A Design Environment for Automata: Supporting Children's Construction of Mechanical Reasoning and Spatial Cognition

Ph.D. Dissertation Proposal

Glenn R. Blauvelt
Department of Computer Science
University of Colorado at Boulder

19 February 2001

1 Introduction: Learning in the real world

The new technologies that the world races to embrace affect every facet of our lives. But not every new technology makes our lives better. Choosing the wrong technology for an application often has serious and costly side effects. In this document I will examine some of the side effects which have been introduced as computers have become more ubiquitous in educational settings. I will then propose a system of tools for middle school age children to use in building the mechanisms for mechanical automata which addresses some of these side effects.

1.1 The value of interaction with the physical world

For millennia, technology was embedded both in the processes for creating physical objects as well as in the objects themselves. It was impossible to separate one from the other. Advances in metallurgy led to more and better plows, pots and polearms. Paper making and moveable type led to books being cheaper and more plentiful. The users and creators of technology became educated through their interactions with it. A technology's users often understood it as well as its creators. This understanding was common, because the nature of these objects encouraged examination. Function was rarely deliberately hidden and users could understand many objects by studying them. If the observations occurred in the object's natural setting, the knowledge constructed was similarly situated and had a meaningful context.

Quite a different situation exists today. We now produce objects of great complexity and sophistication but with manufacturing processes unintelligible to all but a handful of experts. The objects themselves are inscrutable to consumers who are deterred from gaining access to their workings. These "black box" objects actively discourage examination of their function and often the only way to learn about the objects is in an environment (such as a classroom or book) which exists independently of the objects.

1.2 Objects as educational tools

The relationships that people develop with the objects that populate their world are both personal and unique. The importance of these relationships has not been lost on educators. When Friedrich Froebel invented kindergarten in the early nineteenth century, he sought to establish an environment where children could engage in directed activities with a variety of carefully designed physical objects (his "gifts") [5] which, he believed, would allow children to transcend the purely mechanical nature of the objects to a more detached and artistic appreciation of the nature of the relationships of child, world and object. This was a powerful notion.

In the twentieth century, many educators have extended and adapted Froebel's use of artifacts as educational catalyst. This epistemological view was labeled *constructionism* by Seymour Papert, one of its most outspoken proponents. Building on the *constructivism* of Jean Piaget [22], Papert argued that in order to effectively construct knowledge one had to be involved in the construction of a "public entity, whether it's a sand castle on the beach or a theory of the universe" [20, page 1]. He argued that the objects need not be physical, but virtual objects need to be ones that children can trade places with (such as the LOGO turtle) in order to benefit from *syntonic learning*[1] [21].

Physical manipulatives are commonly used in classrooms today to illustrate or reinforce material in the curriculum (Cuisenaire rods in math classes, for example). New varieties appear all the time, but with the common goal of supporting the transfer of knowledge from the teacher to the student. Attempts are seldom made to use manipulatives for non-goal directed or discovery learning.

1.3 Computers as educational tools

In the twenty years since Papert published *Mindstorms*, computers have proliferated in Western society and many children now have computers in their homes as well as their schools and libraries. Computers are multipurpose tools and have come to play diverse roles in education. From mathematical visualization to physical simulation to assessing a child's ability to construct reading summaries, computers can reduce the strain on teachers and provide a stimulating (and often entertaining) environment in which children can work. Programs like Math Blaster and Reader Rabbit have been used by thousands of children and form the core of the computer aided instruction programs in many schools. Children are now routinely taught to use word processing and spreadsheet programs. These types of software have been joined more recently by sophisticated software development tools created specifically for children. Programs like SimCity, Cocoa (formerly KidSim) [30] and AgentSheets [26] offer innovative environments in which children can construct their own simulations and games to solve problems of interest to them. These programs allow children to view the invisible and examine the complex in ways that were previously impossible.

---

[1] In discussing the way a Turtle makes a circle (move a little, turn a little) Papert notes "... the Turtle circle is *body syntonic* in that the circle is firmly related to children's sense and knowledge about their own bodies. Or it is *ego syntonic* in that it is coherent with children's sense of themselves as people with intentions, goals, desires, likes, and dislikes." [21, page 63]

Because of the power of computers, many schools and school districts are opting to spend more of their budgets to acquire, maintain, and network computers. However, these increased expenditures need to be compensated for in other places, and traditional school activities like shop classes and field trips are being trimmed or eliminated to provide the necessary funds [19].

1.4 Current practice limits opportunities

In many schools computers have moved out of the classroom (where Papert saw them having their greatest impact) and into computer labs, full of machines and overseen by a computer specialist who is often not a teacher. In many cases, labs either replace a teacher for the purpose of rote drill or are used in an attempt to make children computer fluent. Even when schools use computers for less pedestrian purposes, it is likely that students will bring less away from the experience than they should. These trends of using computers as teacher substitutes and simulated reality environments remove the knowledge that children construct from its natural setting and limit its usefulness.

This move away from physically situated educational activities to artificially situated ones is disturbing. If children need physical interactions to hone their abilities to think and function in three dimensions then having children view an object rather than hold it may be doing them more harm than good. As situated learning opportunities disappear, contextualized knowledge becomes more difficult to construct [21]. One response is to replace these lost activities with other real world activities. Making computers integral to the new activities permits us to continue allowing children to use computers while expanding the contexts of that use.

2 Addressing the situation

One way of realizing this integration of computers and manipulatives would be to design software and hardware systems as tools for building real world objects giving children an opportunity to learn by making [28]. While this is an uncommon approach to educational technology, it's not new. It addresses the desire to have both computer activities and contextualized knowledge construction. A careful balance between the virtual and physical components of such activities must be struck in order to maximize benefits. Determining appropriate types of artifacts for construction depends on what skills or knowledge it is hoped children will acquire from the process. Previous work in this area (see section 6) suggests that good artifacts share some common attributes. Among these are:

1. Their function and method of operation should be overt. Understanding is assisted by observation [27], and it's difficult to observe what can't be seen.
2. Their construction should be a pleasant experience. If creating objects is frustrating, the number of objects created will be small, their quality and complexity will be greatly reduced, and interest in them will be quickly lost.

3. They should be meaningful to the creator. This can come from a sense of personal investment, from an aesthetic point of view or from the social interaction that occurs during their creation [3, 8, 17].

Several interesting topics present themselves when thinking about the tools and objects just mentioned. Discussing a few of these briefly may give some notion of the richness of the design space.

2.1 Let kids become designers and engineers

Creating objects from your imagination can be an exhilarating experience. Children are encouraged to approach the creative process like an artist, but they are seldom encouraged to approach it like an engineer. This might be because the tools available to children and adult artists are substantially the same. Small hands can hold a full size paintbrush. The creative tools used by adult designers and engineers have little of this same accessibility. Programs like AutoCAD have steep learning curves, intimidating interfaces and require the user to have knowledge about design in the domain. Although there are no obvious reasons to suggest that children couldn't take advantage of such tools, sophisticated examples for children don't exist. Viewing the work of child artists hints at what we may be missing by not having a body of work created by child engineers.

