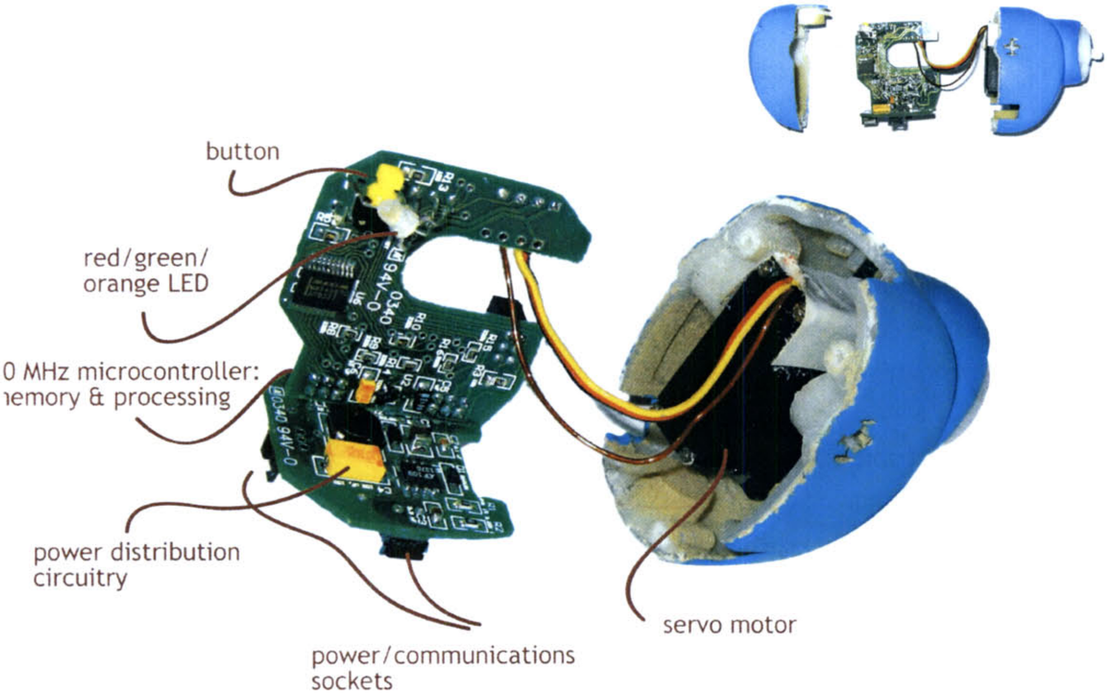

3D model of the topobo active case

Topobo's distributed design allows it to be a "high level" interface for thinking about kinematic systems because it lets the user focus on the global behavior of their creation. When a button is pressed, all of the Actives synchronously record their local motions. If a user makes a circular ring of Actives and teaches it to roll across the floor like a tank tread (the "wheel"), he or she only needs to understand and program the overall deformations of the ring. The Topobo system automatically decomposes the global motion in to local motions.


a topobo "wheel" which rolls like a tank tread

Technical Specifications

The Actives' on-board custom electronics handle power distribution, memory and processing, and multichannel serial communications. A 24V power bus is locally stepped down to 6V with a buck converter and then is dropped to 5V with linear regulator that powers the digital electronics. This minimizes the effects of power losses in the system, limits noise transfer between Actives and reduces current requirements. A 40 MHz Microchip microcontroller handles local processing and network communications. A one-time calibration sequence measures the range of motion of the servo and correlates input and output position data. During record, the microcontroller reads the servo's internal potentiometer at 20Hz using a 10 bit ADC and writes scaled 8 bit values to local memory. This provides about 30 seconds of record data at 3/4° output resolution, which is accurate compared to the backlash in the servo's 4 stage gearbox. A custom peer-to-peer serial networking protocol can transfer data between Actives at 9600 BPS. Specialized line



inside the topobo active

the custom clutch on the active output shaft to protect the gear train

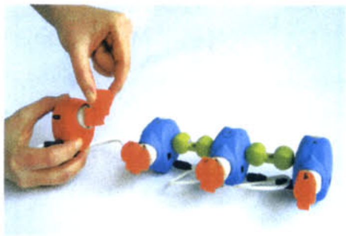
drivers allow hot-swapping power/communication connections between Actives. A TowerHobbies HS81-MG servo motor with 170° rotation because was chosen for its high strength to weight, robust metal gears, ease of back driving, and included sensor and drive circuitry. The servos' output shafts are outfitted with a custom clutch to protect the gears from excessive torque. Further technical specifications can be found in Appendix A.

3.7 Centralized Control

While highly irregular or interconnected structures like the "wheel" benefit from a distributed motion system, different kinds of motions can be constructed by control of the motions of individual Actives. We developed the concept of the "Queen" and "backpack" to allow centralized control of a creation. In our original prototype system, all of the functionality for centralized control was built into the Queen, with a series of Queens programmed with different functionalities - Copy Queen, Delay Queen etc. In an attempt to distinguish local/global control and transformation of behavior, we have since separated these functions. As part of a creation, a Queen offers a global control structure while a backpack works to transform the behavior of the Active to which it is attached, either locally (on a regular active) or globally (on a Queen).

Queens

Queens differ from regular Actives, by their color, the accent orange. If a recording is started by pressing the button on a Queen, that Queen controls the entire network. The basic Queen transmits a direct copy of motion: the user turns the output shaft on the Queen and all of the other Actives synchronously mimic the Queen's motion. This introduces surprising possibilities. For instance, a linear string of Actives can gradually curl into a circle or by connecting Actives with tetrahedral pieces, a spiral can be created. Two facing Actives, such as the legs of a symmetrical animal, will exhibit opposing, mirrored motions, a tangible example of spatial translation.


programming with a queen - each active copies her motion


actives connected with tetrahedrals and programmed with a queen create a spring-like helix

Since a Queen does not need to be mechanically attached to the creation it is programming, it can also be used as a remote controller. Remote programming with a Queen gives a user synchronous input and output feedback during programming, allowing a user to actively debug their creation's motion while they are composing it. Using a queen as a remote control, the creation can respond to the physical conditions of the real environment, not interrupted by the user's grip.


a linear sequence with direct copy creates a circle


the same linear sequence with a decay message forms a spiral


the same linear sequence with a delay message creates a wave

backpack prototype

Backpacks

The concept of the "backpack" emerged from investigating information and behavioral control from biological systems. This concept has recently gained popularity as a model for decentralized digital networks. The idea that complex system behavior can emerge from a simple set of rules provides the guiding principle. The Topobo backpack provides a means to physically embody a varying system behavior by moving and forming in response to a mathematical function.

The backpack prototypes are small "discs" which connect to an Active both mechanically (through a LEGO connector) and electrically (through one of the communication ports) and feature a knob (potentiometer) for control of the behavior that they send. They can be connected either to a regular Active, where their behavior affects only that Active, or to a Queen, where their behavior is sent through the system based on a specific transforming function.

The backpacks connected to Queens take advantage of Topobo's peer-to-peer network architecture. The Actives can easily increment a variable each time a message is passed, so the motion of each Active in a network can change based on distance from the backpack. Full development of the backpack functionality is still in a prototype phase but several scenarios prove to illustrate how they can be used to physically embody a mathematical function.

Decay Backpack causes the Actives motion to be incrementally scaled smaller as it is passed from the source. A linear string of Actives can gradually curl in to a spiral.

Time Delay Backpack aggregates a time offset before playback of the Queen's motion. A linear string of Actives can move with wave-like motions.

Faster/Slower Queen increments a change in period as a motion is passed. Due to Topobo's looping playback, a linear string of parts can exhibit harmonic interference patterns.

sending a delay through this "caterpillar" causes it to move with a wave-like motion

3.8 Compromises, Constraints & Additions

While Topobo has been successful at fulfilling much of its original design criteria, it still has much room for improvement.

Mechanical/Electrical connectors - Wires & Batteries

One of the most common comments from people playing with Topobo is a request to get rid of the wires. The wires serve as both a communication means between Actives as well as a connection for spreading power through the system. Getting rid of the wires would entail two areas of re-engineering. The first would be to add batteries to each Active. We decided not to attempt this because of the many constraints already guiding the design of the Actives, including the need to optimize the torque to weight ratio for the servo motors and our design criteria to keep the Actives as small and light as possible. Getting rid of the wires would also involve implementing a new communication scheme. This would entail integration of the electrical/mechanical connectors and adding sensing circuitry to each of the passives in order to rout communications. Because of time and engineering complexity, we opted to continue using the wires. There is one advantage to using cables to connect Actives: when examining the system behavior based on Backpack control, it is easy to visualize and reconfigure the network topology. However, in an ideal design, Topobo would not have separate cables.

Active Design

In many ways, we feel that the design of the Actives is not fully resolved. We consider them to be too large and not sculpturally similar enough to the passives. In the current design of creatures, the Actives often end up feeling like "body" of a creation while the passives serve as the "limbs." Ideally, there would be no distinction between Passives and Actives. All joints would be actuated with the exception of the notches. This is not possible because the current Actives are too large and heavy, but future developments in actuator technology may facilitate this goal. A major incremental improvement to

a more abstract creation, less like a "body" with "limbs" - this creation cartwheels the existing Actives would be to design them with more oblong proportions so that they are more similar in shape to the Passives.

One major benefit of smaller and stronger actuators would be in mesh construction. Mesh structures require looping structures for strength and stability. In order for meshes to be ergonomic, rings of Actives need to be small and flexible, which is not possible with the current implementation of Topobo. The most major mechanical limitation is the actuator design. Rotary motion is limiting, and a 2 or 3 degree of freedom actuator would profoundly improve the types of structures that could be built and animated with Topobo. Linear actuators would also be a welcome addition and we hope that future developments in actuated modeling systems address this limitation.

Saving Motions

One simple and welcome addition to the interaction design would be the ability to recall saved motion sequences. Currently, the last stored program can be recalled by double clicking a button. However, saving and replaying older programs, either using backpacks or another interface technique, would be beneficial. As with any building system, it is enjoyable and beneficial to save successful creations and saving motions would be a necessary element of a Topobo creation to save and later recall. However, we can also anticipate complications with this idea-- recalling a motion also requires a user to recreate the physical structure in the same form. Replaying a motion on a different form could cause the creation to attempt to move into physically impossible structures and break itself, we can't accurately anticipate how much of a problem this would be.

Control Structure

While the Backpacks present one example of a feedback loop, in general Topobo lacks a sophisticated control structure to model "intelligent" behaviors. This was a conscious design decision made to allow people to focus on mastering the basics of processes like kinematic locomotion, but a control structure would be an interesting addition for more experienced users. A timeline model might facilitate children's storytelling and graphical representation of dynamics and changing center of gravity could help more advanced students transition lessons learned with Topobo to other academic forums like high school physics. More standard visual representations of the influence of Backpacks on motions could also help students understand how properties like growth, decay and wave dynamics behave in nature. The advantages of what various virtual system extensions could add to the system are discussed more thoroughly in Chapter 5.

Topobo on the Go

Topobo, like all digital manipulatives, is designed upon the premise that learning improves by engaging the body and physical activities-- using physicals objects to learn about the physical world, provides a significant benefit. For learning about kinematic systems, the strength of the interaction with Topobo lies in being able to utilize the conditions and laws of the real physical world. In many ways, we have not explored this enough. Experiences with Topobo would benefit from incorporating elements that are added to Topobo creations and using Topobo in a greater variety of environmental conditions.

Constructive assemblies such as Topobo offer an idealized version of a mechanical system, they are easily accessible because all of the pieces "fit" properly together. Incorporating other kinds of materials, however, would allow for an exploration outside of the ideal, open up the possibility for

topobo meets the "real" world

topobo mimics leaves in the trees

look right and left - a topobo "wheel" crosses the street

a topobo caterpillar in the grass

the system to break down, when further learning based on investigation could occur. We could begin to "accessorize" Topobo, for example giving Topobo "shoes" to experience different types of friction or a "cape" to add wind resistance. In one situation, we wrapped two connected Actives in gray felt, creating an elbow joint which moved with two degrees of freedom, the addition of felt completely changed the character of the interaction. Simple additions such as this provide and attempt to appeal to different audiences suggest different kind of engagements and interaction scenarios. Stereotypically, the idea of "dressing up" creatures may have greater appeal for girls and may engage them to learn about physical principles and kinematic systems in a social construction and from a perspective of which they are comfortable, a possibly powerful notion in the context of physics and robotics education.

We also see value in attempting to create a relationship of Topobo to the natural and built environment. Taking outside of the laboratory, and placing Topobo in real world contexts would also expand the potential for learning, for example, exploring locomotion on different types of terrain, and in the context of different types of motion - wheeled, biped, flying swimming. Inclusion of Topobo into a natural construct also easily sets up a metaphorical relationship - in form and behavior - to the natural world. Observations and representations of how Topobo behaves both similarly and differently from the things that surround us offers a glimpse into the relationship of the natural and mechanical.

topobo in a feathered coat - photo courtesy Margot Breteton

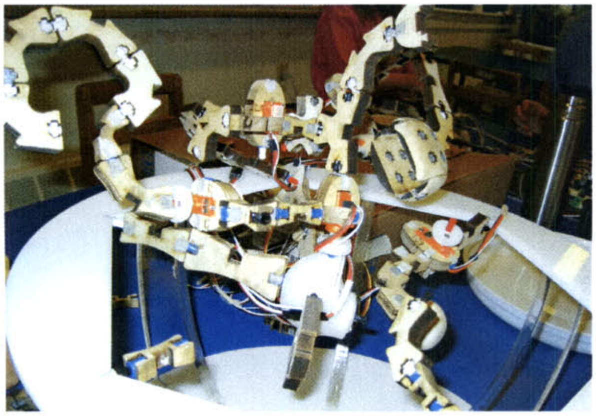
Chapter 4

Topobo in Action - Evaluation in the Classroom

Two sessions of evaluation with Topobo were conducted over the past year. The first was very informal with kindergartners and second graders. The second was more structured and involved older students - two physics classes of eighth grade students. In total, the classroom studies involved 25 kindergartners (5-6 years old), 22 second graders, and 32 eighth graders and have provided a means to evaluate Topobo's effectiveness as an educational tool for children at various educational levels.

4.1 Kindergarten and Second Grade Studies

We brought an early Topobo prototype to a Montessori-inspired elementary school in order to evaluate its technical features, design principles and our educational goals. We spent two hours each in a second grade class and a kindergarten class playing with Topobo. These Montessori-inspired classrooms featured many examples of models, toys, and manipulative materials. Only one computer was present in each classroom and it was strictly for teacher use. Two researchers worked with several groups of approximately 4-5 kids. We started by showing children two possible models and how they could



a second grade collaborative creation

manipulate them. Then we assisted them with assembling and programming their own models.

