Beyond Record and Play

Backpacks: Tangible Modulators for Kinetic Behavior

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ABSTRACT
Digital Manipulatives embed computation in familiar children's toys and provide means for children to design behavior. Some systems use "record and play" as a form of programming by demonstration that is intuitive and easy to learn. With others, children write symbolic programs with a GUI and download them into a toy, an approach that is conceptually extensible, but is inconsistent with the physicality of educational manipulatives. The challenge we address is to create a tangible interface that can retain the immediacy and emotional engagement of "record and play" and incorporate a mechanism for real time and direct modulation of behavior during program execution.

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

Author Keywords
Digital Manipulative, Education, Toy, Learning, Children, Modular Robotics, Programming by Demonstration, Tangible Interface.

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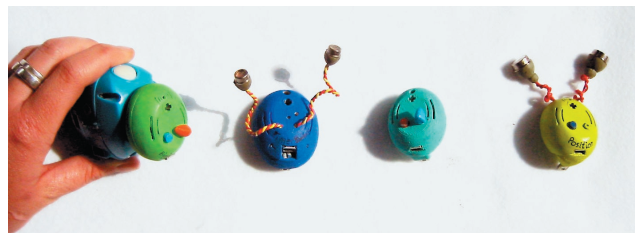

Figure 1. Four Backpacks - Bigger-Smaller, Time Delay, Faster-Slower and Offset.

ACM Classification Keywords
K.3.1: Computers and Education: Computer Uses in Education. H.1.2: Models and Principles: User/Machine Systems. H.5.2: Information Interfaces and Presentation: User Interfaces.

INTRODUCTION
Recent interface design work in digital manipulatives has sought to build on the success of educational manipulatives and constructivist learning, while engaging learners in new ideas about dynamic systems through the use of computer technologies. The general goal is to create tools and environments with which children can create concrete models of different kinds of dynamic systems. In testing their models, children will develop theories (mental models) about how those systems behave. Children then can test their mental models by experimenting and changing the concrete models they have built [1, 2, 15, 20].

Digital manipulatives have employed several different styles of interface design that encourage children to create and test their models in different ways. These range from very immediate models like "record and play," a form of programming-by-demonstration, to textual or iconic symbolic programming.

Digital manipulatives that employ a traditional programming paradigm, such as LEGO Mindstorms, (figure 2) are praised for their flexibility and abstraction, but are difficult for novices to learn and use [21]. Due to their abstraction, models created with them are easy to fine-tune and edit because behavior is parameterized. Since they are designed

Figure 2. LEGO Mindstorms (left) and curlybot record and play (right).

after existing engineering tools, these systems can also introduce complex ideas about feedback and emergence in ways that cleanly map to expert design systems. However, these systems present divergent interaction models for physical model making and behavior-creating. Since the GUI and physical modeling paradigms are decoupled and conceptually different, parallel modeling of objects and their associated behaviors can be difficult for some learners.

Systems that employ record and play have been argued to be more experiential in nature and more intuitive for users than other programming paradigms [1, 8, 22]. With these systems children can express their own desires, intention and aesthetics in their model, because the structure of the model can reflect a learner's aesthetic desires rather than the symbolic structure of the system. This flexibility has been argued to facilitate learning because people become emotionally engaged with their work and focus on it deeply. However, since decoupling the physical and symbolic models results in systems that have no clear "handles" to edit the programs, interfaces for manipulating the programs' dynamics are not obvious. This absence of an interface to play with the programs means that children have fewer tools to understand the program's roles in determining the overall system behavior.

In general, systems that employ record and play are not thought to be very extensible. This has implications for digital manipulatives where children are, in part, modeling behavior. Extensibility is critical to make a system remain engaging as learners advance and want to experiment with more abstract concepts. A question then, is how to create digital manipulatives that retain the immediacy and emotional engagement of record and play and incorporate some of the flexibility and sophistication of control structures, feedback and parameterization of data, all concepts that are part of a traditional programming paradigm.

BACKPACKS

Backpacks (figure 1) introduce parameterized transformations, sensors and feedback to a modular robotic building system with specialized modular components.We chose the Topobo system [18] as a platform for this work.

The original Topobo system:

Topobo is a constructive assembly system with kinetic memory, the ability to record and playback physical motion. For instance, a child can build a dog and teach it how to walk by twisting the dog's body. The dog will then walk on its own. Topobo is comprised of "passives" (static plastic parts), and "Actives," which are motorized modular robotic modules with memory and communications. Normally, in a structure with many Actives, all of the actives will synchronously record or playback their own local motions. However, if a special active called a Queen is used, all of the other actives will mimic the Queen's motion. Through rapid iteration, children ages 8-13 used Topobo to create walking robots and develop an intuition for how torque, leverage, balance and local-global interactions affect such kinematic systems [18].