An unfortunate characteristic of many software programs for children is the way that the users are talked down to and their abilities marginalized. Building design tools for children shouldn't imply that those tools would be simplistic or minimally functional. Quite the opposite; these tools would need to be full featured and sophisticated in order to support a child's imagination and approach to working. The design process will probably be quite different when children do it and the tools should anticipate those differences and work naturally with them.

2.2 Provide a space where art, math and science overlap

One of the most interesting aspects of design tools is that they do not live fully in any one world. In fact, the space they occupy is one where traditional educational practices have shown little benefit from the application of educational technology. In most classrooms learning science, math and art are seen as separate endeavors. In cases where there are attempts to merge them (usually art with either science or math) the results are often artificial. Children see little value in these exercises and receive few benefits from them. As Papert says, "The children can see perfectly well that the teacher does not like math any more than they do and the reason for doing it is simply that it has been inscribed into the curriculum. All of this erodes children's confidence in the adult world and the process of education. *And I think it introduces a deep element of dishonesty into the educational relationship.*" [21, page 50].

This space has tremendous potential as a domain for exploration. Providing children with tools that they can use to navigate this space in ways of their choosing allows the exploration to become very personal. The problems that they examine will most likely be ones that interest them and the knowledge they will build will be valuable in both the short and long terms. They will have the opportunity to examine the relationships between the domains in natural ways and then be able to verify their results in the real world. Children will be encouraged to take part in determining what it is that they will learn[2] [12].

2.3 Allow kids to create personally meaningful artifacts

Anyone who has spent time around children (or remembers their own childhood) knows that children love to make things. Even those of us who lacked skill at traditional activities like drawing or painting actively sought out and found ways to express our creative nature. Providing an environment which helps children through the difficult steps involved in moving their ideas from concept to physical object can reduce the barriers to these activities. Computers are ideal for this. They can work at the user's pace, allow mistakes to be easily corrected, and provide a wide variety of tools which have predictable and repeatable behaviors.

2.4 Take advantage of novel technologies

In the last decade the tools available for fabricating physical objects have increased in variety, number and availability. Where color printers were once found only in large businesses because of their cost, they now are common in homes. So too, the availability of computer controlled machine tools (lathes, mills, routers, etc.), laser cutting tools and 3-dimensional printers and stereo-lithography devices is increasing. While still too costly and complex for home use, these devices are increasingly finding their way into schools, museums and community centers. They offer children rapid and accurate fabrication of objects without requiring unrealistic skills and they encourage children to imagine beyond their abilities to fabricate.

2.5 Build computer models of physical artifacts

Building models of physical objects in the computer takes on a new significance when the modeling environments are paired with this new crop of output devices. Modeling a block and tackle in AgentSheets may illustrate mechanical advantage, but it doesn't go very far toward creating one that can be used in a dozen experiments that aren't obvious in the virtual example. One solution would be to extend AgentSheets so that it could generate the files one of the new output devices needs in order to fabricate the parts. But the program was never designed with this in mind and the internal representations it uses to describe the objects in the simulation can't be used (or even easily modified) to create the necessary machine readable code.

Design tools for children should be built with physical object end products as a requirement. The internal representations of objects could be described by the important attributes of the corresponding physical objects (height, thickness, diameter, etc.). The

---

[2] Research in self-directed learning, as commonly defined, has focused primarily on adults. Providing children with opportunities to direct their learning may be an important way of augmenting other educational approaches.

software could use these attribute values to create two- and three-dimensional screen images of the objects as well as the machine readable code for the output devices. In a sense, the internal representation would not only describe the virtual objects but the physical objects as well.

2.6 One approach

While a little has been done to address the previous five issues individually, there has been no systematic research effort devoted to their combination. Curiously, research on the benefits of such systems seems to have eluded research agendas. This is especially interesting given the current interest in studying technology for children and the many interesting research questions this work could address.

The focus of this proposal is one entry point into this domain. By choosing the cognitive skill of mechanical reasoning for evaluation and by providing tools with which children can construct mechanical apparatuses to use in constructing knowledge related to that skill I will start to explore this new territory.

3 Thesis Question

The preceding sections show the breadth of the issues surrounding the use of technology in general, and computers specifically, for knowledge construction. This proposal focuses on a small subset of these issues and is guided by the following question:

> **Can a computer application for the design and construction of mechanical automata accelerate the acquisition of mechanical reasoning and spatial cognition in children or increase children's proficiency in these areas?**

4 What I propose to do

The goal of the work described in this proposal is to assess the effects that using computers to build physical objects have on certain cognitive processes. Many possible families of objects could be used for this assessment, but I have chosen the mechanisms used in mechanical automata (see section 5.2). To answer the thesis question, I will build software tools to design and fabricate mechanisms and will use that system and the objects created with it to look at the impact they have on the mechanical reasoning and spatial cognition abilities of children.

4.1 Build an environment for design and creation

The first goal of this research will be to construct the system described in section 8. The design of the system has three first principles: children are its intended users, mechanism components are its primary end products, and a laser cutter will be the primary output device. The design and construction of the system will provide me with opportunities to explore issues in the domain of design tools for children.

4.2 Explore mechanical reasoning and spatial cognition

The second goal of the research is to use the completed system and its products to evaluate its effects on the mechanical reasoning and spatial cognition abilities on its users. In the process, I will have opportunities to examine other work in the domain and compare this work to it. I will also have opportunities to refine the assessment process and determine more effective ways of conducting it.

5 Automata as a design domain

5.1 What are automata?

The definition used here is quite different than that commonly seen in computer science. Automata[3] are three-dimensional caricatures of real world objects (usually people or animals) which, by means of an applied force, exhibit motion or behavior. These motions are the result of mechanisms which transfer their output to the figures and scenes. For example, the body of the pig in figure 1 moves up and down as the handle is turned. The wings are hinged where they meet the body and the middle of each wing is held at a fixed distance from the base by a stiff wire. When the pig moves, the wings appear to flap. Trying to draw distinctions between what I see as automata and other devices such as mechanical banks and wind-up toys is difficult and, as it would have little impact on the proposed work, will be ignored.

Figure 1: Flying pig. Designed by Keith Newstead, made by Sue Stolpe. 24cm high.

---

[3] Automaton comes from the Greek *automatos* meaning self-acting.

5.2 The choice of automata

There are a number of reasons for choosing the design and construction of automata as the domain for this proposal.

5.2.1 Automata have a long history

The history of automata can be traced back to at least the second century BCE in the work of Hero of Alexandria[4] He described a substantial number of intricate and clever machines to demonstrate principles of hydraulics, pneumatics and physics.

Over the next two millennia, the steam and flowing water used to power the designs of Hero would be augmented and replaced by springs, clockwork mechanisms and electric motors. As technology introduced better materials and the ability to create more elaborate and elegant components, automata became more complex and smaller in size. Automata became everyday sights in European cities as early as the fifteenth century when mechanical figures were added as ornamentation to public clocks [14].