We introduced Topobo to the second grade group by comparing a walking creation to ourselves walking. When Dave, a normally impatient child, came to one of the tables where we were sitting and manipulating Topobo, he immediately became engaged. First, Dave started to manipulate and rearrange the parts in spontaneous and creative ways but Topobo soon became part of his ongoing activity and experience. Dave was working to create his own walking animal with the Queen. When something stopped functioning as he had expected, Dave drew on the earlier models that we showed him, and tried to emulate some of the configurations, especially the local-global interaction and the feedback between parts. He was trying to run a new creation, but suddenly he realized that the creation didn't work as he has planned. He broke his focus, stopped his ongoing activity and then asked: Why? What happened? Why it is not walking?

a second grade "static" scorpion suggests that the system can be fun even without the technology

This breakdown in the ongoing activity of building a Topobo model may have produced a certain conceptualization in Dave's mind: he may have started 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 have given Dave new insights into kinematic systems.

Our guiding and scaffolding was certainly useful and helped Dave to quickly form complex conceptual Topobo models. In the future, teacher guiding may be very helpful for facilitating in-depth conceptualization and kinematics thinking by comparing Topobo to natural locomotion. Topobo appeared to support Dave's "education of the senses" in which materials and objects support learning experiences that help children develop their sensory capabilities, control their own learning process and learn through personal exploration [Piaget 1976].

classroom set-up for topobo play

4.2 Studies with Early Adolescents

Later evaluations with two eighth grade "Physics by Design" classes focused on Topobo's role supporting design, experimentation and conceptual abstraction. These students normally engage 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. A preliminary worksheet asked the students to describe 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

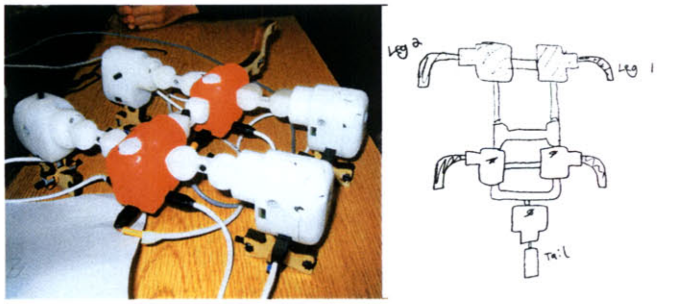
eighth graders at work

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.

4.3 Iterative Design

The second evaluation session a week later 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 consisted of 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.

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 with a more iterative process.



a compartmentalized strategy - a drawing of an intended creation, and the creation built in Topobo - this creation didn't walk

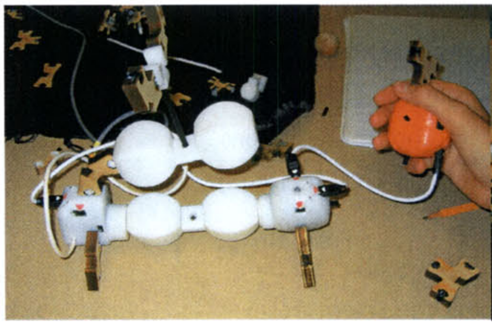
This data shows that an interface design should support active iteration by allowing users to quickly and easily transition between interdependent processes. Users often need to test many ideas to incrementally develop a successful design. Topobo appears to support this, evidenced by compartmentalizers transition to active iteration. However, these findings also suggest that Topobo would benefit from an ability to save and reuse motions, so that forms can be edited and motion could be kept consistent.

This process of designing and testing also shows how building with Topobo leads older students to employ the Scientific Method. Students began by observing the action of their creature, creating a hypothesis on how to improve it, and testing that hypothesis with experimentation. While Topobo can be thought of as a system to specifically teach concepts of kinematics, for children capable of "formal operations," (11+ yrs.) [Piaget 1976] in can also be described as a tool for teaching students to think like scientists.

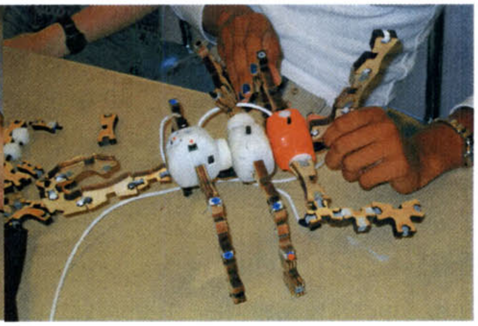
4.4 Centralized Control

At the time of our evaluation, the functionality for centralized control was embedded entirely in the Queen, we had not yet created the backpack as an addition to the system. Different kinds of Queens were created - a copy Queen (how all Queens function now) or a delay Queen. During our evaluation we tested only the copy Queen.

Our evaluation of the Queen is inconclusive. Some students had success using the Queens. Many 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, eg. "how far did the leg move from its static position." However, a Queen forces Actives' movements to be based on the Queen's absolute positions. Students would often carefully position 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 motors synchronized with the Queen. This can be fixed by reorienting the Actives when they are recording, but the kids



an eighth grade creation using the Queen as a remote controller



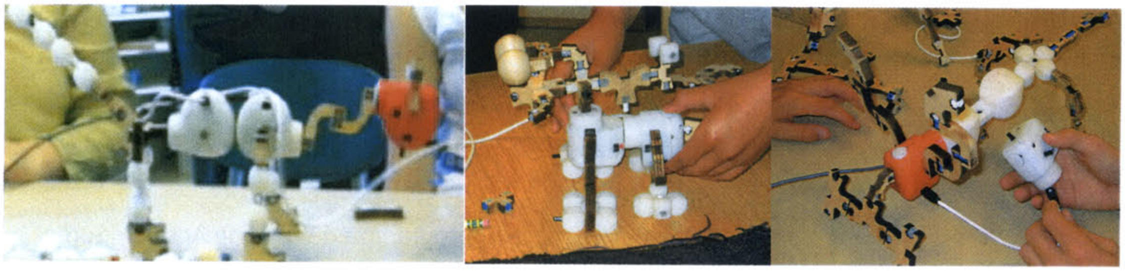
an eighth grade creation using the Queen as part of the creation

often thought something had broken and stopped their program before they could analyze and fix it. Their fear of broken parts was exacerbated by the fact that a software bug occasionally caused Queens to act erratically. After students were surprised by a Queen a few times, they would often give up and return to direct manipulation.

We have since fixed the software bug which caused the confusion in the evaluation. However, this study showed us that a minor bug can be an obstacle to learning if it causes greatly unexpected output. We have also noted that In our future evaluations, the Queens may require more scaffolding than the direct manipulation with Topobo.

4.5 Animals and Machines

Kindergartners, second graders and eighth graders all related to Topobo models with their "familiar knowledge" about machines and animals. 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 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



eighth graders built their creations using their familiar knowledge about animals and machines

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.

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 [Papert 1976]. 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.

We also found evidence to support that for younger children, Topobo may function as what Papert considers a transitional object. In Papert's view, a transitional object allows the children to make sense of tasks in terms of everyday familiar experience, but supports them in moving into the world of the abstract [Papert 1976]. As a digital manipulative for understanding physical kinematics systems (like one's own body), Topobo may be a transitional object. We hope that further research will help us evaluate this hypothesis.

4.6 Age Range Findings

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,

2nd graders at play

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 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. 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 Topobo 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 degree of freedom 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.

an eighth grader proudly
shows off his work

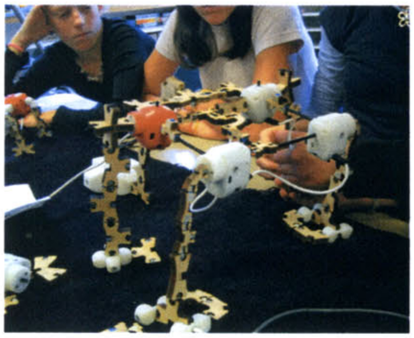
We tested Topobo with a wide age range to evaluate its success as medium designed to be both accessible and complex for a wide audience. Eighth graders compared it to LEGO Mindstorms as a programming tool, and several students suggested that the addition of sensors and environmental feedback would improve 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" [Vygotsky 1978] 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 cognitive transitions.

4.7 Domains of Knowledge

We found that Topobo can help students ages 7-13 to learn about several educational concepts:

Balance: When objects move, their center of gravity changes. Topobo draws attention to this fact when children make things that fall over. Learning how to control falling can lead to an understanding of familiar dynamic processes such as walking.

Center of Mass/Center of Gravity: Several groups of students built creations that were initially very tall and tended to fall over when they moved. One student described shortening the creation's legs to keep its weight closer to the ground. He referenced how it is easier for babies to crawl than walk.



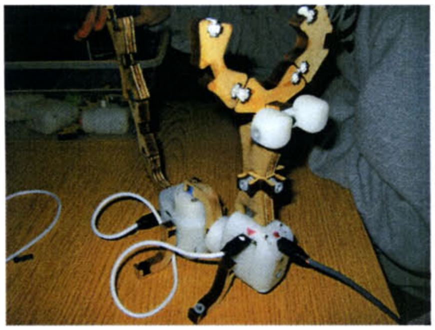
eighth graders experiement with the center of mass of their creation by manipulating the length of the legs

Coordination: When Topobo is directly manipulated, sequential motions are easy to record. A child might shake his Topobo dog's head, and then wag his Topobo dog's tail. However, shaking the dog's head and wagging the dog's tail at the same time is difficult because the child needs both hands to do either one of the activities. In order to coordinate these motions, it is necessary either to cooperate with other children (coordinating people) or to use a Queen (which coordinates movements in time). The Queen encourages developing an understanding of how coordinated movements can change a whole system.

two eighth grader program with coordinated movements

Relative motion: A second grader built a long string of static parts with an Active part at each end. He programmed each end to wiggle back and forth and observed the ends shaking. Upon suggestion from an adult, he tried holding a shaking end, and was amazed to see his entire creation wave wildly back and forth.

This drew his attention to the idea that movements in a connected system are relative to one's frame of reference.



a "moose" with two degrees of freedom in its body

Movement with Multiple Degrees of Freedom: A Topobo Active provides motion in one degree of freedom. One pair of eighth grade girls quickly figured out how they could connect two Actives with an elbow piece to create 2 degree of freedom rotational motion. By applying this technique they were able to quickly create a walking moose. While they could not explicitly describe how it worked, their implicit knowledge of these dynamics was evident when they refined the same kind of motion in a different creation a week later.

Relationships between Local and Global Interactions: The educational value of understanding relationships between local and global interactions has been investigated at length with object-oriented programming languages such as AgentSheets and StarLogo [Resnick 1999]. Topobo makes certain systems concepts tangible with the Topobo Queens. One group of 8th graders discovered that faster legs (local) do not make a faster animal (global). Another group of three boys figured out quickly 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.

In general we have been excited to see children responding favorably to Topobo and have been easily and intuitively able to comprehend how to operate the system. We are particularly encouraged that children from ages 5-13 when asked what age range they thought Topobo was designed for, they responded their own. We hope this shows that Topobo offers an entry point for children at all stages of development and contains enough depth to engage deeper and more meaningful interactions with children as they grow. The question remains, however, as with many informal evaluations with educational tools, what specifically is being learned, how is that knowledge being retained and how is it proven?

4.8 Further Evaluations and Awards

In addition to the classroom evaluation, Topobo has been shown in several exhibition settings including Wired NextFest in San Francisco in May 2004 and it was used as part of a designers/ educators workshop at the Summer Designs Institute at the Cooper-Hewitt National Design Museum in New York city. Topobo was also awarded Design Distinction in the ID Magazine Annual Design Review 2004, an honorable mention in the DIS 2004 Design Awards, and an honorable mention in Interactive Art at the Prix Ars Electronica 2004, where it will remain on display for a year starting in September 2004. It will also be shown at ArtBot: the Robot Talent Show in September 2004 in New York. As Topobo gains more public exposure and a wider range of audiences has the chance to experience it, we hope to gain a better understanding of the how it can be used as a tool for kinetic exploration outside the realm of a purely educational context.

kids in a wide range of ages interact with topobo at Wired NextFest, San Francisco, May 2004

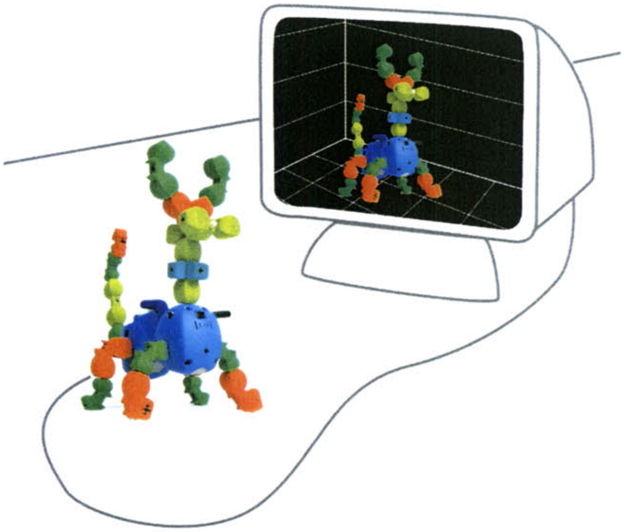
Chapter 5

Virtual System Extensions and Applications

5.1 Limitations of a purely physical system

The design of Topobo is firmly rooted in the belief that a physical modeling system provides the most appropriate interface for experimenting with motion and kinematic systems because it responds directly to the forces of nature that constrain real dynamic systems. But in order to more thoroughly understand the advantages of a purely physical system, we must also recognize how such a design decision prescribes a set of constraints on what can or cannot be achieved with the system. We can take an inverted looked at the system's functionality by questioning, how have we limited what can be explored by keeping the system purely physical? What advantages does a graphical or screen based environment offer in terms of data visualization or gestural representation that a physical system cannot?

The exact parameter which defines Topobo's strength, its ability to respond to the forces of nature around it, also defines its limitation, it cannot step outside of our physical world to teach us about systems on a different scale or resolution, or of alternate materiality. Because Topobo functions as a material extension of our own body's gestures, we are limited by the gestures which we can give it. This capacity becomes powerful in understanding organic types of motions and allowing us to deconstruct them into a mechanized form. But how can we compare these types of gestures to motions prescribed by mathematical functions?



a virtual extension - topobo with a GUI

5.2 A Topobo Virtual Extension

Going beyond the physical system as a secondary investigation for this thesis, I began the development of a Topobo virtual extension to consider how the Topobo system could be expand learning of concepts in physics and kinematics with the use of a GUI. The development of the virtual system was done under the premise that a virtual representation would not attempt to take the place of the physical system, but rather physical and virtual representations would work in tandem to expand the capabilities of the system as a whole. The Topobo physical system would provide a means for experimentation which could them be expanded to a virtual simulation. The initial physical experimentation would keep users grounded in reality when embarking into the virtual, providing a richer learning experience that virtual simulation alone. By examining how the virtual environment varies in relationship to the physical, the user is forced to enquire about what invisible environmental forces are at work in the physical world, expanding on what they would of considered with only the physical. Essentially, the ability to better understand the physical, lies in the comparison of the physical and virtual through the process of separating out and changing individual parameters in the complex, dynamic environment. In addition, the virtual environment allows for an extension in scale and temporality of the Topobo system.