When using Topobo, a child will make a model, record a motion, and watch it play back. If he would like to change the movement of his creation, he will start over and record a new motion. Although a child can flexibly edit the shape of his physical model, he cannot edit the "shape" of his recording (the program).

Backpacks Design:

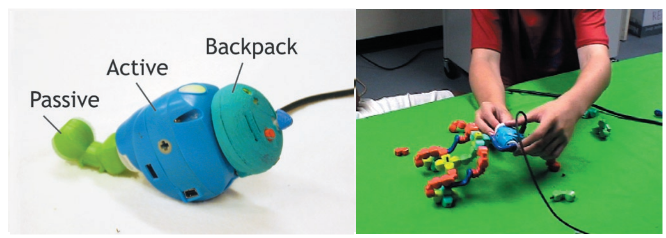

Figure 3. Faster-Slower Backpack attached to Active (left). A student modulates a creation's playback frequency (right).

Backpacks allow children to modulate recorded Topobo motions. They are physical parts with a button and a knob that can be snapped onto an Active to modulate the phase, amplitude, frequency, or orientation of playback motions (figure 3). These effects are described using familiar words, where phase is called *Time Delay*, frequency is called *Faster-Slower*, amplitude is called *Bigger-Smaller*, and orientation is called *Offset*. If we think of Topobo in terms of grammar, a child's physical creation is a "noun," its recorded motion is a "verb," and Backpacks are "adverbs."

Backpacks have three different modes — local, global and distributed — that give children tools to explore their creations' local-global interactions in detail.

Local: When a Backpack is attached to an Active, it affects only that Active.

Global: A Backpack is attached to an Active, and its button is pushed. Or, the backpack is attached to a Queen. The Backpack identically affects every Active in the structure.

Distributed: A Backpack is attached to a Queen and its button is pushed. The backpack affects all Actives and its modulation is proportional to an Active's number of network hops from the Queen. Here, the rate of change is controlled with the Backpack's knob.

In the spirit of a building toy, Backpacks are modular: many may be used in parallel, in either local or global modes. They are designed to embody the principle of "coincident input/output" that is dominant among tangible interfaces [11]: when a backpack is removed from the system its effect disappears, and the Actives will revert to their original recorded motions. In Topobo terminology, Backpacks are neither "Active" nor "Passive" because they introduce a new paradigm to Topobo that is physically static, but computationally dynamic.

By using Backpacks in different ways, we will explain how they allow children to experiment with sensors, conditional behaviors and feedback in their kinetic creations with a physical model-making paradigm.

DOMAINS OF KNOWLEDGE:

Children can use Backpacks to explore many ideas about local-global interactions that determine the behaviors of their creations. They can also explore ways that motion patterns can generate organized behavior in distributed systems. Although the original Topobo Queens and Augmented Queens illustrated some of these ideas, Backpacks allow children to more specifically test how local motion components like phase can affect a creature's overall movements.

Controlled Asynchrony

A child has made a dog that first turns its body and then shakes its head three times. Faster/Slower Backpack might be used to make a dog's body turn faster. The body is now out of sync with its head's movements.

Phase Shift

Time Delay Backpack changes the moment at which an Active will start its loop relative to the other Actives in a creation. For instance, imagine a dog that is initially programmed to wag its tail and then shake its head. A child might attach a Time Delay Backpack to its tail and turn the knob on the Backpack to make the tail wag in sync with the head's shaking. Similarly, a dog that is trained to twist its front and back legs in sync may be adjusted so that it twists its front legs first. In this way, the dog can be made to walk. Conversely, making the rear legs twist first may make the dog walk backwards. This introduces ideas about positive and negative phase shift.

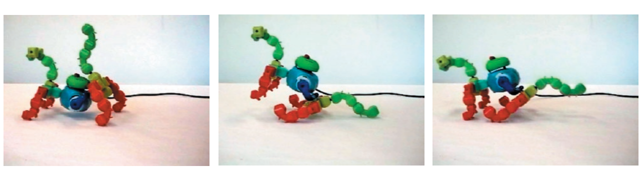

Figure 4. Frequency is modulated to make this dog gallop.