In the eighteenth century a number of talented European craftsmen produced some of the most elegant automata ever. One was Jacques de Vaucanson, a physician who, while training, started work on a "moving anatomy" of the human body as a tool for medical education and research. He never completed this project, but he did construct several life size automata. The best known of these was a duck made of gilt brass (figure 2) that waddled, quacked, swam, ate and excreted foul smelling pellets. Pierre Jaquet-Droz, a contemporary of Vaucanson, produced life size human figures that drew, wrote and played the clavichord [2].

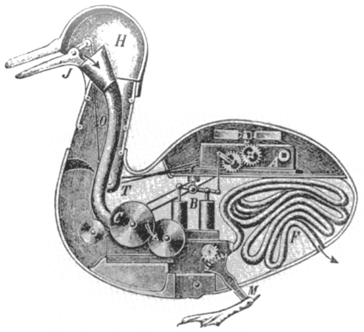


Figure 2: A cross section of Vaucanson's duck. This contemporary illustration is probably inaccurate but shows how the duck might have been configured.

While automata are uncommon in the United States today, there remains a vibrant community of crafts people in Europe keeping the tradition alive and bringing a contemporary flavor to their work [32, 4].

---

[4] While not true automata, figures of humans and gods with arms and jaws moved by levers were produced by the Egyptians as far back as 2000 BCE.

5.2.2 Automata have often been high-tech showcases

The technology used in constructing automata was often state of the art. Price [23] argues that the technologies of fine mechanism and scientific instrumentation evolved from automata, not the other way around. When Hero designed automata he used steam power, a new and fascinating innovation. Clock and watch gears and springs found their way into the automata of the seventeenth and eighteenth centuries. As new metal alloys (and later plastics) were developed they also found use with automata makers [14].

Today, "state of the art" often refers to computers. While computers can be added to automata[5], they may better serve as one of the state of the art tools used to create automata.

5.2.3 Automata combine technology with art

It is hard to imagine children becoming excited about building mechanisms if those mechanisms were built without a context. Watching children at the Boston of Museum of Science's linkage exhibit ("The Wall of Linkages") confirms this intuition. Children typically walk up to one of the linkages, press the button to see it move, and after ten seconds they walk away. By combining these types of mechanisms with art objects, automata exhibit a charm absent in the mechanisms themselves.

The figures of people and animals and the scenes in which they are set are often finely crafted, beautifully executed works of art. Beyond the construction of a mechanism, automata can allow children the opportunity to be as creative as they desire. They can choose the figures, settings, tableaus and behaviors that evoke the emotions or tell the story that they want.

5.2.4 Automata engage the viewer

Viewing and playing with an automaton engages the viewer intellectually and emotionally. Automata are different from most sculpture; they must move in order to be fully realized.[6] The most engaging are hand operated, drawing the viewer into active participation with the automaton and removing the necessity to observe at a distance. Automata can be whimsical, eerie and a hundred other adjectives, but each has a mood and an attitude which demands a response from the viewer.

5.2.5 Building automata can extend kids' existing skills

By the time children reach middle school they've been exposed to a variety of techniques for creating objects. From coloring, to drawing, to painting, to sculpting in clay, to cutting shapes from paper and pasting them together, children are encouraged to be creative. Because of this, most of the techniques necessary to design and assemble automata are familiar to children in middle school. Even if a child has never worked with wood, she probably has molded shapes from clay or carved them from soap. Assembling a mechanism for an

---

[5] Some automata already use relays, switches, motors and cams to more precisely coordinate large numbers of actions.

[6] Alexander Calder and Arthur Ganson are examples of sculptors who incorporate motion into their work.

automaton from prefabricated parts is similar to building with LEGOs. Children coming to the building of automata will be in familiar territory.

5.2.6 The mechanical components are interesting

While the figures and settings of an automaton initially draw attention, the motion and behavior pull the viewer in. Sculpture isn't expected to move, but automata do and this is the job of the mechanism. The right mechanism creates the right motion and discovering that perfect match can be both entertaining and educational. Having a variety of choices for components (which can come from designing parts as they are needed) allows the automaton maker the freedom to play with the motion, to discover unexpected behaviors and to explore the directions they suggest. It also allows the maker to create mechanical parts with the same care and attention to form and appearance she uses with the figures and scenes.

6 Previous work

Studying how physical objects affect cognitive processes is not new. The work proposed here builds on several research projects which share common themes about what it means to design, build and learn in the process. It also draws on other currently available resources for exploring mechanisms.

6.1 HyperGami

HyperGami is a software program for constructing polyhedra and was the tool Ann Eisenberg built to study spatial cognition in children [11]. Children use HyperGami to create paper polyhedra and sculptures (sometimes of amazing beauty and complexity) that they most likely would never have made without it (figure 3). Along the way they develop more sophisticated understandings of the spatial relationships within the objects and construct new ways of talking about both the process and the objects.

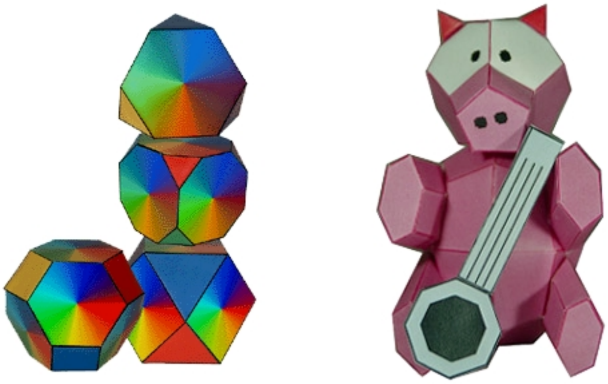


Figure 3: Four Archimedean solids and a banjo playing pig created with HyperGami.

6.2 HyperSpider

HyperSpider is a software program for constructing mathematically based string sculptures and formed the core of Ted Chen's master's research [6]. Based on Space Spider, a toy from the 1960s, HyperSpider provides an environment for creating apparently curved surfaces from a collection of straight strings by making templates for the panels through which strings are run (figure 4).

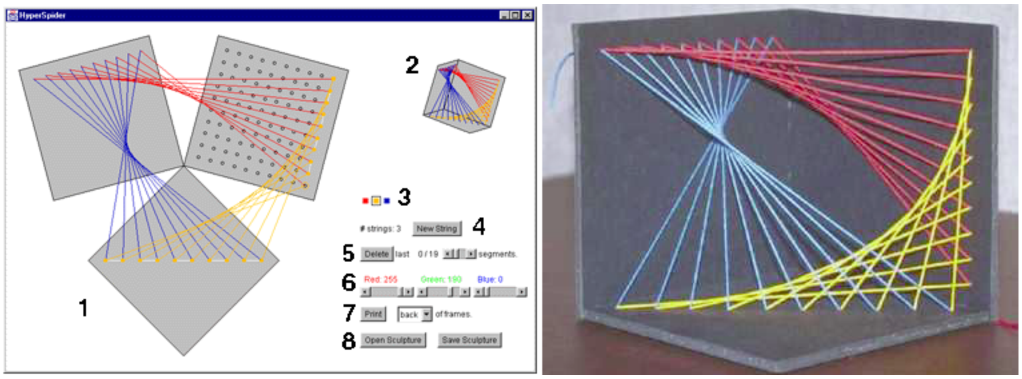


Figure 4: A HyperSpider screen and the sculpture made from the templates generated by that screen pattern.