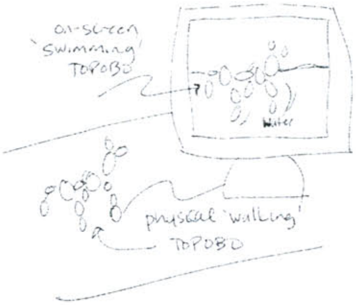
The prototype of the system presents an on-screen representation as a mirror of the physical world, but with an environment of variable parameters which would be impossible with the constraints of the physical world. The front end and representational graphics of the GUI environment has been created in custom Java, using the physics simulator, Open Dynamics Engine (http://ode.org) developed by Russell Smith for simulations of environmental controls. At the time of this thesis, the system offers only the basic functionality of representation of a Topobo creature moving on screen and does not yet provide any interesting conclusions on the benefits or disadvantages of the variants which a GUI could provide.

However, I have identified three modes to allow manipulation of different contextual parameters which I plan to explore to determine if a GUI can expand conceptual understanding of physical systems. Environmental complexity and material simulation will address spatial and material issues, motion choreography and scalability will address temporality and coordination of movement, and mathematical functions and graphic representation, the most complex of the three, will provide models for comparison between the organic recordings and local rule-based behavior of Topobo in the 3D world and the motions of systems as determined by centralized control of a mathematical function.

Environmental Complexity and Material Simulation

This mode will allow for manipulation of the systems environmental parameters as well as the material properties surrounding and making up Topobo creations. As a starting point, users could change the direction and intensity of gravity. For example, what if gravity acted as a centripetal force originating from an object's center of mass, how would a creation need to be changed in order to overcome such a force? This mode could also be used to set up comparisons to the environments of different planets in our solar system and set up a connection between the larger global forces at work in our universe in relationship to their local impact.

The manipulation of "friction" would include changing both the properties of the surface on which Topobo resides, or the properties of the "substance" in which Topobo is



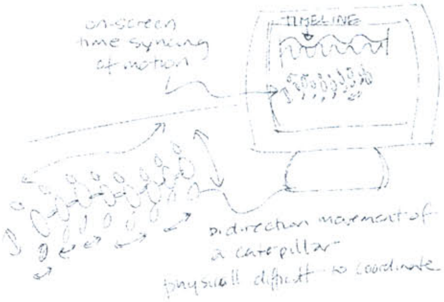
concept sketch - material simulation

enveloped. Topobo creations could be faced with textured terrain or a directional wind to alter their progress, or, with a more complex simulation engine could be placed in a water environment where a creation that once "walked" now has to "swim." Alternatively, the material properties of the Topobo pieces themselves could be altered. For example, what if Topobo is made of feathers? What if Topobo components are wrapped in rubber or made entirely of steel? Manipulations such as these would change inherent material properties such as weight and density, as well as effect the environmental interactions these changes would incur, such as wind resistance. Material manipulation could also include freeing a Topobo creation from the physical limitations of the existing servo motors, both in terms of how quickly the motors could be driven and their torque to weight ratio; the motors could be simulated to be faster and stronger than our existing system.

In order to gain a meaningful understanding from manipulating environmental and material parameters, it is important for the interface design to afford an intuitive method for observing the cause and effect of individual changes on the entire system. Each change may be singled out by allowing the user to only make one change at a time or to save temporal snapshots of progressive changes for comparison. It is also important for the physical Topobo to maintain a role in the comparison to ground the experience back to the body motion through which Topobo was programmed. Experimentation will determine how differentiated the physical and the virtual models can become while still maintaining such a relationship.

Motion Choreography and Scalability

When programming Topobo, it can be difficult to coordinate the motion of different Actives involved in a single creation. While the recording process can encourage collaborative play, it can also offer frustration if a desired action is too complicated. In this situation, using a Queen is one possibility, although coordinating the motion using a GUI may offer more flexibility. Using GUI motion choreography would allow users to program an initial motion of Topobo in the physical world and then manipulate and time synchronize interconnected motions or sets of motions on-screen. For example, a creation of a caterpillar may involve two distinct motion patterns, that of the legs moving forward in one pattern and speed, and the body moving sideways at another. Exploring the relationship for coordination between these motion sets would prove easier by setting up a time line to plan the rhythmic and spatial relationships of the two motions. Attempting to time sync these in a virtual environment may encourage users to explore more complex intercoordinated networks of motions than they would of visualized with only the physical Topobo.

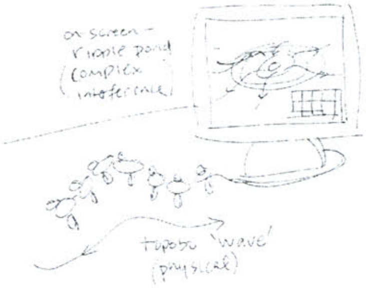


concept sketch - motion choreography

Additionally, a virtual environment allows for an extension in scale of the Topobo system. One very limiting constraint of the current physical Topobo is the number of Actives available, and realistic expectations of assembling a physical network. An on-screen representation of Topobo would allow users to copy sections of creations and repeat then in multiple patterns and branching structures. This would prove especially useful when applied to creations using a Queen and backpack. A physical behavior parameter started by a Queen could be multiplied to show a simulation of the system with thousands of Topobo parts which may result in resonant motion or visual patterns not evident from just a small number of Topobo Actives in motion. Such a features may also reveal complexities in the global motions of forms that loop back on themselves for strength, or whose behavior is magnified and becomes more evident when viewed with a multiplicity of parts, such as structures mimicking springs.

Mathematical Functions and Graphical Representation

As a decentralized system, Topobo has the capability to represent how a local rule can lead to an observed global behavior, such as a delay propagated from a Queen creating an apparent wave flowing through the network. The peer-to-peer rule governing this behavior however, does not show more complicated patterning as determined by the physical



concept sketch - mathematical functions

laws governing natural systems (mathematical functions and algorithms). For example, in nature the behavior of ripples in a pond of water is determined by the wave equation which accounts for complexities in behavior such as waves bouncing off the edge of a pond and returning to add interference to the existing pattern. A physical network of Topobo can be constructed to mimic this behavior using a delay Queen, however would lack the complex interaction of wave interference. Creating an on-screen representation of this system governed by the precise wave equation allows for observation of the behavioral discrepancies in the simple repeated motion in Topobo and the more complex natural behavior. Essentially, this mode of GUI representation would attempt to bridge the gap between a simplified physical representation of a more complex natural physical phenomena and the abstract language of a mathematical equation.

5.3 Physical/Virtual Information Exchange

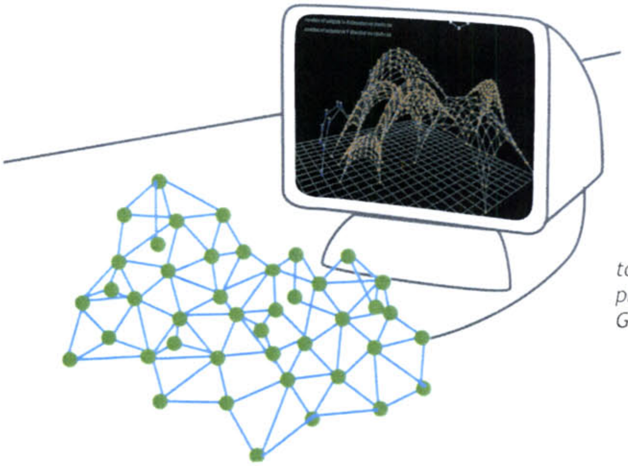
In order to communicate with a centralized computer (PC), a Topobo creation is connected to a separate external PCB which functions like a backpack, using the same PIC microcontroller and the standard Topobo communications protocol, allowing it to process and rout messages through the I/O ports. One of the ports, however, communicates to a computer through a serial connector. Using Topobo's communication protocol, the computer sends a message through the external PCB to poll for data from the first Active to which it is connected, the "root" Active. When the "root" Active receives the signal, it passes this message on all of its channels, one at a time. This establishes a communication chain for the structure and allows each active to have a unique "ID" determined as its path from the "root" Active.

Once the message gets to an Active that has no "children," no Actives connected to it downstream in the chain, that PIC will send the position of its servo back upstream. After a PIC gets data from a channel it appends that data to the channel number it came from. Then, when a PIC has data from all of its children, it adds its servo position on the front of its data and sends it upstream as an array in the data portion of another message. This data accumulates into an array at the PIC at the root "Active", which send it to the computer with its own position. Using custom software, the computer then parses this array to find Topobo's topology based on the position of each individual servo.

Chapter 6

From Constructive Assembly to Meshed Surface

This thesis thus far has addressed the educational applications and implications of using Topobo as a constructive assembly, either alone or with a GUI interface. The construction of Topobo into a meshed surface begins the second phase of the original conception of the Topobo project: to design an actuated surface which could serve as a modeling tool and interface to an on-screen 3D modeling environment. It also marks a conceptual shift in thinking about the Topobo system: in investigating the educational value of modeling kinetic systems in relationship to the real physical environment, as with the constructive assembly application of Topobo, the learning arose in dissecting and understanding the cause and effect of variations of motion between individual Actives. In forming an actuated surface, however, we are now seeking the individual elements to blend together to create fluid flexible motion, ideally thinking of chains of Actives joined together in a "weave" like that of a textile. The development of the ten Topobo primitives and the GUI and virtual mirror additions provide the initial framework for this part of the project, however, developing the physical geometries and graphical interface for the mesh is still on-going research work. I will discuss the mesh from a conceptual perspective as well as explain my initial developments.

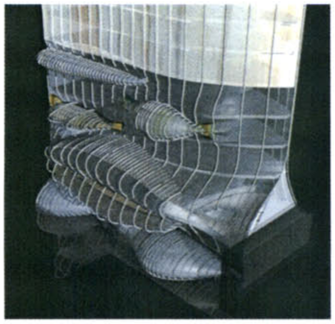


topobo mesh concept drawing - physical mesh as interface to a GUI modeling environment

6.1 The Digital Design Shift

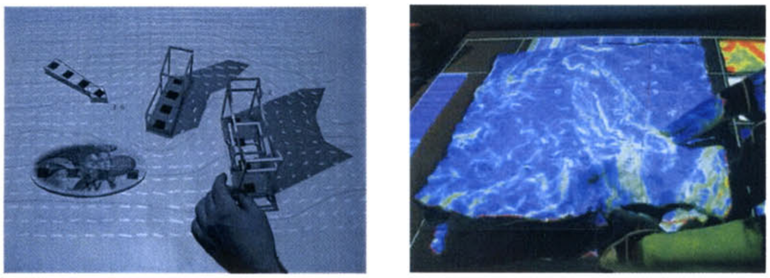
The Topobo mesh is conceived of as a modeling tool for 3D sculpting for architects and designers. Such a tool attempts to build a bridge between the changing practice of design and the digital technologies which support it. Because design tools influence the designs which arise from them, as the practice of design becomes increasingly technological, digital design tools must help to foster a blurring between the natural and the artificial, the organic and the constructed. In the book Skin, Ellen Lupton describes this phenomenon,

> "The rise of digital media over the past decade has changed the practice of design, providing tools for making objects and buildings that resemble living creatures - modeled with complex curves and forms - while remaining distinctly artificial...Surfaces have acquired depth, becoming dense, complex substances equipped with their own identities and behaviors...Flexible membranes are embedded with digital and mechanical networks." [Lupton 2002].



Eyebeam Atelier, digital rendering for competition, Greg Lynn FORM, 2001 - a building with an organic "skin" surface - modeled with complex forms and curves

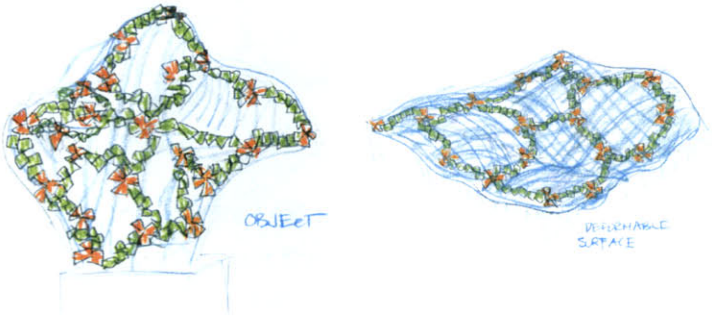
A shift from the rectilinear nature of CAD/CAM software tools to NURBS based tools which use algorithmic formulas to generate and change soft, curved forms has allowed organic forms to be designed more easily with digital tools. The interfaces to NURBS based software tools, however, still primarily the mouse and keyboard, deny the creator the process of sculpting soft fluid forms directly in three dimensions. Topobo attempts to create an interface which serves as an extension of the designers natural process of thinking, building and making in physical materials.



Tangible Interface design tools - URP (left) for urban planning and Illuminating Clay (right) for landscape design

The development of Topobo as a design tool seeks to build on the success of several past projects inside the Tangible Media Group which explored design tools as an appropriate application for Tangible interfaces. Urp [Ishii 2002], a project for urban planners, tracks the positions of 3D physical models of buildings and projects simulation data for wind flow and shadow patterns onto the 2D surface where they are placed. While this project allows users to track 3D objects, the digital information in response remains in two dimensions. A later project, Illuminating Clay [Piper 2002], provides a freeform sculpting medium which moves toward three dimensionality. Designed as a tool for landscape designers, users alter the topography of a clay landscape model while the changing geometry is captured in real-time by a laser scanner. The geometry is then analyzed by a library of landscape functions and results are projected back in real-time onto the surface model. While Illuminating clay provides the physical affordances of real clay as a sculpting material, it does not provide a mechanism for the computer to change the physical interface based on the data, the interaction loop is one-directional.

This is the point at which Topobo's gestural recording and playback capability becomes instrumental. Topobo aims to provide a physical sculpting medium that is bi-directional: a user can manipulate a form, and a computer can give computational feedback by manipulating the form. A creator's gesture becomes the input mechanism, and the system's actuation becomes the output; using motion to create a coincident input and output space for the designer. Can the actuation and 3D possibilities of Topobo mesh move beyond where these projects have reached their limitations?