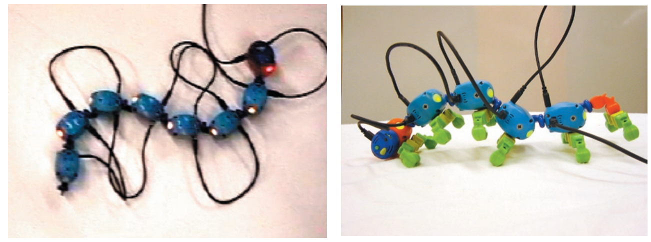

Figure 5. Distributed Time Delay leads to waves (left) and a walking caterpillar (right).

Distortion

Bigger-Smaller Backpack scales the recorded motion of an Active. Motions are scaled relative to the start position of the recording. Children may discover that, since Actives rotate only 170°, amplified motions may get "clipped" during playback.

A seven year old boy used Faster-Slower Backpack to make a walking dog move faster. To his surprise, its oscillating movements got smaller, rather than faster. With an adult's guidance, he understood that the motor could not move fast enough to play his "faster" recording.

Resonance

Faster-Slower Backpack can be used to see if faster motor movements create faster locomotion. Children can explore ideas related to resonance by building creatures that "gallop" and exploring how they may gallop more quickly when the Active itself is moving more slowly (figure 4). Bigger-Smaller Backpack may also be used to find a structure's resonance, because some creatures walk better by taking larger steps and some walk better taking smaller steps.

Waves

When a child programs a structure with a Queen, all Actives will synchronously mimic the Queen. When a Backpack is attached to a Queen and the user pushes the backpack's button, a Distributed behavior causes the backpack's modulation to increase with distance from the Queen.

For instance, if a Queen is attached to a linear string of Actives, gradual rotations to the Queen will cause the string to curl into a circle. With the Time Delay Backpack, the Queen's movement will be mimicked after a propagation delay that is incremented between each Active in the string. Due to Topobo's looping playback, a wave-like motion results. Turning the knob on the Time Delay Backpack will change the shape of the wave (figure 5).

Spirals

If the child replaces Time Delay Backpack from the previous example with the Bigger-Smaller Backpack, he will cause this same string to curl into a flat nautilus spiral.

Harmonics
Faster-slower backpack can cause the same string to exhibit harmonic resonance.

Time Delay Queen also can exhibit harmonic resonance when children turn a Backpack's knob to see if they can make a sinusoidal caterpillar walk both forwards and backwards with minute changes to the amount of time delay (figure 5).

Sub Networks of Control
Some students have used multiple power cords to create a single creation that has sub-networks that are governed by different Queens. With two Time Delay Queens, A centipede might have one network controlling the oscillations of its body and another that controls the wave-like undulations of its many feet. Coordinating the two motions relative to each other could lead to a robust and interesting centipede robot.

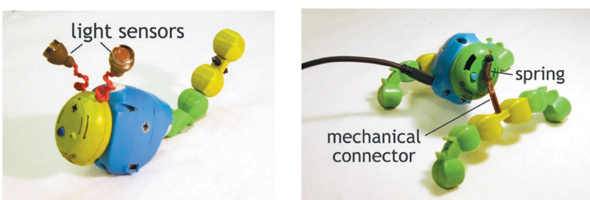

Figure 6. Light sensors replace the knob in Offset Backpack (left). Bigger-Smaller backpack exhibits feedback (right).

Ambient Sensors and Conditional Behaviors
Offset Backpack has two antennae with light sensor "eyes" in place of its knob. It demonstrates conditional behavior and environmental responses when children can use it to build creatures that can change their posture in response to ambient light. For instance, a child can design an ant that walks towards light. By manipulating the orientation of the antennae, children can discover principles about sensors and control; a creature that walks towards light can be made to walk towards darkness by crossing the two antenna to opposite sides of the Backpack.

Feedback
Backpacks can also be used to experiment with feedback. The Backpack's knob is fitted with a mechanical connector that allows it to become part of a creature's body. Now, the creature will behave differently when its posture changes. If the backpack is modulating the same motion that is affecting the position of its input knob, it presents a type of physical feedback mechanism (figure 6).

Evolution of the design
We developed the "local," "global," and "distributed" Backpacks over a two-year design cycle. Distributed Backpacks came first: we sought to make tangible and manipulable the abstract principles demonstrated with the Augmented Queens [18] that were supposed to show how information behavior can model patterns of growth (like nautilus shells) and morphological change (like waves) over time. Since Augmented Queens were very hard for children to understand, the goal here is to make those principles of information change modular and tangible so that children can fluidly experiment with their effects on system behavior. The Backpacks' knobs allows students to more thoroughly and fluidly investigate the problem space.

The local backpack grew from that effort; it was the most obvious answer to the question "what happens if a (distributed) backpack is attached to a normal Active?" Local modulation suggested rich opportunities for control of creations.