6.3 Beyond Black Boxes

Beyond Black Boxes was a research effort to provide children with small general purpose computers with which they could construct their own scientific instruments [27]. While not primarily a software tool like previous examples, the computation and programming become components as inseparable from the finished objects as the physical components. The tools that children build are used to address educational questions in a more directed fashion than objects created in HyperGami or HyperSpider. By creating objects for "doing" science it becomes easier to integrate these activities into existing school curricula.

6.4 Cabaret Mechanical Theatre

Cabaret Mechanical Theatre in Britain sells a design kit for automata (figure 5). It came in response to teacher requests for a tool to help them with the portion of the national curriculum which requires children 11–13 years old to build a mechanical toy [1]. The kit consists of reusable parts to build both the mechanism for an automaton as well as the figures. The mechanical components are few, simple, and of limited variety (there are no gears, for example). Most of the parts in the kit are for constructing the figures of people and animals that are moved by the mechanism. The storage box for the parts doubles as the supporting structure for the automaton. Having this variety of parts facilitates the rapid progression from concept to working automaton, but the kit's major strength is that it eliminates the frustration a child might experience while trying to make pieces by hand. Recent personal experience in trying to cut gears from foamcore board and basswood have illustrated just how frustrating the process can be for adults with tool skills and material knowledge which children don't have.

Figure 5: The automaton kit from Cabaret Mechanical Theatre built into a horse and rider.

6.5 Working Model

Working Model 2D (MSC Software) is a physics simulation package which can be used to design and simulate mechanisms of the type that I am interested in having children work with (figure 6). Because of its high price and steep learning curve, it is more likely to find its way into industry or post-secondary education than middle schools. Much of the power of Working Model is in the detail with which it simulates the forces at work on the mechanism. Model files can be imported into Working Model in drawing exchange format (dxf), but there is no way to create fabrication files for output devices.

6.6 Entertainment programs

The Incredible Machine (Sierra) (figure 7) and Widget Workshop (Electronic Arts) are programs which allow the user to build and debug virtual machines in the style of Rube Goldberg. Activities include creating machines from scratch, debugging machines provided in the program and using a given set of components to complete a partial machine to accomplish a specific goal. While realistic machines are not easy to create in programs like these, the whimsy they bring to the design of mechanisms shouldn't be dismissed out of hand. They provide a valuable chance for children (and adults) to play with the way they think the world works.

6.7 How the proposed work is different

The work proposed here shares common elements with all of the work just discussed. What I will do that is different is to combine the strengths that these systems have into a

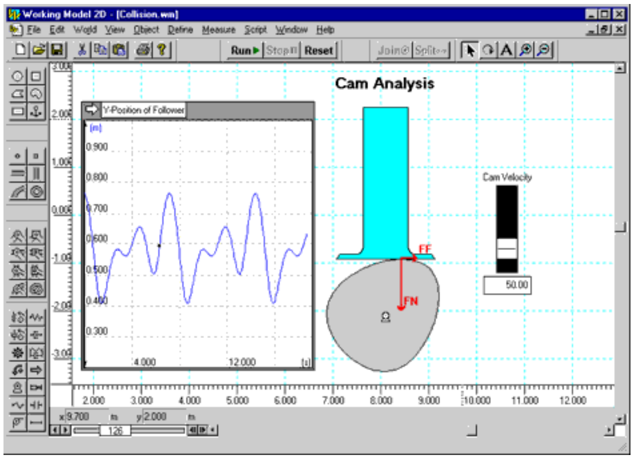
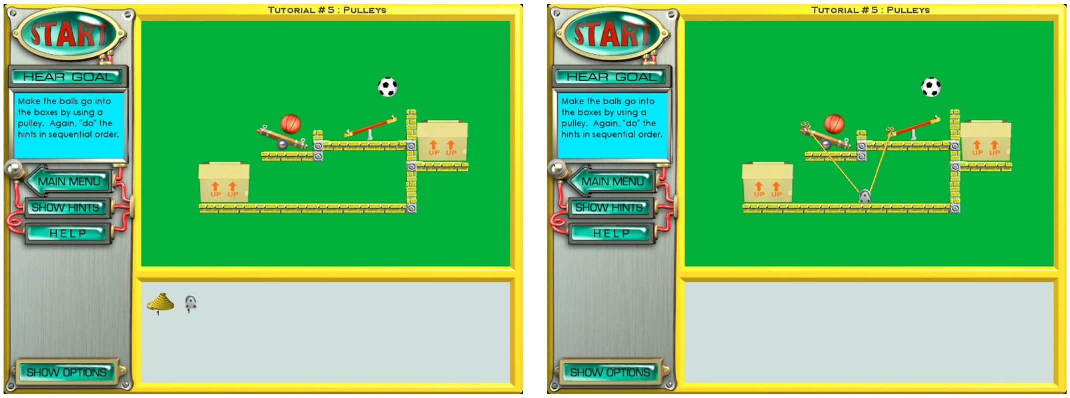


Figure 6: The motion of a three lobed elliptical cam and follower in Working Model. The graph shows the vertical motion of the follower while the black slider to the right of the animation shows the cam's velocity.



Make the balls go into the boxes by using a pulley. Again, "do" the hints in sequential order.

Make the balls go into the boxes by using a pulley. Again, "do" the hints in sequential order.

Figure 7: In this Incredible Machine puzzle, the user must connect both levers with the rope and pulley (bottom panel) in such a way that each ball ends up in one of the cardboard boxes. The initial puzzle is shown on the left and a solution is shown on the right.

single system. The six features that I think are most important to systems in this domain are:

- The system should be designed for children to use.
- The system should be designed with the goal of creating physical objects.
- The system should be designed to allow easy manipulation of on-screen objects to encourage playful interaction before physical objects exist.
- The system should provide libraries of parts from which to create objects.
- The system should encourage users to share what they've created.

System	Children Users	Physical Objects	Play on Screen	Libraries	Share Designs	Formal Assessment
HyperGami	Yes	Yes	Yes	No	Yes	Yes
HyperSpider	No	Yes	Yes	No	Yes	No
Beyond Black Boxes	Yes	Yes	No	No	Yes	Yes
CMT Automata Kit	Yes	Yes	No	No	No	No
Working Model 2D	No	No	Yes	Yes	Yes	No
The Incredible Machine	Yes	No	Yes	Yes	No	No

Table 1: A comparison of the important features with respect to existing systems.

- The system should be formally assessed to determine its strengths and weaknesses.

Table 1 compares these six features across the systems described in this section.

7 Situating the proposed work

As research toward the ICS degree, this proposed work should be appropriate for use in several disciplines. The three that I have identified that could benefit most are cognitive science (psychology in particular), education, and computer science. In this section I briefly propose some representative research topics in these fields. Over the course of the work described here I expect to formulate at least partial answers to some of these.