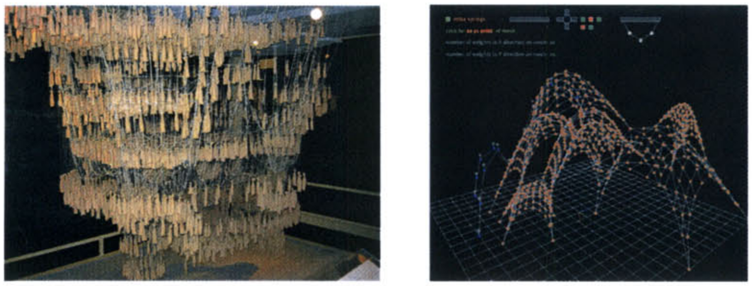
topobo mesh concept sketches - a closed object with constrained volume (left) and a flexible surface (right)

6.2 Kinetic modeling - Static structures

I envision the Topobo mesh as contributing to the design process in two related ways, first as a sculpting medium for static objects - products, buildings etc. Topobo models would be "sketched" in three dimensions and automatically linked to a more detailed on-screen model. One important feature which Topobo could add to this process is the presence of digital constraint mapping. For instance, a designer might sculpt a container using Topobo and then on the systems's graphical interface, constrain its volume to 2 gallons. The designer could continue to physically manipulate the physical Topobo model while the centralized constraint control of the system maintained the physical model's volume at 2 gallons, as the designer pushed in on one side, the model would expand to keep the volume constant.

a constrained object experiment with early prototype pieces

In Spring 2004, I participated in an interdisciplinary workshop at MIT, entitled "Exploring Gaudi's World, 3D design tools for equilibrium," a collaboration between the computer science and architecture departments. The workshop focused on the development of a software design tool for determining the form of three dimensional mesh systems under gravity loads. During the workshop, we attempted to recreate digitally Gaudi's process of using string models to determine structurally efficient forms, as a real-time design and analysis tool. Real

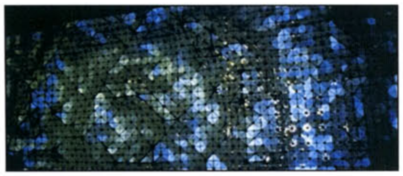


structurally efficient models - a Gaudi string model of La Sagrada Familia (left) and an on-screen string model created in the software tool developed in the MIT workshop, "Exploring Gaudi's World, 3D design tools for equilibrium"

string models display 100% efficient forms as they respond naturally to the force of gravity. As part of the workshop, we sketched designs by building physical string or mesh models often in the beginning stages of the design process and then attempted to recreate those forms on-screen using a mouse and keyboard, an intermediary process which would have been unnecessary if a Topobo meshing tool could have been used. One particularly salient feature created in our digital design tool was the ability to manipulate a model's percentage efficiency in light of a chosen aesthetic or form constraint, an option not possible with a real physical string model. As a physical modeling tool, Topobo could behave like a string model, responding naturally the forces of the physical world, or, its actuation capability would allow for manipulation of the form to off set the structural efficiency in favor of other characteristics, as is possible with our digital tool.

6.3 Kinetic Modeling - Kinetic structures

Topobo's potential as a kinetic modeling tool, however, may be best utilized in another area of changing architectural practice, a transition from static structures to what Bill Mitchell calls "programmable construction machines" [Snoonian 2002] Kas Oossterhuis builds on this notion, "Active programmable architecture based on real time calculation techniques is the way to the near future for the practice of architecture and for the building industry" [Oossterhuis 2002]. As a kinetic sculpting device, the Topobo mesh could be used as a physical design tool which responds as both input and output to a parametric virtual representation of both shape and motion. This would allow design professionals the possibility to physically experiment with kinetic and gestural expression in architecture in the same way they experiment with existing physical materials and offers a tool to explore surface formation as the physical embodiment of mathematical functions or a centralized algorithm.



Mark Goulthorpe, Aegis Hyposruface, 2001 - could topobo become a tool for testing patterns in kinetic architectural surfaces such as this one?

Mark Goulthorpe's Aegis Hyposurface [Snoonian 2002] provides the impetus to examine Topobo in the larger conceptual framework as a parametric modeling tool supporting the growth of kinetic architecture. The systems is a facetted metallic surface that has potential to deform physically (driven by pneumatic pistons) in response to electronic stimuli from the environment (movement, sound, light, etc.) or as controlled by a centralized mathematical function. As Goulthorpe describes it "The piece marks the transition from autoplastic (determinate) to alloplastic (interactive, indeterminate) space, a new species of reciprocal architecture." [Snoonian 2002]. Goulthorpe has shown particular interest in Topobo, viewing its potential to provide a scaled down modeling system for testing patterns and sequences for kinetic architecture applications such as this.

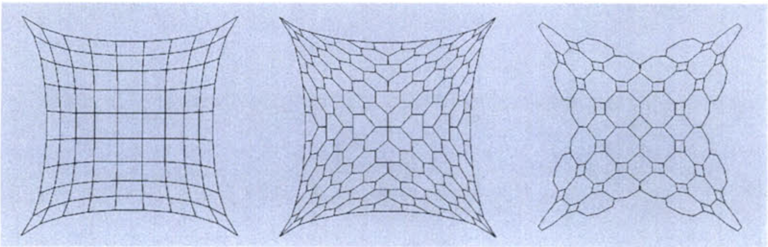
6.4 Determining Mesh Geometries

As I began the investigation of the ways to structure a Topobo mesh, it became clear that the mechanical movement afforded by the surface and the algorithmic determinants defining the virtual representation should be analyzed in tandem, figuring out how they could inform one another. Is there an appropriate compromise in physical form which maximizes the flexibility of the surface, while remaining consistent with the method of creating an on-screen parametric model? Design software tools employing NURBS are based on an inherently dynamic system, using algorithmic formulas to allow lines and surfaces to be continuously recalculated and adjusted. Conceptually, this is consistent with Topobo's kinetic functionality, shifting between recording and playing back servo position data over time. The further question lies in the geometric relationship to actuation, should the physical copy the virtual if the virtual can't copy the physical?

I then examined existing meshing strategies and found three categories of meshing patterns as possibilities for structures - repeated patterning, force line structures and branching structures.

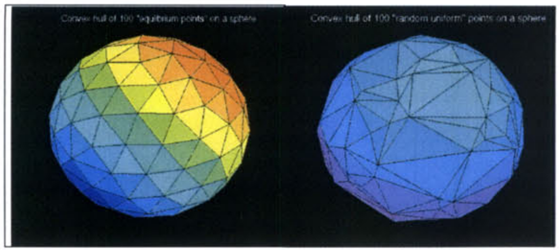
Repeated Patterns

The most simple style of meshing, these examples show a specific geometric "unit" (either a single shape or multiples combined) repeated consistently. These cases are symmetrical about the center point.

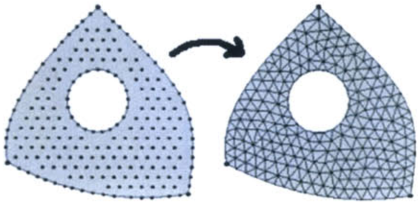


repeated patterning meshes - images courtesy Axel Killian

Within the area of repeated patterning, the concept of Delaunay triangulation arose with particular interest because of its relationship to the algorithmic process of creating surfaces in 3D modeling software. Delaunay triangulation is a method for dividing a surface into a set of triangles, based on a set of points specific to that surface. The surface is triangulated by drawing lines between any two points whose Voronoi domains touch. The Delaunay triangulation has the property that the circumcircle of every triangle does not contain any points of the triangulation, this property becomes important when looking for options to maximize mechanical movement and flexibility of a surface.



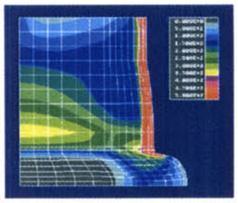
Delaunay triangulation can occur with both regular (left) and irregular (right) sets of points



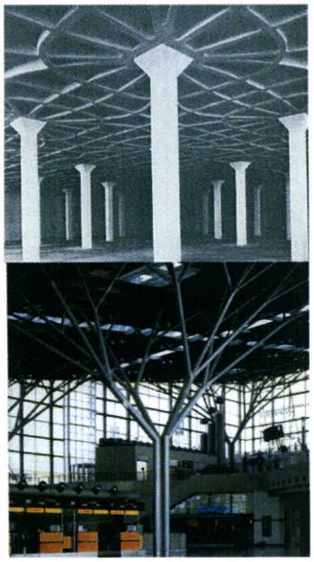
Delaunay triangulation

Lines of Forces

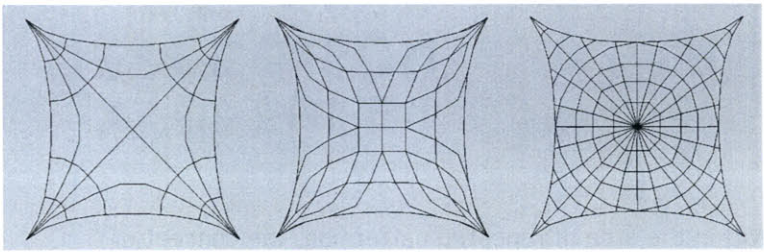
Patterning based on lines of forces maximize structural efficiency; the geometry is determined by the flow of forces through the surface based on structural loading, mimicking the visuals created by finite element analysis. While this works well for static structures, it does not prove to be an effective strategy in a dynamic surfaces where the forces are constantly in flux.



a rendering of finite element analysis - lines of force



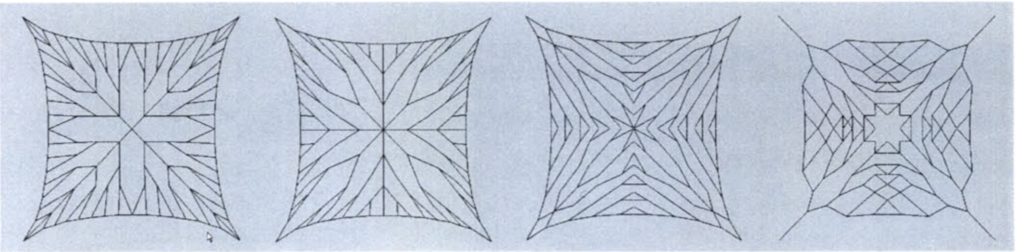
examples from architecture - a "line of force" structure by Luigi Nervi (top) and a "branching structure" at the Stuttgart airport (bottom)



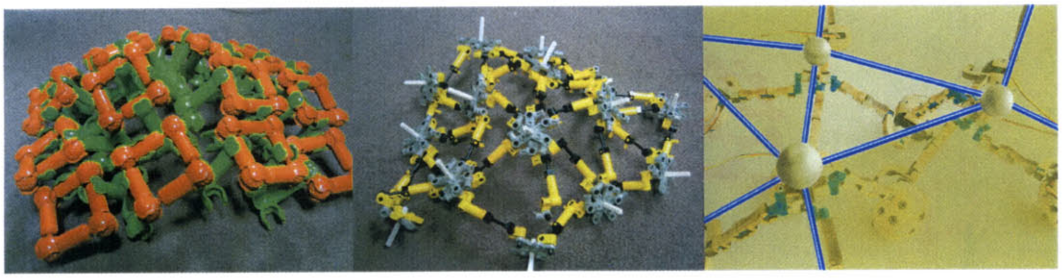
lines of force meshes- images courtesy Axel Killian

Branching Structures

Branching structures are formed by the biforcation of individual elements in a regular symmetric pattern. They mimic natural structures like trees. I was attracted to this patterning as it is closely aligned to Topobo geometric forms, deriving inspiration from how organisms grow, however, it has not proved to be a flexible mesh structure due to mechanical constraints.



branching structure meshes - images courtesy Axel Killian

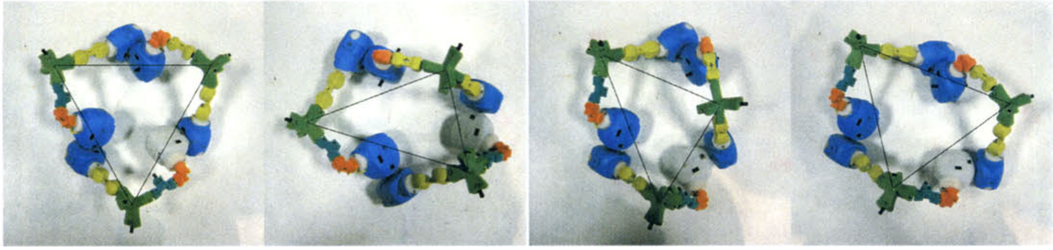


topobo mesh models - a square mesh (left), triangular mesh (center), and a virtual overlay on a physical mesh (right)

6.5 Building a Topobo Mesh

To start my explorations in building a mesh, I have focused on a repeated pattern triangular mesh as it could be best identified as a physical structure with an algorithmic on-screen corollary. The mesh is constructed by creating a repeated pattern out of geometrical "units" (a triangle for a triangular mesh, a square for a rectangular mesh, or a hexagon and pentagon together for a "soccer ball" mesh.) Each geometrical unit consists of a combination of Actives which serve as actuators to provide motion with multiple degrees of freedom, and passives which serve as "nodes" to define the surface. To create a side of each unit, (like a spline) three Actives are joined to each other with the shaft of the servo motors offset at 90 degrees in relationship to each other, and then joined on the ends by passives, the "nodes," This arrangement creates the flexibility of a ball and socket joint although offset in space by the dimensions of the Active. It is possible to use only two actives between each node, although flexibility of the mesh becomes more limited. The chains are then connected node to node as sides of the geometric units, to form the repeating mesh pattern. The information exchange between the Active units in the mesh and a connected PC occurs analogously to Topobo

building splines with topobo



a single three node triangle built with topobo, in four different positions, with 2 degrees of freedom (2 actives) between each node

creatures in the virtual mirror extension, each Active sending its position data through the decentralized network to control its counterpart in the on-screen model.

6.6 Limitations of the System

When discussing the mesh from a conceptual perspective, I have been omitting many serious mechanical and computational issues which create stumbling blocks to materializing a Topobo mesh and providing a meaningful interactive experience with it. Three of the most important unresolved issues include granularity and resolution, synchronous input and output, and predefined geometry.