Once we tested the local mode, we realized that creations with only one Active had the advantage that backpack motions could be conceived as global or local modulations. Through informal studies and interview, users told us that global modulations seemed fun and conceptually interesting. This led us to create a global mode for Backpacks.

Sensors and feedback techniques also evolved from work with children and professional researchers. Some users have commented that the Offset Backpack is the best design because its "eyes" suggest its function. This has encouraged us to develop more specialized interfaces to physically embody the ideas of time, speed, and scale.

Although we were tempted to create separate Backpacks for the three different modes (eliminating "invisible state"), we chose to keep the modes coupled to encourage students to make discoveries about the various effects of modulation to overall behavior. This coupling is also intended to lead students to form and compare both centralized and decentralized conceptual models of dynamic systems.

EVALUATIONS WITH CHILDREN
Our evaluation of the Backpacks took place in a variety of settings with children aged 6-15. Throughout our design process, we frequently showed the system to children to determine its ease of use and affordances for manipulating its controls and combining it fluidly with the Topobo system. These sessions informed the final physical and interface design of the Backpacks.

Kindergarten —Third Graders
We evaluated the Backpacks to explore their effectiveness in how tangibly manipulating motion parameters could facilitate the development of abstract ideas about motion. We conducted several informal afternoon sessions in a home environment, with eight children ranging from K-3rd grade, a mixture of boys and girls. The children were first introduced to the Topobo system, demonstrated how to use it and shown several Topobo creations which took advantage of the Backpack capabilities. They then had an afternoon of free play with the Topobo system and Backpacks with help available from researchers accustomed to working with children and Topobo. Most of the children in the session had

Figure 7. K-3rd graders suggest new backpacks.

not played with Topobo before, except for one third grade girl who had experienced early Topobo prototypes in her kindergarten class, and another seven year old boy who had evaluated Topobo informally in approximately six sessions in the previous two years.

Eighth Graders

Our next evaluation took place in the eighth grade classroom, in a physics-by-design class. We conducted two sessions with two separate classes, with a total of 26 students. These students had no previous experience with robotic or programming systems and had not been taught a foundation in dynamics or kinematics. However, the school they attended had a hands-on approach with manipulative materials available as part of the curriculum. In the first session, the students were introduced to the Topobo system and Backpacks and given free play with the system.

In the second session, the children were shown successful walking creations we had built, some of which utilized the Backpacks. We demonstrated how the Backpack parameter control could manipulate walking. Following the introduction, half the class was given these built creations to analyze—take apart, change, rebuild—while the other half were instructed to create their own walking creatures. In between the sessions the classes were given homework workshops to test their conceptual understanding of the Backpacks and all the students were interviewed at the end of the last session.

In both of our evaluations, we found that the Backpacks were an accessible interface for children to explore different parameters and introduced a set of concepts that ranged in complexity. All of the children were able to use the Backpacks, although a greater conceptual understanding was articulated by the eighth graders. Showing the children built creations with the Backpacks in use and allowing them to deconstruct their behavior greatly accelerated the children's conceptual understanding. This was a necessary first step with the younger children to engage totally with the Backpacks.

The Backpacks that described more concrete physical concepts—moving Faster-Slower or Bigger-Smaller—were easier for all the children to observe, understand, utilize and describe. One eighth grade boy commented on how the Faster-Slower Backpack made getting his creature to walk easier. "You could probably do it without it, but it makes it a lot easier...rather than having to rerecord it every time you want to change the speed...you can also get it a little bit more precise with the Backpack." When employed in a creation, the children were able to understand that the Delay Backpack made the Actives move one after another, thus dissecting a fluid motion into its constituent parts. However, they did not articulate a direct connection to wave-like motion. The Offset Backpack proved to be the most difficult for the children to dissect; children could interpret that the sensor made the creation move toward the light, but only one group of eighth graders was able to articulate an obvious correlation with how the motion of the motor was changing (offsetting to one side) in relationship to the overall walking behavior that the creature demonstrated.