7.1 Cognitive science

In cognitive science the questions involve how a child's cognitive development is influenced by interacting with physical objects. Some of these questions are:

- What does interaction with physical objects mean to the cognitive development of a child? The evidence suggests that the nature of our interactions with the world shape the kind of development that takes place.
- What may be the unique developmental qualities provided by the manipulation of objects? Are there objects or classes of objects which are most appropriate for acquiring given skills or skill sets?
- What qualities are most often found in personally meaningful objects? Can any guidelines be developed which might suggest more appropriate objects for a particular area or a particular child?
- What features might be designed into objects to enhance or augment the experiences children have and the outcomes they obtain?

7.2 Education

Tools like the system proposed here provide yet another way of studying education in the constructionist framework. Giving children a way to create their own “things to think with” suggests the following questions:

- What benefits might be realized by having children build the objects they use in constructionist activities? Might this differ significantly from the results obtained by using artifacts supplied to them? If children can build automata why not tops or kaleidoscopes?
- Since children will spend time both using the computer and working with the pieces they create with the computer, what constitutes a good balance of time spent on each activity? Will patterns of use in groups of children (for example those who spend more time designing as opposed to those who spend more time fine tuning and embellishing their automata) be reflected in their cognitive changes?
- How does this approach fit into the broader notion of technology for education? What similar work is being done?
- Could these kinds of activities become part of a formal curriculum? Would they supplement existing practice or supplant it?

7.3 Computer Science

Computer environments for children have been the subject of large amounts of research [29, 31, 15], but this research often raises as many questions as it answers. When designing a system to be used in answering the thesis question, some of the following questions present themselves:

- What do design tools for children look like? How do they differ from design tools for adults and how are they the same? What are the specific issues relating to:
  - User interfaces for children in the domain of designing physical objects.
  - Understandable and meaningful ways of manipulating and animating the virtual representations of real world objects.
  - Reducing the complexity of the software environment without reducing its capabilities.
  - Making a maximum of functionality available to users, regardless of their comfort level or level of expertise.
- What does it mean for a system of this type to have access to a laser cutter for the fabrication of components?
  - Will children be more anxious to use the system if they’re not responsible for shaping all of their own parts?

  - If the designs that a child can realize don't depend on her ability to fabricate the components, will we see an increase in both the quantity of automata being built and their complexity?
  - What other recent innovations in output devices might be used to extend and expand on this work? How might this work change if in addition to (or instead of) a laser cutter we had a rapid prototyping machine (stereo lithography or 3-D printer)?

- What lessons can be learned from the users about the appropriateness of the system? What do users need to know about the system and domain to efficiently use the system? What don't they need to know? What difficulties do users have with the system [24]? Which system features support the users and which hinder them? How is the system used? What do users have in mind when they first sit down to create a mechanism (a story, a motion or something else entirely)?

- What constitutes educational technology? Is it just the computer software, or does it extend to new output devices and the objects that children build? How might the current definition be expanded to reflect what is learned from this work?

8 System description

This section covers the system I plan to build. Implementation of this system has already begun and it is hoped that a reasonable prototype will exist in six months. As currently envisioned, the software consists of three modules:

- The component design module where the individual pieces needed to build mechanisms are created
- The virtual assembly and testing module where the individual pieces can be combined to test their fit and see their motions
- Libraries of components and mechanisms from which components and mechanisms can be used and to which they can be added

Each module is described in more detail below. It is important to keep in mind that the software is seen as complete only at a unified upper level, no module is intended to stand alone. My belief is that users will work in all of the modules many times during the making of an automaton, switching between them as needed. The system's ability to encourage this working style is one of its goals. A detailed, fictional example of a user designing an automaton with an optimal version of this system is given in Appendix A.

8.1 Software to Design and Specify Mechanical Components

The foundation of the system (and the first portions of it to be implemented) will be modules to design the individual mechanism components. I currently plan to allow users to build cams, gears and shafts, which seems to be an optimal subset of components. Many of the more complex devices (linkages and ratchets, for example) used in automata [18] can be built from combinations of these parts. Further, most automata I have observed are constructed from limited combinations of these components. This module will also have provisions for creating the structural pieces necessary to support the mechanism components and to create crank handles for the mechanisms.

Users will be able to specify the parameters of each component they build over ranges fixed in the software. These limits will be concerned with practicality (a cam doesn't need 20 lobes) and manufacturability (finding basswood in widths greater than 4 inches is difficult). For size parameters, an increment will allow only a fixed number of values between the established minimums and maximums. This will lead to a greater differentiation between the components which can be made while still producing an acceptably large number of different components. It will also encourage users to experiment with available sizes without having to worry about the choice of initial parameters.

The components will be designed in separate two-dimensional environments, one for each category of part. Since most parts will be fabricated from strip wood and plastic sheet, nothing is lost at this stage by ignoring material thickness. The design modules for each component will (as much as possible) maintain a consistent look. Users will have the option of specifying component parameters explicitly or by playing with the motion that a component will produce. The first will work well when the user knows what she wants and wishes to complete a part quickly while the second will allow her to fine tune or play with the motion without having to know a priori what the component should look like. When she is satisfied with the part, she can save it as a text file which can be used by the software to create screen representations or output device files (see section 8.5).

8.1.1 Cams

A cam is a device which converts the rotary motion of the shaft to which it is attached to the linear motion of the follower that rests against its surface (see figure 8). Cams are widely used in automata mechanisms. Initially the software will allow users to create only snail cams; eccentric cams will be added later. No plans exist to add elliptical cams to this version.

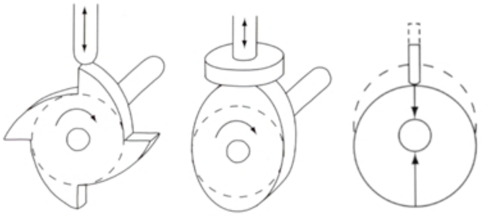


Figure 8: From left to right: a snail cam, an elliptical cam and an eccentric cam. The rotary motion of the shaft is converted to linear motion in the followers which rest against the radial surface of the cams.

8.1.2 Gears

Gears are objects which transmit rotary motion to other gears (see figure 9). Gears must be used in groups of two or more. Each gear rotates in the opposite direction of the gears it mates with. The ratio of the number of teeth of mating gears is equal to the ratio of the forces on the gears and inversely proportional to their relative speeds.

Two types of gears will be available to users: spur gears for coplanar rotation and pin wheel gears for orthogonal rotation. To get the same level of efficiency and accuracy provided by spur gears when changing the plane of rotation would require bevel gears. But the ease of construction of pin wheel gears more than compensates for their somewhat poorer performance. In virtually all of the automata I have observed, pin wheel gears are used for this purpose.

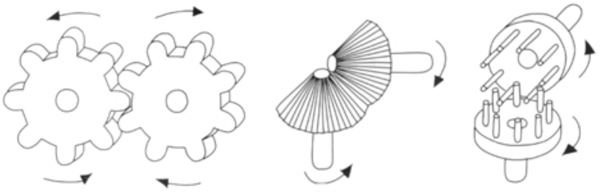


Figure 9: From left to right: spur gears which transmit rotation in a plane and bevel and pin wheel gears which change the plane of rotation.