Granularity and Resolution

The most obvious concern with using Topobo as a meshed surface is the size of the actuators. In addition, in order to get sufficient degrees of freedom rotation, multiple Actives must be chained together to create splines, and thus each triangle of the mesh becomes much larger than seems useful in a modeling material. This also establishes a disconnect between the resolution of the physical and virtual representations; detailed changes occurring in the virtual world would not be reflected in the physical model. Given such a low resolution model, an added importance is given to the accuracy of each individual actuator, small discrepancies in servo position would lead to large discrepancies in the physical model. Motors, however, are getting smaller, and greatly decreasing the size of the Actives would improve the resolution and the system's applicability to more generalized modeling. With actuators at their current size, Topobo could be thought of only as a rough 3D "sketching" tool.

Predefined Geometry

The sensing method of the current Topobo network relies only on the electrical network established between the ports of the Actives, which means the mechanical connections between the Actives and Passives of a mesh, and the orientations of those connections, cannot be sensed. The geometry of a mesh must therefore be physically constructed and then digitally constructed as a predefined surface structure in the virtual modeling environment, meaning it is not possible to and reconfigure the surface geometry during use. This creates limitations in shape complexity and physical flexibility of the surface. This limitation, however, comes as a decision we made early in the design process to avoid the technical complications of using mechanical-electrical connectors for every Topobo piece. With greater engineering development, a Topobo set where every piece, both Active and Passive, has built in sensing capabilities is technically feasible and would allow for reconfigurability.

Synchronous Input and Output

The Topobo system of gestural recording is based on sequencing - user input during record mode, actuated output during playback mode. While essential for testing kinetic simulations, this input-output modality creates possible complications with the interactive experience of sculpting with the surface in scenarios such as constraint mapping. For example, a time delay would be present between user input and the computer feedback making it difficult to have a fluid sculpting experience. Experimentation with the system would determine how much of a problem this would raise in the experience. A possible solution exists in adding the ability to sense force input during playback. Again, technically more complicated but feasible.

Chapter 7

Conclusion

Throughout this thesis, I have presented the Topobo system as an interface which encourages playful expression and rapid experimentation with different kinds of structures and motions in a variety of applications. As a set of primitives, it provides a platform for generalized actuated modeling. Topobo's programming by example provides immediate haptic feedback because the interface itself responds to the forces of nature that constrain the system, making it an appropriate system to aid in the modeling process. Although Topobo creations are built of many parts, Topobo's distributed design allows the user to focus on the global behavior of a structure as the movements of a single coordinated system, whether in teaching a creature to walk, or sculpting with a meshed surface. Because its design is inspired by nature forms, Topobo naturally lends itself to creating bioamorphic structures which can represent simulations from the micro to the macro scale.

I have also discussed evaluation results from Topobo's contribution as an educational digital manipulative, in use in classrooms to allow children to more intuitively investigate pedagogical concepts in physics, and have laid the foundation for a conceptual shift to thinking of Topobo as a meshed surface design tool. My research investigation has covered many of the interaction possibilities for Topobo and the directions I aim to pursue in the future. In conclusion, however, I would like to recontextualize Topobo's contribution on three different levels - examining the Topobo pieces as objects themselves, examining them as a tool kit for gestural and kinetic manipulation, and examining them as fused- in the form of a sculpting "material."

7.1 Topobo as a computational object

As tangible media begins to evolve into a more sophisticated genre of interface, the role of the tangible object in contributing and relating to its digital syntax also has the capacity to become more meaningful. Up until this point, the specific correspondence of meaning between physical form and computational data in tangible interfaces has remained relatively underexplored. In The Responsibility of Forms, Roland Barthes posits on the relationship of the form of objects to what they symbolize and how form can determine their related associations.

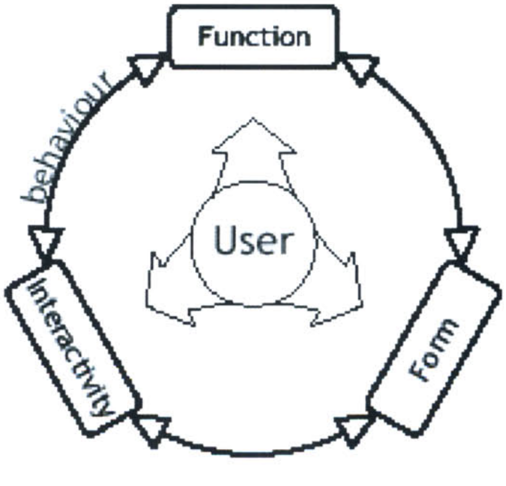
> The interest lies in the fact that these objects are acknowledged inductors of associations of ideas or, more obscurely, of actual symbols. Such objects constitute excellent elements of signification: on the one hand, they are discontinuous and complete in themselves, which is, for a sign, a physical quality; and on the other hand, they refer to clear, known signifieds; hence they are the elements of a true lexicon, stable to the point where we can readily constitute them into a syntax. [Barthes, 1982]

While he is not referring specifically to a digital paradigm, these words of Roland Barthes define for me a new methodology for thinking about the role of objects in the context of tangible interfaces. On the surface, a physical form, whether abstract or symbolically imbued, describes an aesthetic which naturally references cultural symbolism as well as memories, emotions, or associations of the user. Objects that are used as part of a tangible interface, however, must also be representative of the digital information or function to which they are correlated. The objects can be thought of as handles to digital information, or as abstract practical forms in themselves.

Because objects exist in shared physical space, they naturally lend themselves to becoming an extension of our bodies, as tools and symbols. These objects can become pieces in models which we create to represent and simplify a chosen microcosm. By taking advantage of our haptic relationship to objects, we can more closely observe and relate to the digital nature of that which is intangible to us in such an environment. For me, Topobo's formal qualities present an attempt to better embody and correspond to the digital data which it represents. The organic yet regular form of the Active seeks to highlight not only its kinetic capabilities but also correlate to the "organic" gestural data which it records, the motion of the human body. This relationship in Topobo has led me to the question, what other kinds of objects would also benefit from examining more closely interconnected form, function, and digital behavior and how can this guide the design of future tangible interfaces?

7.2 Topobo as a gestural prototyping tool

It is well known that together form and function inform the product design process, but with digital products, and increasing levels of interactivity and information embedded in such products, digital interaction must also contribute intimately to early stages in the design process. As evident in the design process of Topobo, the interconnectedness of form, function, and behavior should determine the development of any computational object. In their paper, "Form, Interaction and Function, An Exploratorium for Interactive Products," Frens and Djajadiningrat discuss the need for a mechanism which can incorporate digital-mechanical behavior, through sensing and actuation, into the prototyping process, "Programming the behavior of interactive models goes beyond mere definition of the fact that parts of the model move. It is also about how and when they move. It is about the 'feel' of the interaction" [Frens 2003].



Frens and Djajadiningrat's product development loop

As a fundamental unit of kinetic memory, the Topobo Active could exist as such a tool. We have created the current form of the Active to function specifically in the domains we have explored, but the embodiment of the concept of kinetic memory could take many forms. Breaking down Topobo's functionality into its simplest form leaves a single button, small PCB and actuated shaft. These discrete elements could form a kit of tools, available in various categories of shape, size and strength, and be embedded into diverse configurations of early design models. They could help prototype interactions with products using single repetitive motion, or with further development, the elements could be integrated into a broader control structure of the product for more causal functionality. When put forward as a generic tool, I believe designers would come up with alternative uses for Topobo's functionality and could help complement the product development loop- form, function, interaction- as a tool for the early stages of design.

7.3 Topobo as a new material

The functionality of Topobo as a meshed surface tool suffers from severe limitations in terms of mechanics and resolution. However, as actuators become miniaturized and distributed networking technologies become more robust and scalable, a system like Topobo has the possibility to behave less like a modular robotics system of discrete elements and more like a continuous material. In its current form, Topobo is by no means the much sought after digital clay. However, by stepping outside of current technological limitations to examine Topobo as an actuated surface, we begin to explore the interactions possibilities a more generalized TUI material could provide with the features of actuation, coincident and synchronous input and output, and scalability. Topobo's research contribution lies in how to configure those interactions into meaningful experiences and applications. It has the possibility to become a platform to explore ideas made accessible by kinetic modeling and the interaction processes which a generalized digital manipulable material could provide for continued research in those directions. With Topobo as an interface material, we can continue to harness our existing skills as human beings while investigating how digital technology can help augment and articulate those skills.

Bibliography

Anderson, D.; Frankel, J.L.; Marks, J.W.; Agarwala, A.; Beardsley, P.A.; Hodgins, J.K.; Leigh, D.L.; Ryall, K.; Sullivan, E.; Yedidia, J.S., Tangible Interactions and Graphical Interpretation: A New Approach to 3D Modeling. Proceedings of Siggraph 2000, ACM Press (2000).

Barthes, Roland, The Responsibility of Forms. New York: Hill and Wang, 1985.

Brosterman, N. Inventing Kindergarten. New York: Harry N. Adams, Inc, 1997.

Buxton, W, *Less is More (More or Less)*, in P. Denning (Ed.), The Invisible Future. The seamless integration of technology in everyday life. New York: McGraw Hill, 2001.

Duff, Yim, et al. US Patents 6,454,624: Robotic toy with posable joints, 6,575,802: Robotic toy modular system with distributed program and 6,605,914: Robotic toy modular system.

Esposito, C., Paley, W., and Ong, J., Of mice and monkeys: a specialized input device for virtual body animation. Proceedings of Siggraph 1995, ACM Press (1995).

Fitzmaurice, G. Ishii, H., Buxton, W. Bricks: Laying the Foundations for Graspable User Interfaces. Proceedings of CHI 1995, ACM Press (1995).

Flores, Fernando and Winograd, Terry. Understanding Computers and Cognition: A New Foundation for Design. Norwood, N.J.: Ablex Publishing, 1986.

Frei, P., Su, V., Mikhak, B., and Ishii, H. curlybot: Designing a New Class of Computational Toys. Proceedings of CHI 2000. ACM Press (2000).

Frens, J. W., J. P. Djajadiningrat and Overbeeke, C. J. (2003). Form, Interaction and Function, An Exploratorium for Interactive Products. Proceedings of the Journal of the Asian International Design Conference Vol. 1, Tsukuba, Japan, CD-Rom ISSN 1348-7817

Gorbet, M., Orth, M. and Ishii, H., Triangles: Tangible Interface for Manipulation and Exploration of Digital Information Topography. Proceedings of CHI 1998, ACM Press (1998).

Gropius, Walter, and Wensinger, Arthur, The Theatre of the Bauhaus, Middleton: Wesleyan University Press, 1961.

Ishii, H. and Ullmer, B. Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms. Proceedings of CHI 1997, ACM Press, (1997).

Ishii, H., Underkoffler, J., Chak, D., and Piper, B., Augmented Urban Planning Workbench: Overlaying Drawings, Physical Models and Simulation. Proceedings of IEEE and ACM ISMAR 2002, ACM Press (2002).

Iwata, H., Yano H., Nakaizumi, F. and Kawamura, R. Project FEELEX: adding haptic surface to graphics . Proceedings of Siggraph 2001, ACM Press (2001).

Juice website, Nate Waddoups, http://www.natew.com/juice

Kotay, Rus, Vona, and McGray. The Self-reconfiguring Molecule: Design and Control Algorithms, Workshop on Algorithmic Foundations of Robotics (1999).

Leach, Neil (ed.), Designing for a Digital World, London: Wiley Academy, 2002.

Lupton, Ellen, Skin: Surface, Substance + Design, New York: Princeton Architectural Press, 2002.

Mandel, Mike, Making Good Time, California Museum of Photography, University of California, Riverside, 1989.

Maubant and L. Moura (Eds), Architopia: Art, Architecture and Science, Portuguese National Science Foundation, February 2002.

McCullough, Malcolm, Abstracting Craft: The Practiced Digital Hand, Cambridge: the MIT Press, 1996.

Oosterhuis, Kas. Architecture Goes Wild. Rotterdam, 010 Publishers, 2002.

Open Dynamics Engine website, Russell Smith, http://ode.org

Pangaro, G., Maynes-Aminzade, D., and Ishii, H., The Actuated Workbench: Computer-Controlled Actuation in Tabletop Tangible Interfaces. Proceedings of UIST 2002, ACM Press (2002).

Papert, S. Mindstorms: Children Computers and Powerful Ideas. Cambridge, Massachusetts: Perseus Publishing, 1980.

Patten, J., Ishii, H., Hines, J., Pangaro, G., Sensetable: A

Wireless Object Tracking Platform for Tanible User Interfaces. Proceedings of CHI 2001, ACM Press (2001).

Piaget, Jean. The Grasp of Consciousness. Cambridge: Harvard University Press, 1976.

Piper, B., Ratti, C., and Ishii, H., Illuminating Clay: A 3-D Tangible Interface for Landscape Analysis. Proceedings of CHI 2002, ACM Press (2002).

Popper, Frank. Origins and Development of Kinetic Art. New York Graphic Society, Greenwich, Connecticut,1968.

Ramos, Vitorino Ramos, On the Implicit and on the Artificial: Morphogenesis and Emergent Aesthetics in Autonomous Collective Systems, from Architopia Book/Catalogue, Art, Architecture and Science. Maubant, J.L, Moura, L,. (Eds.) pp.25-57, Portuguese National Science Foundation, February 2002.

Resnick, Martin, Berg, et al. Digital Manipulatives: New Toys to Think With. Proceedings of CHI 1998, ACM Press (1998).

Resnick, M. Decentralized Modeling and Decentralized Thinking. Modeling and Simulation in Precollege Science and Mathematics, edited by W. Feurzeig and N. Roberts. Springer: New York (1999).

SodaPlay website. http://www.sodaplay.com

Snoonian, Deborah, The case for a digital master builder Architectural Record, May 2002.

Strohecker, C., and Donovan, B., Dino Stable, Media Lab Europe, http://www.medialabeurope.org/el/project.php?id=19

Taylor, Mark, (ed), Surface Consciousness, London: Wiley Academy, 2003.

Thompson, D. On Growth and Form, Cambridge: Cambridge University Press, 1952.

Tisdall, Caroline, and Bozzola, Angelo. Futurism, London: Thames and Hudson Ltd, 1977.

Vygotsky, L.S. Mind in Society. Cambridge: Harvard University Press, 1978.

Yim, Duff, Roufas. PolyBot: a Modular Reconfigurable Robot, IEEE Intl. Conf. on Robotics and Automation, (2000) San Francisco, CA.