Fluid Integration Into Play

An important attribute of the Backpacks was observed in how the Backpacks were integrated into the creative process of using Topobo. In past studies with Topobo, researchers found that users who worked iteratively—going back and forth between building the creation and programming motions—had more success in making a creation walk. We found that the Backpacks integrated seamlessly with this iterative process, while adding a new element with

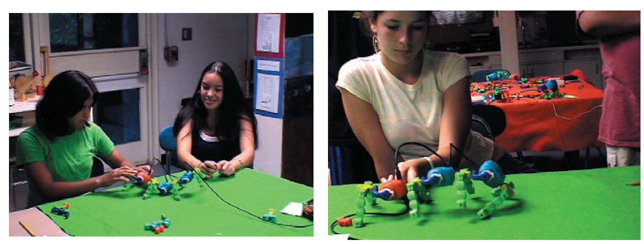

Figure 8. 8th graders experiment with models and behavior.

which to iterate. In one session, two eighth grade boys were working on a walking creation with the Faster-Slower Backpack. Throughout their process they explored adding and removing passives to change the weight balance of their creature, reprogramming its motion, and changing the speed with the Backpack knob — all in a fluid and experimental manner. They cited the Backpack as being a necessary part of their creature, because it allowed them to control the speed of their creation without having to also reprogram (and thus overwrite) the motion pattern.

A Logical Next Step

In one situation, two eighth grade boys had built a creation with a single active that walked forward and then attempted to make their creation turn in one direction. Through

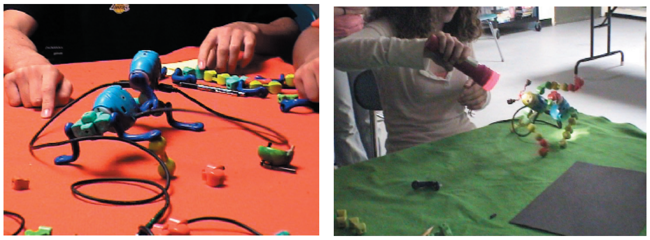

Figure 9. Students discover how to "steer" a walking creature with a second Active (left). Offset backpack can also steer a creature, but is harder to conceptualize (right).

experimentation they found that they could successfully change the form of the structure, adding and subtracting passives to its legs, or could manipulate its motion, adding a new Active to its back which functioned to offset the motion like a steering column (figure 9). In essence, these boys had struggled to discover the principle embodied in the Offset Backpack, which could have easily facilitated their iterations. This situation supports the idea that the Backpacks are building on motion principles already inherent in the system, but are providing a more abstracted and flexible form for students to approach and investigate the concepts they demonstrate; the Backpacks' functionality is a logical inclusion in the Topobo system.

Conceptualization

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

Beyond Children

Throughout our research, dozens of adults (some of them leading robot designers), have experienced the Backpacks with the Topobo system. All of these users expressed enthusiasm for the Backpacks, especially those people who are professionally focused on examining the relationship between geometry and movement. Scientists and experts possessed a particular excitement about the distributed Backpacks, recognizing the importance and extensibility of them as a tool to understand the applications of concepts such as wave propagation or system dynamics. They described Backpacks as reflecting the real high level ways of thinking about robotics and motion control, viewing Backpacks as a tool for intuitive manipulation within a control structure.

Summary of Evaluation Findings

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

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

DISCUSSION

From Play to Abstraction

A central question to different kinds of design tools concerns ease of entry (the "learning curve") and the potential complexity and sophistication of models created with a tool (the "ceiling"). One of the original pedagogical arguments with Topobo was that children of widely ranging developmental levels became engaged with Topobo because it was easy to learn and there were many points of entry for different learners; many levels of complexity were embedded in the system. However, children who were adept with manipulating abstract ideas [6] wanted to manipulate their recordings in different ways. Backpacks increase the complexity with which children can design, control and understand their creations.

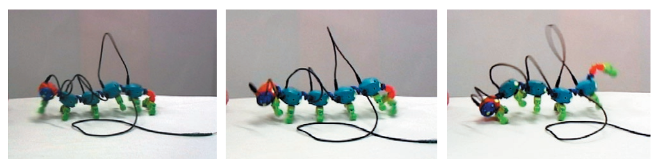

Figure 10. This caterpillar has been built to explore principles of phase shift and wave propagation.

Whereas an informal system like Topobo can lead to accidents and discovery, a pedagogical benefit of providing parameterized control via manipulatives is that advanced learners can fluidly transition between building, dissecting, and controlling their model. Control is one level removed from spontaneous creation, and Backpacks may help children to discover what, exactly, makes a behavior successful. This may benefit learning, since, as Ackerman argues, effective learning often involves temporarily standing back from the learning experience to reflect on it in more objective terms [1, 2].

If a child working with Time Delay Backpack discovers that some Topobo creations walk almost entirely because of phase relations between parts—and almost any oscillating motion can result in walking—the student may then form a theory about phase and walking. She can later build a walking robot with LEGO Robolab whose movements are based on phase shifts.