8.1.3 Shafts

Shafts are rods or dowels of circular cross section. In the mechanisms for automata they can serve any of four functions (sometimes more than one at a time):

- They can be cam followers which carry the linear motion from the radial surface of a cam (figure 8).
- When fixed to either the automata structure of another component they can be an axis around which one or more other components rotate.
- When fixed to components and allowed to rotate within the structure they can transfer rotary motion between those components, even at a distance.

8.2 Software to assemble virtual mechanisms

Once two or more components have been designed, a logical step is to see how they fit together. This could wait until the components have been fabricated, but incorrect components would only be identified after committing them to wood or plastic. By providing a means of assembling and then animating the two-dimensional representations of the components, the user is given the ability not only to test their fit but also to analyze their motion, at a time while changes can be made with little effort or expense. This module will give the user many of the same opportunities for analysis as she would have with the physical components: testing the fit, building sub assemblies and viewing the motion of the components.

8.3 Libraries of components and mechanisms

Browsable libraries of parts comprise the third module of the software. Maintaining an inventory of existing pieces is a job which all designers and engineers do. Emulating this behavior as a part of the system will encourage users to reuse existing items when they feel that it's appropriate.

The libraries and their associated browser serve two functions:

1. The components and mechanisms in the libraries can be used as starting points for new designs [25]. A child may want to look at examples of what someone else has done in order to get ideas, or she might search for a component close to what she needs with the intention of modifying it rather than starting from scratch. Since this software is intended for users with diverse skill levels, background knowledge and creative drives, it seems fair to assume that not having examples available when a user first works with the software may be too great a hurdle for some users to overcome.
2. The libraries serve as repositories for new components, mechanisms and automata. Users will be encouraged to add what they design to the libraries. A single user may build a stockpile of "off the shelf" components for use in future projects, or she may add items she has received from other users. On machines shared by multiple users, the libraries will serve as a forum for idea exchange.

Initially the libraries will contain a small number of components and mechanisms which I will create, but as users contribute their own designs the number and variety of entries will grow, giving users an investment in the quality of the resulting system and ownership over some of its parts.

8.4 Appropriate user interfaces

The interface between user and system is a core component of each of the software modules. When building a system of this type, attention to detail in the user interface is critical. Commercially available professional design products like AutoCad and Working Model tend to have complicated or obscure interfaces. All of the power of the program is available all of the time and a steep (often vertical) learning curve is common. With a design tool for children who have neither the domain background nor cognitive skills of their adult counterparts, this style of interface cannot be tolerated. I will draw on the literature in both task-centered user interface design [16] and designing interfaces for and with children [9, 10] to guide the development of the interface, not only with regard to look and feel but also useability and appropriateness.

8.5 User readable file format

The files that the system uses will be written in English text. In much the same way that the description contained in XML files can be used by many different kinds of programs [7], these system files will be used by all modules of the system to generate the screen images and output device files for the system. This will make the system more accessible and understandable to users since the files will be text records of the design parameters of components and mechanisms. Having files in a text format will encourage users to exchange their designs and will make the designs intelligible to users. It is conceivable that these design files could be printed in hobby magazines and craft workbooks and that they could be exchanged via e-mail or posted to Web sites. This in turn could contribute to automata construction becoming a social activity and communities being formed by builders.

8.6 Why this system is different

While this system shares important concepts with existing systems (most notably HyperGami and the Cabaret Mechanical Theatre automaton kit) it is different for a number of reasons:

- It is a system that provides all of the features mentioned in section 6.7.
- It is a system that provides support for the design of both components and assemblies.
- It is a design and production system whose target users are children.
- It is a system for children to use to create mechanical automata.
- It is a system that will never be tastefully produced by Microsoft or Sunburst.
- It is a system that includes the use of a new kind of output device as a core component.
- It is a system that encourages users to exchange ideas and designs and to build communities of users.
- It is system that can be used to investigate questions in cognitive science, education and computer science.

9 Evaluation

9.1 What will I evaluate?

The skill called mechanical reasoning is really composed of two separate abilities: understanding the spatial configuration of machine components and being able to determine the kinematic and dynamic relations between those components [13]. One of the goals of creating this system will be to determine how its use, and interactions with the objects created with it, affect these abilities in children. The system testing and evaluation will take place over a period of at least three and possibly as long as five months.

9.2 How will I evaluate?

My goal is to recruit 20–30 middle school children, 11–13 years of age as subjects for the user tests. I will attempt to distribute ages and genders as evenly as possible in this population. Some of these subjects will be assigned to a control group while the others will be assigned to one of two experimental groups. One of the experimental groups will be given automata to examine and play with while the other experimental group will design and build the automata they interact with.

9.2.1 Evaluation before the experiments

A variety of test questions will be used to assess the children's levels of ability before the experiment is run. These questions will be drawn from the psychometrics literature in the areas of mental animation and spatial visualization. These questions will be as concrete as possible. The children will be presented with components, mechanisms and automata and will be asked to describe them and speculate on how they work. Some children will have an opportunity to play with automata before this portion of the test, others will only have an opportunity to watch part of a video about automata construction. The distribution of the test results will be evaluated and subjects will be placed into categories based on the distribution. This will be done so that results from the testing upon completion of the experiment can be assessed with respect to initial ability levels [13].

9.2.2 Evaluation during the experiments

Ongoing evaluation of the experimental groups will consist of observations of the users as they work with the software and as they build their automata. I will audio tape all of the work sessions for transcription and, if permission can be obtained, video tape as many sessions as possible. At intervals over the experiment I will interview the users to obtain additional information not evident by observation.

9.2.3 Final evaluation

At the conclusion of the experiment, all of the subjects will be tested in the same manner as the pre-test. The pre- and post-experiment results will be compared both by group and across the population. Of particular interest will be the speed and accuracy with which subjects determine the function of components and mechanisms and how the language subjects use to talk about the domain changes over time.

10 The contributions of this research

When completed, the research described in this proposal will have made the following contributions:

- It will have added data to the discussion of the value of providing children with personally meaningful artifacts and how those objects influence children's knowledge construction and skill acquisition.

- It will have specifically addressed the previous point with respect to the impact of automata and their mechanisms on mechanical reasoning and spatial cognition in children.
- It will have looked at important issues related to creating design and engineering environments for children and how the knowledge gained might be leveraged into other kinds of technology for children.
- It will have created a tool for use in the study of a number of questions in cognitive science, education and computer science.
- It will have raised additional questions in these fields that are worthy of further study.

11 Exposures

The possible problems which may present themselves fall roughly into three categories.