Appendix A
Further Technical Specifications and Topobo "Active" PCB Diagram

The Actives' on-board custom electronics handles power distribution, memory, processing, and multichannel serial communications. Upon suggestion from electronics guru and former professor Paul Horowitz, we use an 18V power bus that is locally stepped down to 6V with a non- isolating buck converter and then is dropped to 5V with a linear regulator that powers the digital electronics. This minimizes the effects of power losses in the system, limits noise transfer between Actives and reduces current draws through our miniature connectors. A 40 MHz PIC microcontroller handles local memory, processing and network communications. At manufacture, a one-time calibration sequence measures the range of motion of the servo and correlates input and output position data. During record, the microcontroller reads the servo's internal potentiometer at 36Hz using a 10 bit ADC and writes scaled 8 bit values to local memory. This gives us 34 seconds of record data at 3/4° output resolution, which is accurate compared to the backlash in the servo's 4 stage gearbox. The sensor is filtered by an RC low pass filter (f3db ~ 10 Hz) to remove high frequency noise. A custom peer-to-peer serial networking protocol can transfer data between Actives at 57000 BPS. Mini USB-b connectors and specialized Maxim line drivers protect digital electronics during hot-swapping power/ communications cables between Actives. Our early decision not to use batteries keeps Actives lighter and avoids the need to regularly maintain power sources.

Scalability

A major goal of the electrical engineering was to create a scalable system that could accommodate up to 100 Actives at once. The high voltage power bus facilitates scalability by limiting current requirements and noise transfer. In general, the peer to peer networking protocol is scalable both in software and in hardware. Compared to a multi drop bus such as RS485, the peer to peer arrangement is more fault tolerant to floating grounds that can occur at the ends of long chains of Actives because immediate neighbors will always have close relative power and ground levels. So far, we have not exceeded Topobo's limits of scalability, but as the number of Actives in a creation increases, we suspect the main bottleneck will be series resistance in long chains of Actives. Series resistance may either affect data transmissions (which is sensitive to floating grounds), or motor driving ability (which requires high startup currents). Nonetheless, large structures do not always work as quickly and reliably as small ones. Topobo is susceptible to floating ground loops that can occur when people create large electrical rings of Actives. Large structures tend to work faster and more reliably if they are powered from multiple distributed points. If future systems need to increase scalability, one approach may be to use a higher voltage (24V - 48V) power bus.

Software: Distributed Computation and Control

The autonomous functions of an Active include motor calibration, local recording and local playback. The remaining computation is devoted to a network communications protocol that is designed to be fault-tolerant and flexible. We expected children to arbitrarily create various network loops, push buttons in parallel, start recording with one button and stop with another, and do other "non standard" things with Topobo. Therefore, the system is designed to cause Actives to stay in synchronized states amidst any possible network topology, to easily incorporate new nodes that might be added to the network, and to easily forget nodes that are removed from the network. The major challenge in the firmware development was coordinating two time sensitive tasks, motor control and serial communications. While our servo requires a low duty cycle signal (about 40 Hz), it must be extremely consistent and is not fault tolerant, so motor control has priority over network communications.

Motor Control

The servo is driven by sending a 40 Hz TTL signal whose peak is 1-2 ms long. Varying pulse widths correspond to absolute output positions measured from a potentiometer that is connected to the output shaft of the servo. Our microcontroller creates servo pulses using a two timers that change the duty cycle of the pulse based on 8 bit position values. No two servos are the same, so a valid range of pulse widths is established for each Active during a calibration sequence that is performed at time of manufacture.

Motor and Sensor Calibration

The calibration algorithm correlates input potentiometer readings from the servo to corresponding output pulse signals. The mechanical range of the servo is smaller than the electrical range of the pot, so we do not use the full range of the ADC. The calibration scheme first determines the absolute minimum and maximum potentiometer readings for the servo by overdriving the servo to the left and right mechanical stops while reading the ADC. A series of measured pulses then gradually drives the servo to the left and right stops while the ADC is concurrently read. When the ADC value matches the previously recorded minimum or maximum value, a minimum or maximum pulse width is recorded for the servo. These maximum and minimum pulse and ADC values are stored in EEPROM and all subsequent pulse widths are created along a linear scale between the minimum and maximum pulses. Similarly, all subsequent 10 bit ADC reads are linearly scaled to an 8 bit value between 0-254 before being stored in memory. The calibration scheme is convenient for a number of reasons. It allows us to use the full range of the mechanical motion of each Active, get full resolution out of 8 bit storage registers in a data array used for position recording, and standardizes all positions readings across Actives. For instance, it is due to this standardization that the Queen is able to easily communicate a "copy" command despite significant inconsistencies among Actives' hardware.

Record and Playback

During normal local recording, an Active will read its ADC at about 36 Hz and write values to a 1Kb data array. When playback is initiated (or when the array is full) the data is copied to nonvolatile flash memory and is then passed as an argument to the playback function, which simply uses the calibration results and recorded position data to recreate a series of servo pulses at 36 Hz. This gives us a maximum of about 34 seconds of recording time. One improvement to this scheme is to record at half the rate and linearly interpolate values during playback using a simple average. This approach has been proven to work and gives the user over a minute of recording time. By writing to flash memory, programs can be recalled if an Active is temporarily unplugged.

Communications

Peer to peer communications are handled exclusively in software, giving us 4 channels of serial communications with data rates at around 57000 bits per second. The networking protocol uses two wires for communication, generally used as "clock" and "data" that are by default pulled to Vcc with 220K pullup resistors. In the program's main loop, an Active will routinely poll for messages on all channels. If an Active wants to send a message, it will pull the clock line low and wait for the data line to be pulled low by the neighbor. If no neighbor is present, the channel will timeout and the Active will check the next channel. If the handshaking is returned (the receiver pulls the data line low), the sender will begin clocking data at a predefined rate. Bytes are transmitted with a parity bit and arrive in 1-5 byte packets handled by a software data buffer. An error in parity will cause the receiver to request the bad bytes be resent. An Active can only send or receive on one channel at one time, as we have no hardware buffers. Messages arrive with a message type (denoting a type of state change, for instance) an argument, and a message ID. Message ID's are used to prevent propagation of a message in a network loop: if the same message type and ID is received twice, the message is killed.

Message Types

The most common messages are state changes telling an Active to record, playback, or stop, and synchronization signals. Other message types are Backpack messages and Queen messages that include a position signal. When a message is received correctly, it is immediately sent to all communications channels except the channel the message was received on. After a message is propagated, it is processed.

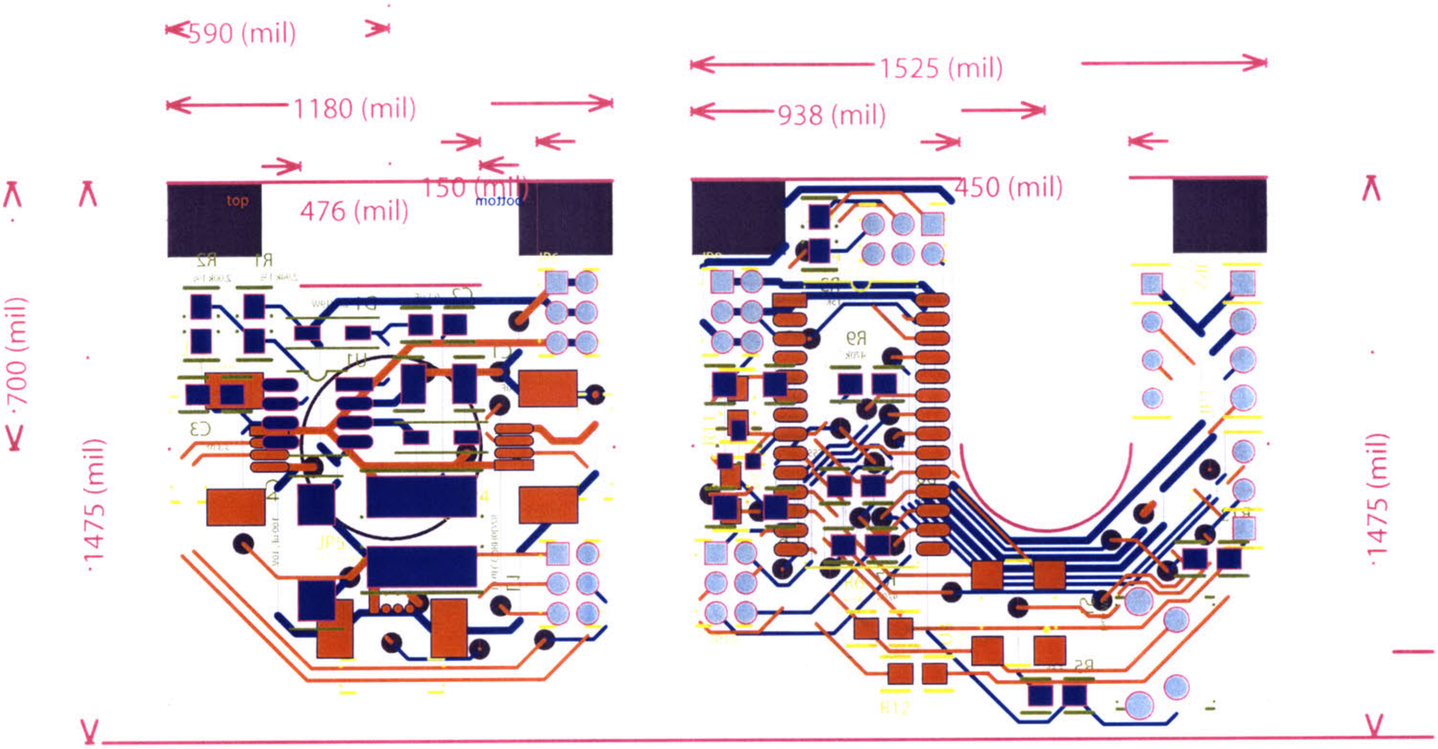
Synchronization

One problem with an asynchronous system such as Topobo is that sometimes Actives record messages of slightly different lengths, causing them to eventually get out of phase during their looping playback. To keep Actives synchronized during playback, they all communicate their loop start to their neighbors. If an Active receives a loop start signal and its own array pointer is near its loop start, the Active's array pointer will jump to its loop start. This is similar to the way symphony musicians stay in rhythm by subtly listening to the cadence of their neighbors. By hearing a signal from one's neighbors, slight errors in timing can be corrected. Backpack Engineering The backpacks are made of a single PCB with two power/communications ports, a button and a potentiometer housed in a plastic case. Their engineering is similar to the Actives with a few notable exceptions. Backpacks have no servo, and thus require much less power. This allowed us to power the Backpacks with a linear regulator instead of the more complex switching regulator used on the Actives. We also do not use a buffered line driver, and instead rely on the mechanical design of the USB connectors to protect I/O lines during hot swapping. Backpacks use the same PIC as the Actives and implement the standard Topobo communications protocol, allowing them to process and rout messages through their two I/O ports. Unlike the Actives, one of the ports is a "male" plug, allowing the backpack to connect directly to an Active without the need for an additional cable.

Backpack Communications

When a backpack is attached to an Active, it will announce to that Active that it is present and pass its backpack identity and pot value to that Active. It will then send an occasional (5 Hz) "I'm still here" message to the Active to denote that it is still attached. Any changes is the ADC, or any received messages will be passed to the Active at normal data rates. If an Active ceases to hear the Backpack's "I'm still here" message, the Active's internal "backpack timer" will timeout, and the Active assumes that the Backpack is no longer present.

Topobo "Active" PCB Diagram



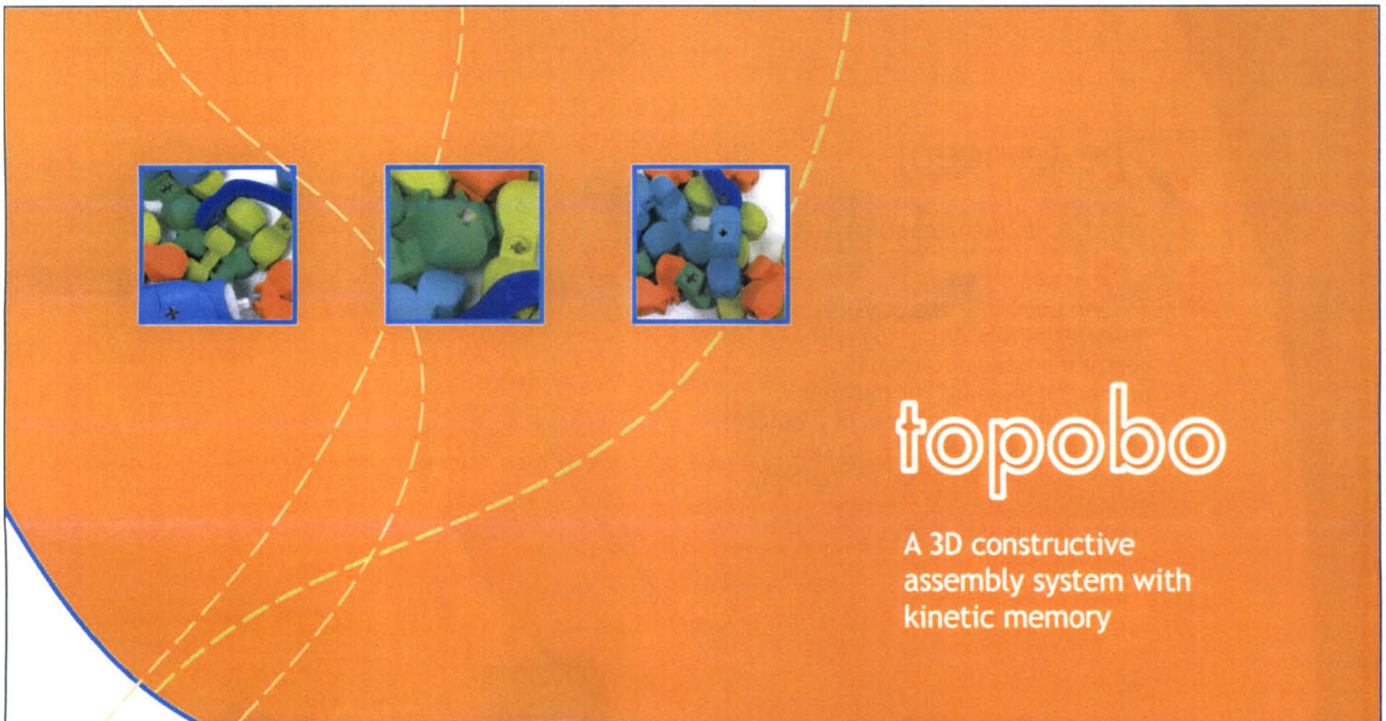
Centerline of Switch Actuator

Elevation of Actuator over board is 4mm

Appendix B

Tobobo Brochure

We originaly developed this brochure as part of our application to ID Magazine's Annual Design Review and have since used it to communicate the concept of Topobo to a non-academic audience



topobo

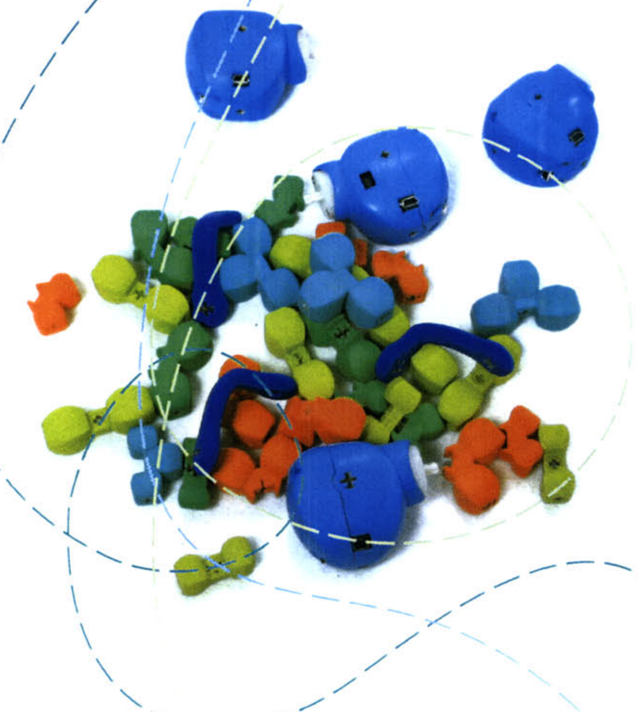
A 3D constructive
assembly system with
kinetic memory

Hayes Raffle
Amanda Parkes
Tangible Media Group
MIT Media Lab

The Concept

What is it like to sculpt with motion?