Knowledge Transfer

In general, for children to be able to transfer ideas about motion learned via Topobo to other domains like math or programming, they have to develop generalized and abstract ideas about motion that map between the two domains. Topobo and Backpacks do not map onto mathematical kinematic models, but phase shifts, frequency and amplitude shifts are represented and manipulated in both paradigms [19]. One advantage to a tangible interface for editing robotic motion is that the control is tightly coupled (in this case, physically) to the output, allowing people to understand and easily manipulate both the physical and computational models. This can help people more quickly discover how the motion leads to the system behavior they see.

TECHNICAL IMPLEMENTATION

The Backpacks are built with an ABS housing that contains a PCB and makes accessible two power/communications ports, a button, and a potentiometer. Sensor Backpacks replace the potentiometer with a photoresistive voltage divider, where sensor input is the differential between the two sensors. For physical feedback, the potentiometer is fitted with a LEGO connector that will self-center with a tension spring.

Backpacks use a 40 MHz PIC processor and implement a custom multichannel peer-to-peer communications protocol, allowing them to process and rout messages through their two I/O ports (figure 10). One of the ports is a "male" plug, allowing the Backpack to connect directly to an Active without the need for an additional cable. The entire object is designed to have a close physical coupling to its host Active, and mates to the back or sides of an Active with a single "snap."

Figure 11. Backpack technology: inside a final backpack (left) and early prototypes (right).

When a Backpack is attached to an Active, it will announce to its "host" Active that it is present and pass its Backpack identity and sensor value to the host. It will then periodically (5 Hz) ping the Active to maintain that it is still attached. When a Backpack is removed, an Active's internal timer will cause the Active to stop applying the Backpack's modulation. Actives can support up to four Backpacks simultaneously.

Most Backpacks have a button that allows them to transition from a "local" to a "global" Backpack. The button press simply changes the internal state of the Backpack, which then sends state and modifiers to the Active. All of the Actives are preprogrammed to handle all variations of Backpack message types.

RELATED WORK

Our work draws on ideas from a number of divergent fields of study, including robotics, educational toy design, audio processing and dynamic modeling.

Children typically learn about dynamics through physical models, like springs, waves and swings. For instance, a child may be asked to explain why a slinky will "walk" down large stairs but not small ones, and be encouraged to develop a theory about resonance. Some cars develop a "rattle" only at certain speeds but not others; on a swing a child can kick higher and higher, but must kick at the right time. All of these physical examples of dynamics can support learning about more abstract descriptions of waves, resonance and harmonics. However, since underlying parameters like phase cannot be isolated and controlled, principles like phase are hard to understand. Backpacks provide handles to control parameters' effects on physical dynamic systems. When kids can model with these properties, they are encouraged to develop more advanced and abstracted theories about them [5, 15].

Other researchers developing digital manipulatives have built systems that are physical instantiations of mathematical, programming, or dynamic models. For instance, Wyeth's Blocks [25] makes simple conditional behaviors tangible through a series of blocks, and Flow-Blocks [28] make dynamic systems models tangible and manipulable. Such systems make feedback, conditional and other complex system behavior tangible and are developed primarily to help children manipulate abstract ideas. In contrast to record and play systems, which are broadly described as expressive, the former instances are more abstract representations that follow a more experiential model [13, 28].

Researchers developing more expressive interfaces have conceived of some modular extensions to introduce ideas about conditional behavior to a record and play paradigm. Frei suggested a simple switch for conditional behavior [8] in which a primary motion is recorded, and then a secondary motion is programmed after touching the switch. Subsequent touches to the switch will toggle between primary and secondary motions. This binary state switch is an interesting idea that could be applicable to a system like Topobo, especially because it would result in complex local-global interactions. While this design introduces a hidden state that may be confusing, binary state change may an accessible way to work with multiple recordings.

Other domains have sophisticated tools to manipulate time-sampled data sets. Musicians who sample, mix and modulate recorded sound have employed different paradigms for record modulation. An tangible analog mixer performs transformations on audio (filters, volume) with a centralized interface. For more flexible audio processing, GUI tools are often used. Dataflow models like MAX/msp allow users to design and apply modular filters (small computer programs)

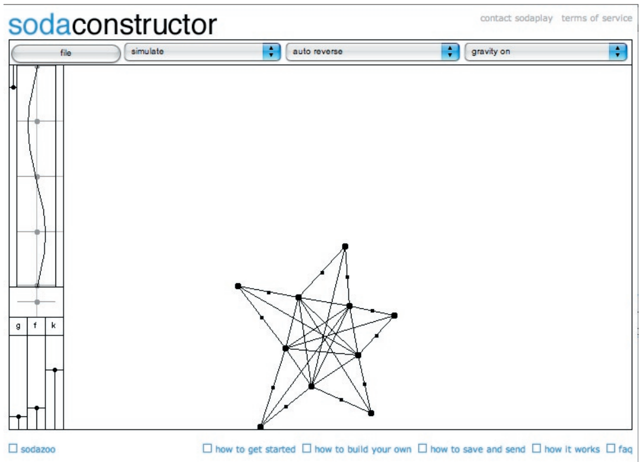

Figure 12. Sodaconstructor is used to model linear systems.