11.1 The system

A number of potential concerns are already evident with regard to the software I hope to create:

- The Java 2 APIs for both 2D graphics will be used in the system. While the 2D API has worked well so far as an AWT replacement for drawing the component profiles and providing a means of animating them, there is no guarantee that it will be as effective for the assembly module. It is very possible that the functionality of the assembly component would be scaled back if the code was either too difficult to write or too cumbersome to use.
- In the past there have been problems with the reliability of the laser cutter. It is hoped that these problems will be addressed early in the Spring 2000 semester but it is a possibility that they may return and limit our ability to use it for generating components.

11.2 The users

A number of problems seem possible since I will be working with children:

- It may prove difficult to get a sample which is large enough and diverse enough to generate statistically significant results.
- Since I've never conducted user tests on this scale the logistics and administration of the experiment will present additional difficulties.
- If users are not sufficiently motivated to work on their own to create the figures for the automata it will be necessary to come up with a plan to minimize the impact this will have on the use of the system.

- Maintaining user interest in the experiment over a semester (or longer) may be difficult and require additional work either on the quality, kind, or number of tools the children have to work with or on modifying the experiment to sustain interest and continued participation.

11.3 The timely completion of the work

- Building the system and conducting the experiment are only part of the work I need to complete over the next year and a half. I still need to complete four ICS courses and one CS preliminary exam before I will be able to defend the dissertation on this work, so competition for my time will be high.
- Funding for the RA I have been working under will expire at the end of the Spring 2001 semester. A replacement source of funding will need to be found and the requirements of the new position may impact the schedule as show in this document.

12 Timeline and Milestones

This section contains an estimated schedule for completion of major pieces of the dissertation work. Since many factors enter into these estimates I fully expected that some or even all of these dates will slip. A contingency which is not shown is to defend in the Winter 2002 semester rather than Spring, thereby adding seven months to the time available for me to complete this work.

12.1 Spring 2001

- Request for research approval from the Human Research Committee
- Component modules designed, coded, tested and integrated. Used by students in Things That Think class (CSCI–7000)
- Assembly and libraries modules design completed

12.2 Summer 2001

- Assembly and animation module designed, coded, tested and integrated
- Libraries and browser module designed, coded, tested and integrated
- All software modules integrated and tested
- Sample components and mechanisms added to libraries
- User selection process completed
- Experimental results process designed and tests created
- Materials needed for conducting experiment and obtaining results gathered

- Experiment trial to assess system usability, data collection methods and experimental design

12.3 Fall 2001

- Experiment conducted and results gathered
- Software documentation written

12.4 Spring 2002

- Experimental results evaluated
- Dissertation written
- Dissertation defense

Appendix A A detailed sample task walkthrough

What follows is an example scenario of one use of the proposed system. Most of this shows how the system I plan to build will work, but some of it is idealized and I currently have no ideas about implementation. This exists to show how the different modules will affect the system's use and to demonstrate how I believe users will continually move back and forth among the modules during the design process.

Jake is a twelve-year-old boy who has used the automata software once before. His first automaton was a dog which chased its tail in circles. The mechanism consisted of a horizontal shaft with a crank for turning the mechanism and a pinwheel gear. A vertical shaft with another pinwheel gear moved the rotation of the crank through ninety degrees. At the top of the vertical shaft Jake and his father had attached a stiff wire in the same manner as a clock's hands are attached. To the free end of the wire they attached a small plastic dog which they had bent into a curved form (so that it appeared to be running in a circle) by heating it with a hair drier. When the crank was turned, the dog moved in a circle around the vertical shaft, just as Jake had wanted.

Because of his success with his first automaton, Jake has decided that his second will be more complicated and funnier than his first. The idea for this automaton comes from Jake's love of tennis. He has often been amused while watching row after row of spectators following the ball by moving their heads from left to right to left to right as though they were all fastened together. What Jake has decided to make is a close-up view of a few spectators in which one of them just can't seem to synch up with the others.

The first thing Jake does is make sketches of what he wants the automaton to look like. He figures that it can be made on a rectangular mechanism like his first one and that turning a crank will cause it to move. Because he doesn't want to make the automaton too big or the figures of the spectators too small, he determines that three people will be enough to do the job. He chooses to make each person three inches tall. Knowing that they are sitting down he figures that each will be two inches wide and two inches deep. With these dimensions he decides that the top of the mechanism frame will be three inches wide and six inches long.

He then sets to work on the mechanism. He already knows the motion he wants; the outer two figures turning their heads from side to side in unison and the middle figure turning his head with just the opposite motion. But after thinking about it for a while, Jake can't seem to figure out a way to make that happen. He knows that pinwheel gears will change the direction of the crank's motion from horizontal to vertical but to get the heads to go back and forth the crank would need to go back and forth and he wants to be able to turn it in a circle.

Faced with this dilemma, he starts up the design software and chooses to browse through his library of automata to see if anything there suggests a solution. He looks at all the entries in the library but doesn't find anything that looks like it could be adapted to his needs. He switches to the library of mechanisms where he finds three mechanisms in which the horizontal input motion is converted to vertical motion. One of these is the same kind of mechanism he used in his first automaton, so he moves on to the others. Both of the remaining mechanisms use eccentric cams, a component he has not used before, so to better understand what they do he switches to the assembly and animation module where he can examine each.

Examining the first mechanism, Jake sees that each of the two eccentric cams has a cam follower located over the center of the cam. Each follower is a shaft with a disk attached to the lower end where it contacts the cam. This added disk gives the follower more contact area with the cam and, he guesses, might make the follower less likely to jam against the cam. He animates the crank and watches the rotary motion being converted to an up and down motion in the cam followers. He thinks that this might work if what he wanted was for the figures' heads to nod, but there is no way he can see to get the back and forth motion he wants.

Looking at the second mechanism Jake sees something very similar. This time there is only one follower for both cams. The cams are separated by about an inch and positioned on the shaft so that when one of them is at its highest point the other is at its lowest. The follower is a shaft located midway between the cams and the disk on the end of the follower has a large enough diameter to touch both cams. The disk has a pin sticking from its edge. Two more pins extend down from the upper plate on each side of this pin. A second, thinner disk is attached to the follower above the upper plate and keeps the follower from dropping any lower into the mechanism.

Jake guesses that each cam will lift the follower in turn, causing the follower to go up and down twice for each turn of the crank handle. When he animates the mechanism however, he is quite surprised to find that he was only partially correct. While the follower does rise and fall each time a cam rotates against it the action of the cams near the circumference of the follower disk cause the disk to rotate, first clockwise, then counterclockwise as the cams on opposite sides of the follower shaft turn the disk. The pins keep the disk from rotating very far in either direction. While there is a small up and down motion to the follower (which Jake isn't sure he wants in his figures' heads) the back and forth motion is just what he wants and he decides to use one copy of this mechanism for each of the figures. Since the figures are all the same size he can get away with using the same size components for each. This means he only needs to design one cam since each pair is the same size, two disks (one on the end of the follower and one above the upper plate), one follower shaft and one shaft for the cams and the crank.