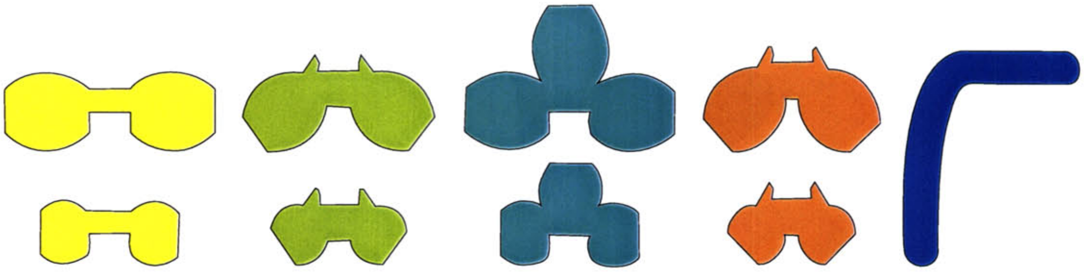
Topobo combines the physical qualities of a building toy with gestural recording capability producing a means for dynamic expression with the press of a button and the flick of a wrist. Topobo works like an extension of the body, giving one's gestural fluency computation and memory.



System Design

The Topobo system is comprised of ten primitives that are connected with Lego Technics® connectors. Nine of these primitives are called "Passive" because they form static connections. One motorized "Active" forms dynamic connections which allows the system to reproduce manipulations to a structure.

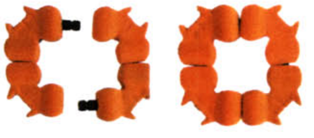
The Passives

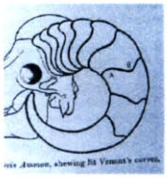


straight tetrahedral (108°) "T" 90° elbow

The Topobo passives can be connected end to end or with their central notches. The Topobo geometry allows for spatial loops

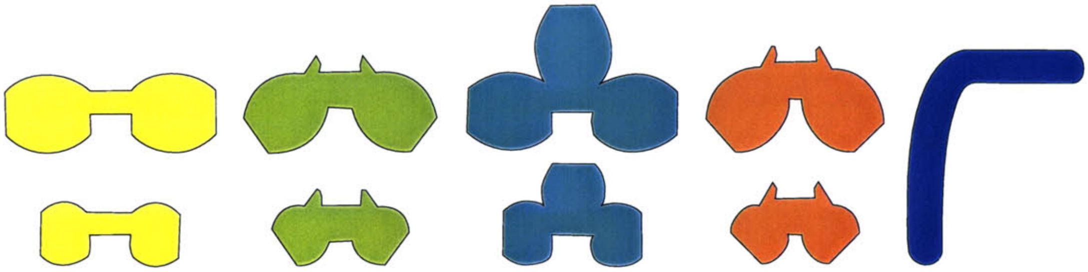
growth patterns & crystal structure inspired the geometry of topobo

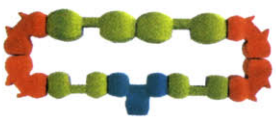




scaling 3:2

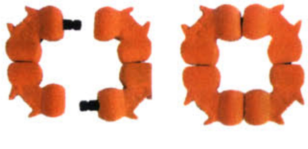
The Passives





The Topobo passives can be connected end to end or with their central notches. The Topobo geometry allows for spatial loops

growth patterns & crystal structure inspired the geometry of topobo



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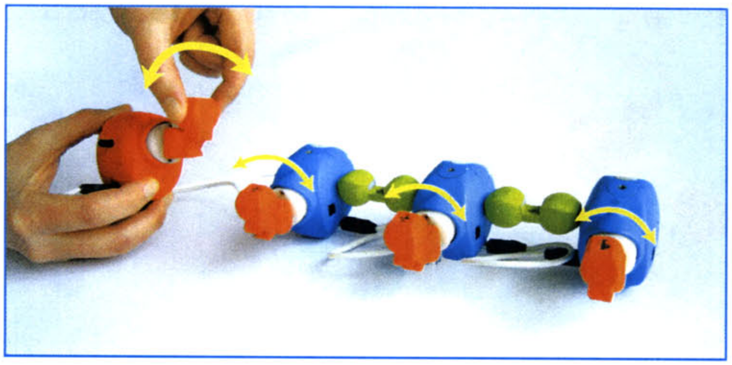
The Queen



Special orange actives called Queens can control many other Actives. In both record and playback, all motions made to a queen are mimicked by the other actives connected to the Queen.

centralized control

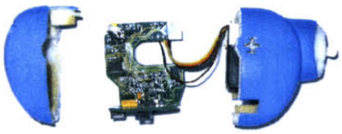
actives connected with tetrahedral passives create a spring-like helix when controlled by a queen.

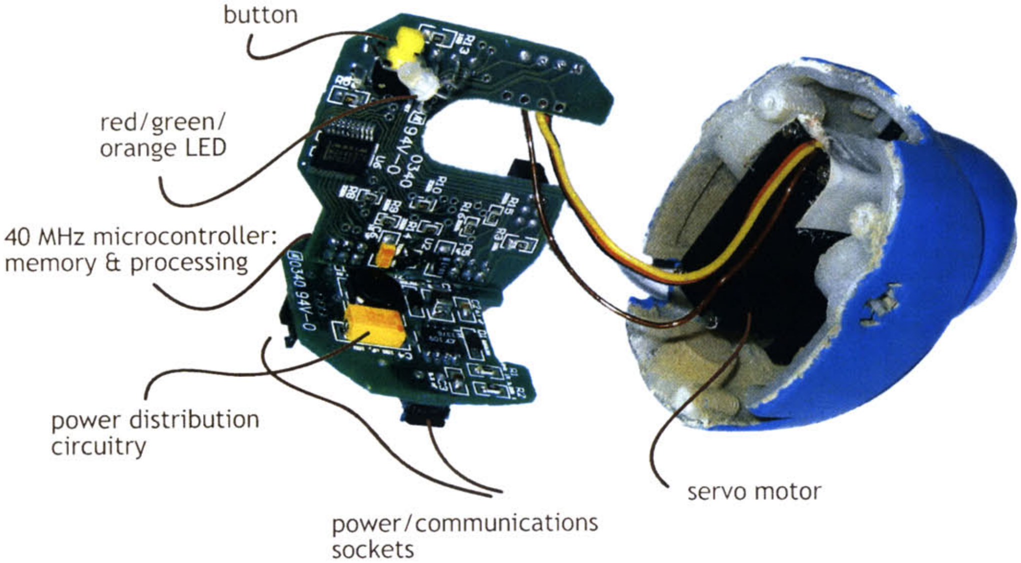
a linear sequence with a queen creates a circle

a special "decay Queen" tells each active to increasingly scale the Queen's motion. a linear sequence creates a spiral

a special "time delay Queen" tells each active to wait before mimicking the Queen. a linear sequence creates a wave.

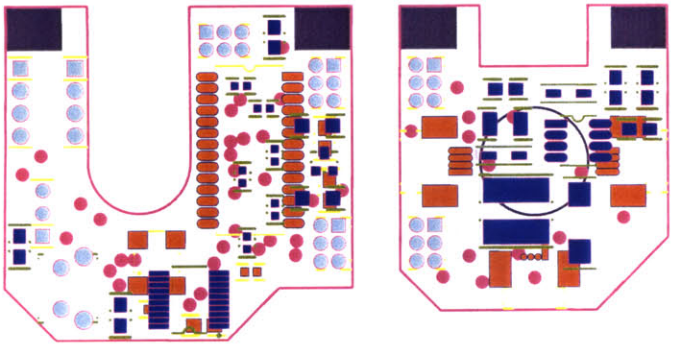
Topobo Technology



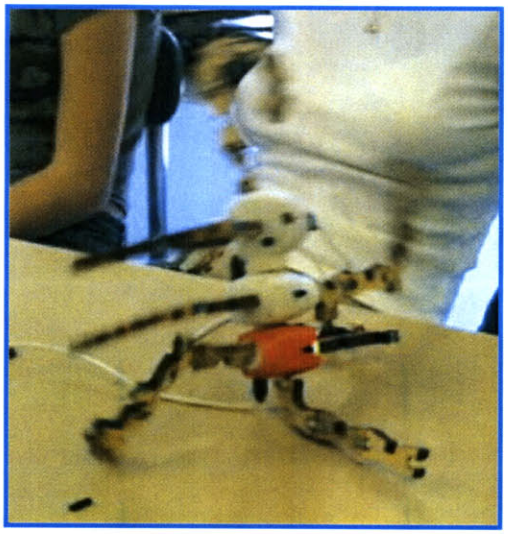


electronics design

Topobo is based on modular robotics technology. Electronics inside every Active handle local memory and processing and power distribution. A custom peer to peer serial network allows Actives to communicate with each other through small, white cables.

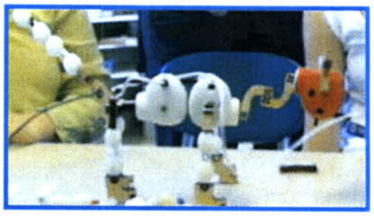


Topobo in action



We found that Topobo can help students ages 7-13 to learn about:

- Balance
- Center of Mass/Center of Gravity
- Coordination
- Relative motion
- Movement with Multiple Degrees of Freedom
- Relationships between Local and Global Interactions

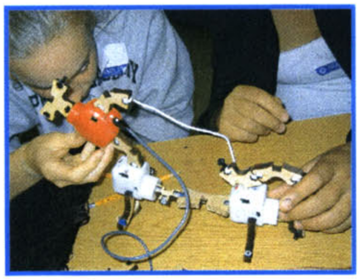


A tool for cooperative learning

When we took Topobo in to the classroom, kindergartners, second graders and eighth graders cooperated to make Topobo creations. Younger kids told stories with topobo and did open-ended explorations. Older kids focused on trying to make things walk.

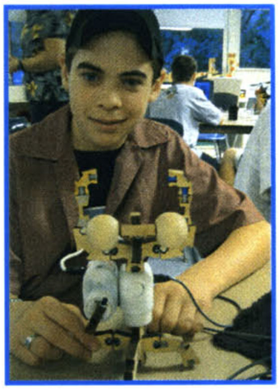
a 2nd grade collaboration

two 8th graders programming together

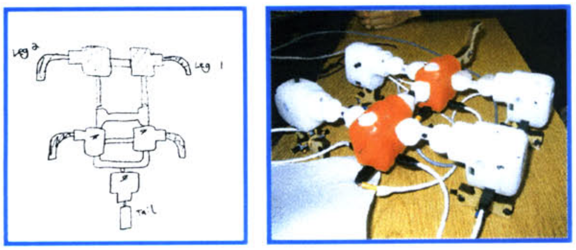


Animals & Machines

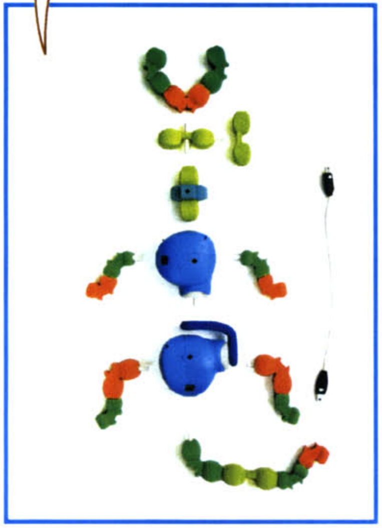
Kindergartners, second graders and eighth graders all related to Topobo models with their "familiar knowledge" about animals and machines. Metaphoric allusions to machines (robotics) and especially to animals ("the elephant," "the ant," "the scorpion," "the horse," "the no-walking man") were descriptive and salient. Many 8th grade students changed their creations based on their ideas about how animals and people move.