to their recordings. Program structures are represented graphically and topologically and the system shares design characteristics with Backpacks, because filters are applied directly to the graphical programs and their effects can be experienced in real time. People have applied MAX/msp to audio, video and robotics, and the "dataflow" programming paradigm suggests interesting GUI extensions to the Topobo system [7, 14].

Dataflow models are one approach to linear systems, which are more broadly used by researchers in many domains [19]. Robotics researchers routinely use linear systems to model and understand the dynamics of their creations, and the principles that Backpacks represent tangibly are symbolically manipulated in their mathematical and programmatic models.

Linear systems have also been used in graphical simulation of kinematic structures. Sims' evolved virtual creatures [23] employed directed graphs, a form of dataflow model. Sodaconstructor [24] is a popular online GUI modeler for creating "walking" creatures that respond to a simulated physics environment (figure 12). Thanks in part to its wide distribution over the internet, a large Sodaconstructor community has explored the roles of frequency, amplitude and phase in simulated locomotion of graphical models.

Other GUI learning tools like Starlogo [21] have allowed children to explore the ways local and distributed rules can lead to surprising system behaviors. We have made a few of these principles tangible with the Distributed Backpacks, although this conceptual domain is rich and may suggest future work in tangibles.

Many theories about phase shift and oscillations that come from biological systems, such as central pattern generators (CPGs) [10], are related to the concepts we present here. Specifically, researchers in modular robotics [12, 26, 27] have explored the roles of phase, amplitude, frequency and orientation in determining their robots' dynamics. In some cases distributed algorithms similar to the Distributed Backpacks have been employed to create wheels, snakes and walking creatures [27]. Our work intends to make these advanced ideas tangible and manipulable by younger students.

From a design perspective, our approach is consistent with Full's argument [9] that "preflexes" play a large role in the locomotion of simple animals like crabs or cockroaches. These creatures, and robots like them, exhibit behavior that may come largely from the interrelationships between an animal's morphology and its control system. In his robotics work, Full places great emphasis on developing the physical and control systems in parallel, which our work also emphasizes.

FUTURE WORK

Children have suggested a number of new Backpacks to us, including reverse, random, and sound input. Their suggestions make sense and imply that children understand the backpack paradigm. Adults who have used the system have suggested Backpacks that allow creatures to exchange motions, and a backpack API with which robotics designers could script behaviors and learning algorithms. Although extensions like artificial intelligence are inconsistent with our current goal to make the fundamentals of motion tangible, all of these suggestions suggest future extensions to the Backpack paradigm.

In order to more fully understand children's engagement with the ideas presented here, more thorough user studies are required. Although children understand the idea of a Backpack, they are often confused by the resulting behavior. This is understandable, since kinematics are complex and Backpacks draw students' attention to this. Backpacks would be best explored with a longitudinal study to determine how Topobo "experts" use and conceptualize Backpacks. Furthermore, more thorough and formal user studies are needed to identify ways in which different aged children can relate to Backpacks. We believe that the underlying ideas presented here range greatly in complexity, and identifying the developmental levels at which children can understand different ideas will allow us to better target specific ideas (and Backpack activities) to different aged children.

CONCLUSIONS

We have presented the Backpacks, tangible interfaces to modulate basic parameters of movement in a modular robotic building toy. We have argued that manipulating parameters of motion—with physical knobs, sensors and feedback—enables children to more deeply design and analyze sophisticated robotic behaviors. We have also hypothesized that making fundamental ideas like phase, amplitude and frequency manipulable may help older children transfer their knowledge from physical activities like Topobo to more abstract symbolic representations of movement like linear systems.

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

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REFERENCES

1. Ackermann, E. Enactive Representations in Learning: Pretense, Models, and Machines, in Bliss, J., Light, P. and Saljo, R. eds. *Learning Sites: Social and technological Contexts for learning*, Elsevier, 1999, 144-154.
2. Ackermann, E. Perspective-taking and object construction: two keys to learning, in Kafai, Y. and Resnick, M. eds. *Constructionism in practice: designing, thinking, and learning in a digital world*, Lawrence Erlbaum, Mahwah, NJ, 1996, 25-35.
3. Ananny, M., Supporting Children’s Collaborative Authoring: Practicing Written Literacy While Composing Oral Texts, in *Proceedings of Computer Support for Collaborative Learning*, (Boulder, Colorado, USA, 2002), Lawrence Erlbaum Associates, 595-596.
4. Ananny, M. *Telling Tales: A new way to encourage written literacy through oral language*. PhD Thesis, Media Lab, MIT: available http://web.media.mit.edu/~ananny/thesis.html [28th February, 2003], 2001, 165.
5. Chi, M. Why is self explaining an effective domain general learning activity? in *Glaser, R. ed. Advances in Instructional Psychology,* Lawrence Erlbaum Associates, 1997.
6. Cole, M., and Cole, S. *The Development of Children*, Fourth Edition. New York, NY : Worth Publishers, 2001.
7. Dataflow programming languages. http://en.wikipedia.org/wiki/Dataflow_language
8. Frei, P. curlybot: *Designing a New Class of Computational Toys*. Master’s Thesis, Massachusetts Institute of Technology. 2000.
9. Full, R.J., Autumn, K., Chung, J.I., Ahn, A., Rapid negotiation of rough terrain by the death-head cockroach. *American Zoologist*. 38:81A. 1998.
10. Ijspeert, A., Hallam, J. and Willshaw, D. From lampreys to salamanders: evolving neural controllers for swimming and walking. In *Fifth International Conference on Simulation of Adaptive Behavior*, pages 390-399, 1998.
11. Ishii, H. and Ullmer, B. Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms. *Proceedings of CHI 1997*, ACM Press, (1997), 234-241.
12. Kamimura, A., Kurokawa, H., Yoshida, E., Tomita, K., Kokaji, S, and Murata, S. Distributed Adaptive Locomotion by a Modular Robotic System, M-TRAN II. *Proceedings of IEEE/RSJ International conference on Intelligent Robots and Systems*. 2004. 2370-2377.
13. Marshall, P.,Price, S., and Rogers, Y. Conceptualising tangibles to support learning. *Proceedings of Interaction Design and Children*, Preston, England, July 1-3, pages 101-110. 2003
14. MAX/msp. http://en.wikipedia.org/wiki/Max
15. Mellar, H. and Bliss, J. Introduction: modelling and education, in Mellar, H., Bliss, J., Boohan, R., Ogborn, J. and Tompsett, C. eds. *Learning with artificial worlds: computer-based modelling in the curriculum*, The Falmer Press, London, 1994, 1-7.
16. Papert, S. *Mindstorms: Children Computers and Powerful Ideas*. Cambridge, Massachusetts: Perseus Publishing, 1980.
17. Piaget, Jean. *The Grasp of Consciousness*. Cambridge: Harvard University Press, 1976.
18. Raffle, H. Parkes, A. Ishii, H. Topobo: A Constructive Assembly System with Kinetic Memory. *Proceedings of CHI 04*. ACM Press, (2004), 869-877.
19. Rao, S. *Mechanical Vibrations, Fourth Edition*. Upper Saddle River, N.J. : Pearson/Prentice Hall, 2004.
20. Resnick, Martin, Berg, et al. Digital Manipulatives: New Toys to Think With. Paper Session, *Proceedings of CHI 1998*, ACM Press, (1998) 281-287.
21. 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), 114-137.

22. Ryokai, K., Marti, S., Ishii, H. IO Brush: Drawing with Everyday Objects as Ink, in *Proceedings of CHI 04*.
23. Sims, K. Evolving Virtual Creatures. *Proceedings of SIGGRAPH 94* pp.15-22.
24. Sodaplay. http://www.sodaplay.com
25. Wyeth, P. and Purchase, H. Tangible Programming Elements for Young Children. *Proceedings of CHI 2002*, ACM Press, (2002) 774-775.
26. Yim, Duff, Roufas. PolyBot: a Modular Reconfigurable Robot, *IEEE Intl. Conference on Robotics and Automation,* (2000) San Francisco, CA.
27. Zhang, Y.; Yim, M. H.; Eldershaw, C.; Duff, D. G.; Roufas, K. D. Phase automata: a programming model of locomotion gaits for scalable chain-type modular robots. *IEEE/RSJ International Conference on Intelligent Robots and Systems* (IROS 2003); 2003 October 27 - 31; Las Vegas, NV. Piscataway NJ: IEEE; 2003; 2442-2447.
28. Zuckerman O., Arida, S., and Resnick M. (2005). Extending Tangible Interfaces for Education: Digital Montessori-inspired Manipulatives. *Proceedings of CHI 2005*.