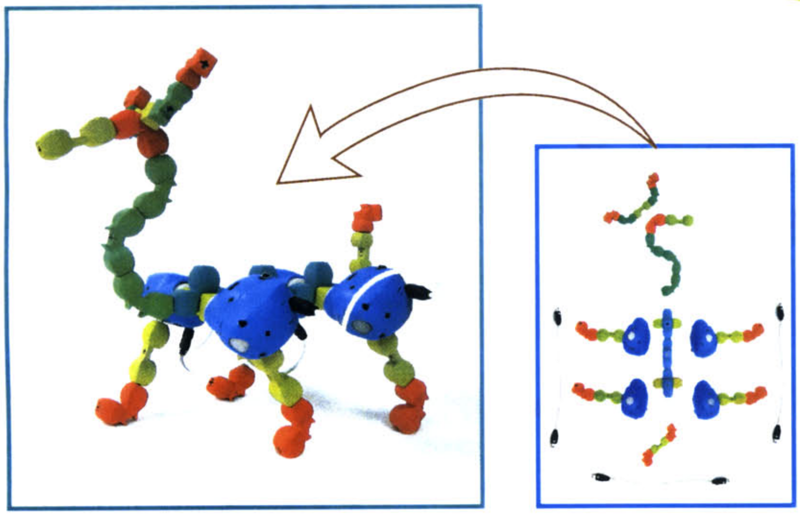
some 8th graders designed their creations on paper



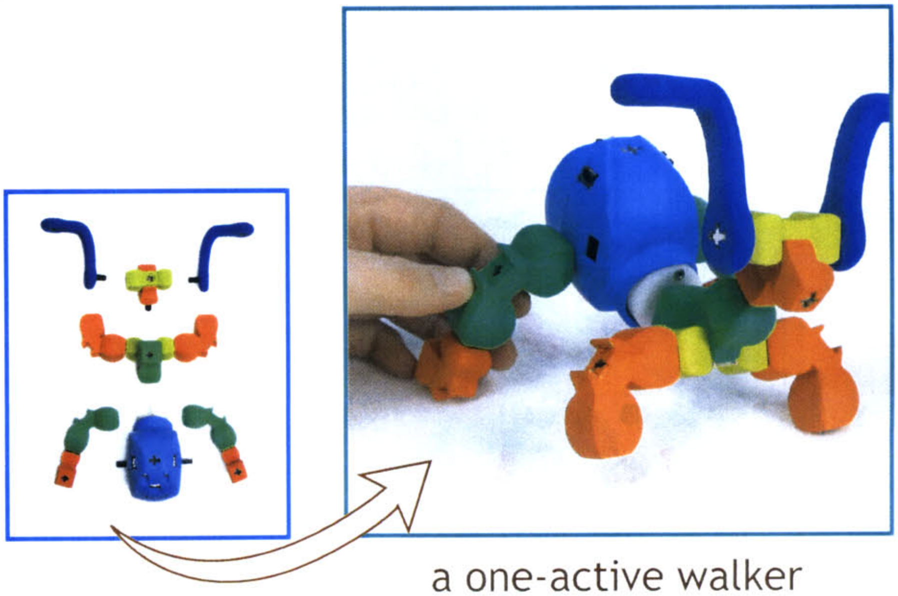
Topobo Creations



a moose

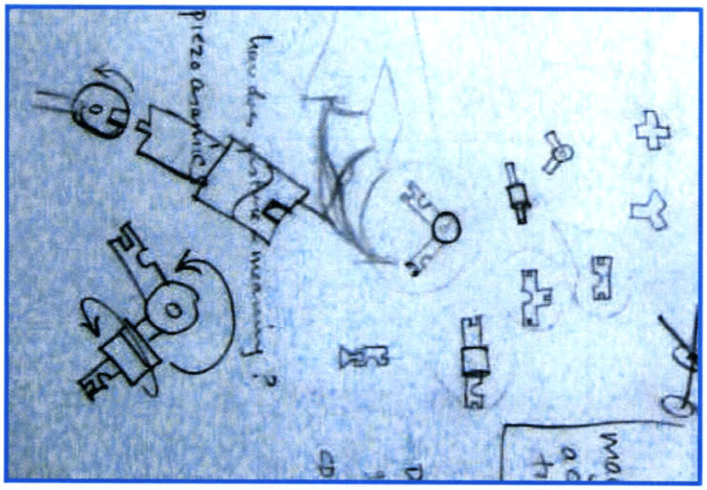


a griffin

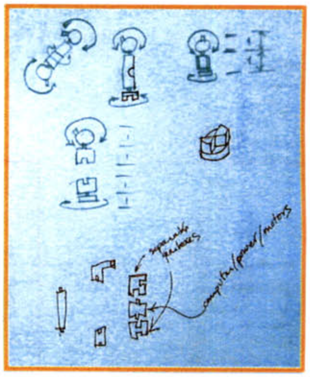


a one-active walker

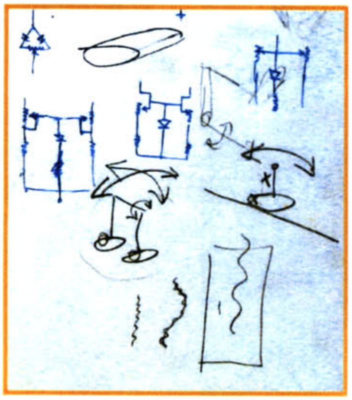
Concept & Early Prototypes



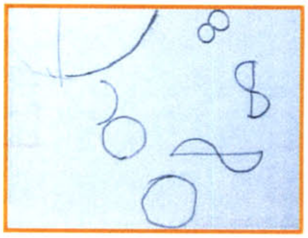
After choosing motors as our actuators, we did drawings to study spatial relationships possible with different arrangements of pivot joints. A branching system was an early choice for geometry.



assembly drawings questioned the possibility of fitting motors and electronics in one designed system.

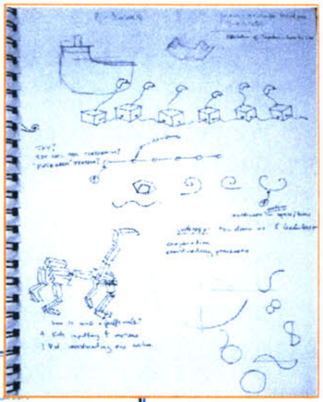


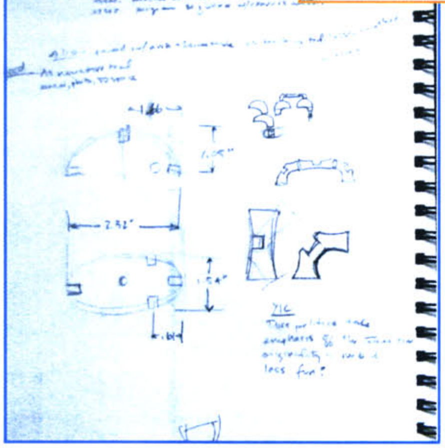
studies of passive walking toys and electronic systems compare concepts of feedback and emergence in mechanical and electronic systems.



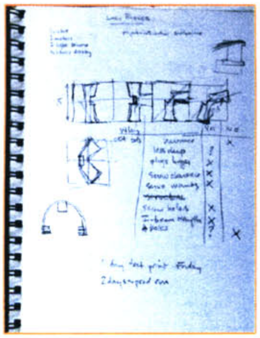
early studies of waves led to the time delay Queen.

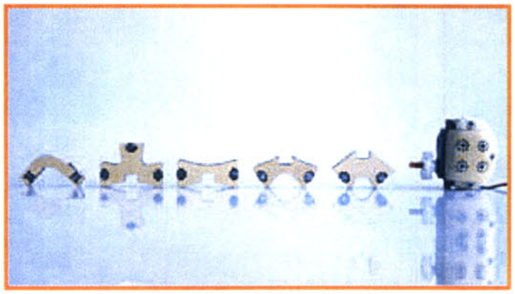
We studied different housings with sketches, clay and cardboard models, and wooden exoskeletons for our electronics and motors.





The passives, which are based on tetrahedral and cubic crystals allow 3D branching structures that could take advantage of rotating joints. They were sketched and prototyped on a lasercutter in a weekend.

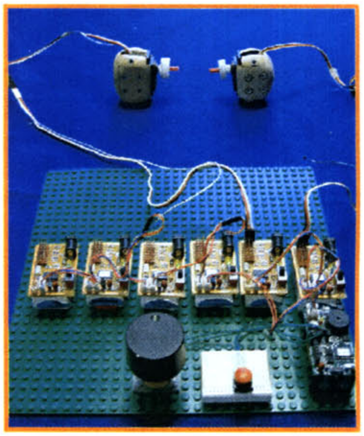




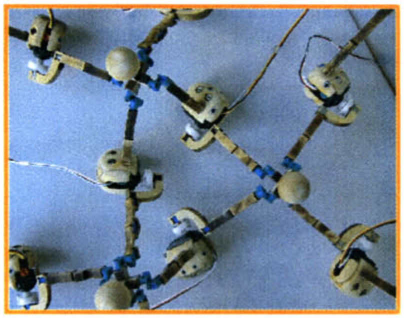
The first prototype was made with wood and servo motors.

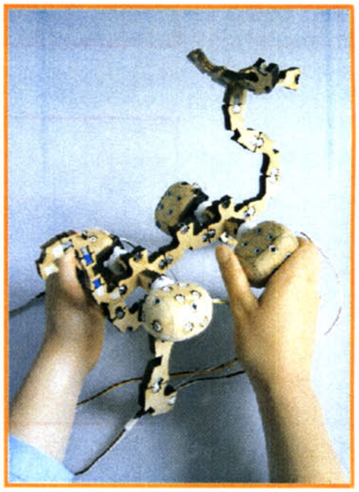
Design Development

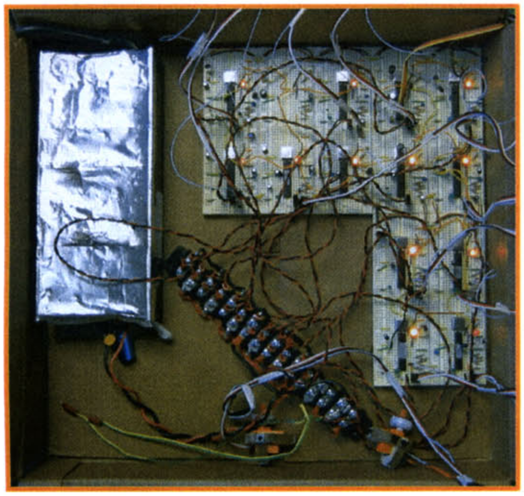
We initially built dozens of physical prototypes out of plastic and paper to study spatial geometries with rotary motion. This led to the development of the current system geometry and a proof of concept using Cricket microcontrollers and servo motors. The Cricket prototype was extremely fast to implement and allowed us to experiment with the capabilities of the system design.



Our first scalable prototype followed, made with wood, hobby servos and breadboarded electronics. Evaluations of this system with kindergartners and second graders helped guide the design of the current system.

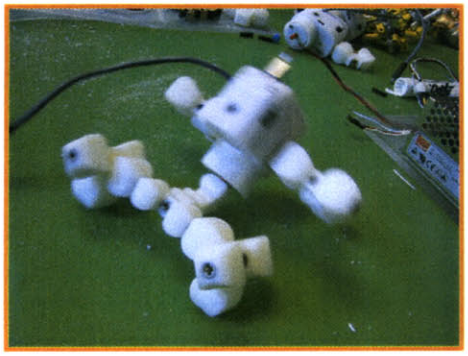




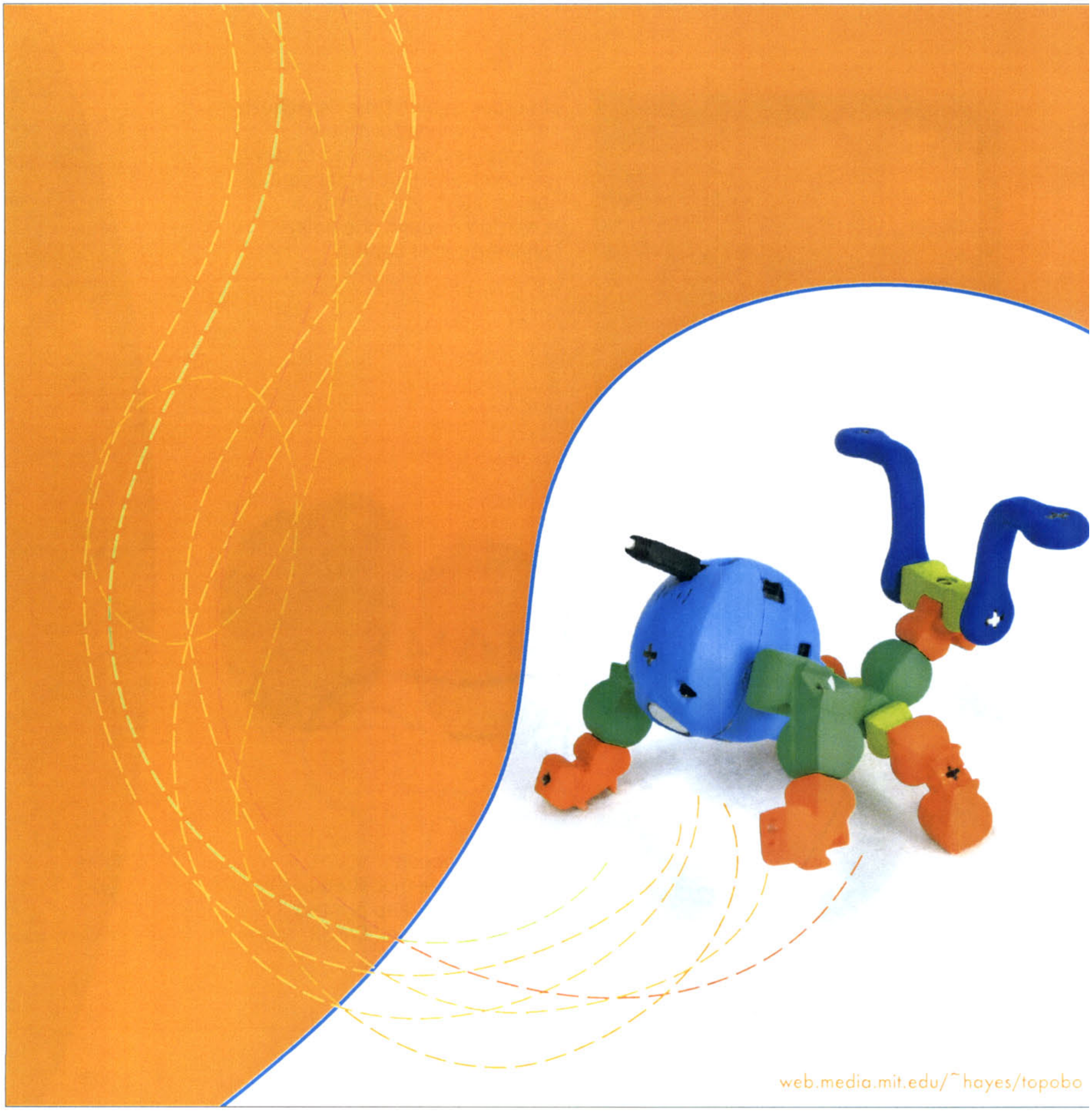


In order to avoid the "spaghetti" of wires we had with our prototypes, we needed to design a power distribution scheme to power all of the parts in a creation through one daisy-chained set of cables

Electronics design began on paper and progressed through many series of iterations from "breadboarded" electronics to printed circuit boards.



After the wooden prototypes, we modelled a plastic housing and printed plastic parts on an FDM 3D printer.


web.media.mit.edu/~hayes/topobo

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This thesis is dedicated to my dad who I know would be delightfully astounded to see what I've been up to since those long ago days we spent building things in the garage...

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