Jake switches to the cam design module. Since his figures will be two inches wide that is also the distance between the shaft followers that will support each figure's head. This means that while he can use the basic layout of the mechanism from the library, he will have to make the components larger. He starts by designing the cams that will cause the shafts to rotate. He chooses the eccentric cam option in the software and enters a diameter of two inches and a pivot offset of one-quarter inch. He's not really certain how big the cams need to be but he knows that he can fit pieces together in the assembly module and change sizes later if he needs to. But he does spend some time playing with the pivot offset, watching the animation and graph of the cam change as the offset value changes. While playing around, he sees that if he specifies a zero offset what he gets is a disk. This makes him happy, since he was unsure how he would make the disks he needs.

After making his cams and disks, Jake switches to the shaft design module. Since his figures will be three inches tall he decides to make the follower shafts 5 inches long. He can change their length before making them. He then makes a two inch long crank. He then switches back to the assembly module and starts putting the pieces together. This module simulates the finished framework so he can see how everything goes together without obstructions. He starts by putting the crank on the cam shaft and indicating to the module where the bearing supports for the crank will be. He then puts two cams onto the shaft, orienting them so that their lifts will be maximum at opposite points in the shaft's rotation. He locates the upper plate, attaches a disk to the bottom of a follower, and positions it between the cams. After determining the lowest point where the follower can be, he puts another disk on the follower above the upper plate to restrict that motion. He animates the motion and sees that it is doing what he had expected. He notices that the follower disk doesn't have the pin of the original and decides to see if that makes a difference as he goes along.

Since the figures on each end have the same motion, he duplicates these steps at the other end of the cam shaft. Animating the result convinces him that these two figures will have the same motion. Since the middle figure moves opposite the end figures he decides to try reversing the position of out figures' cams for the middle figure. When he does this he notices that the middle cams match the orientation of their neighboring outer cams. This seems strange, but adding the last follower and animating the mechanism shows it to be correct. Jake thinks for a minute and decides that if he carefully chooses the diameters of the follower disks he can share cams between the middle and outer figures and that he will only need four cams instead of six.

He goes back to the cam design module and changes the diameters of the disks, making the lower ones larger and the upper ones smaller. Returning to the assembly module, he sees that the lower ones a too large and hit one another so another trip to the cam design module fixes the problem. Switching again to the assembly module he removes the two inner cams and moves the inner two remaining cams so that each is centered below the gap between the disks. Jake is concerned that the cams may not have enough contact with the disks so he goes once again to the cam design module and specifies thicker wood for the cams. Returning to the assembly module he again adjusts the location of the cams and animates the mechanism. To his delight the middle follower turns one direction when the outer followers turn the other. He watches this disharmony for a few minutes until he is certain that there are no surprises hidden in the motion.

After spending more time refining the components by moving between the design modules and the assembly module, Jake saves his components and mechanism to files. He puts the component and supporting member files on a disk to take to the community center where the laser cutter is so that he can cut out the pieces for assembly. He saves all the files into their respective libraries (components, mechanisms and automata) so that he can use them in the future.

Appendix B Reading list for the proposed work

I have identified the following additional readings as potential resources for my research. While hardly a definitive reading list, these will be the next round of papers and books that I read. They are grouped here by general content areas.

Seymour Papert. *The Children's Machine: Rethinking School in the Age of the Computer*. Basic Books, 1994

Seymour Papert. *The Connected Family: Bridging the Digital Generation Gap*. Longstreet Press, 1996

Frank Banks, editor. *Teaching Technology*. Routledge, London, UK, 1994

Robert Pool. *Beyond Engineering: How Society Shapes Technology*. Oxford University Press, Oxford, UK, 1997

John W. Cox. *Mechanical Aptitude*. Metheun & Company, London, UK, 1928

Mary Hegarty. Mental Animation: Inferring Motion from Static Diagrams of Mechanical Systems. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 18(5):1084–1102

Mary Hegarty. The Mechanics of Comprehension and Comprehension of Mechanics. In Keith Rayner (Ed.) *Eye Movements and Visual Cognition: Scene Perception and Reading*. Springer Verlag, New York, NY, 1992

Mary Hegarty and Valerie K. Sims. Individual Differences in Mental Animation During Mechanical Reasoning. *Memory & Cognition*, 22:411–430, 1994

Mary Hegarty, Marcel A. Just and Ian R. Morrison. Mental Models of Mechanical Systems: Individual Differences in Qualitative and Quantitative Reasoning. *Cognitive Psychology*, 20:191–236, 1988

Brian Bolt. *Mathematics Meets Technology*. Cambridge University Press, Cambridge, UK, 1991

Jean Piaget. *The Grasp of Consciousness: Action and Concept in the Young Child*. Translated by Susan Wedgwood, Harvard University Press, Cambridge, MA, 1976

Richard L. Gregory. *Mind in Science: A History of Explanations in Psychology and Physics*. Penguin Books Ltd., Harmondsworth, Middlesex, UK, 1984.

References

[1] Sarah Alexander. Mindfest panel discussion: *Artistic Machines*, 1999.

[2] Silvio Bedini. The Role of Automata in the History of Technology. *Technology and Culture*, 5(4):24–42, Spring 1964.

[3] Jeremy Bernstein. *Cranks, Quarks, and the Cosmos*. Basic Books, 1993.

[4] Jerry Bird. *Cogs, Cams, Springs & Things: An exhibition of Automata and related work*. Towner Art Museum, Eastbourne, UK, 1994.

[5] Norman Brosterman. *Inventing Kindergarten : Nineteenth Century Children*. Harry N. Abrams, New York, NY, 1997.

[6] Theodore Y. Chen. *Hyperspider: integrating computation with the design and construction of educational crafts*. Master's thesis, Department of Computer Science, University of Colorado at Boulder, 1999.

[7] The World Wide Web Consortium. Extensible Markup Language (XML) 1.0 (Second Edition). http://www.w3.org/TR/REC-xml.

[8] Mihaly Csikszentmihalyi. *Creativity: Flow and the Psychology of Discovery and Invention*. HarperCollins, New York, NY, 1996.

[9] Allison Druin, Ben Bederson, Angela Boltman, Adrian Miura, Debby Knotts-Callahan, and Mark Platt. Children as Our Technology Design Partners. In Allison Druin, editor, *The Design of Children's Technology*. Morgan Kaufman, San Francisco, CA, 1999.

[10] Allison Druin and Cynthia Solomon. *Designing Multimedia Environments for Children*. John Wiley and Sons, New York, NY, 1996.

[11] Ann Naomi Eisenberg. *An Educational Program for Paper Sculpture: A Case Study in the Design of Software to Enhance Children's Spatial Cognition*. PhD thesis, Department of Computer Science, University of Colorado at Boulder, 1999.

[12] Gerhard Fischer and Eric Scharff. Learning Technologies in Support of Self-Directed Learning. *Journal of Interactive Media in Education*, 98(4), 1998.

[13] Mary Hegarty and Maria Kozhevnikov. Spatial Abilities, Working Memory, and Mechanical Reasoning. In John Gero and Barbara Tversky, editors, *Visual and Spatial Reasoning in Design '99*, 1999.

[14] Mary Hillier. *Automata and Mechanical Toys: an Illustrated History*. Bloomsbury Books, London, UK, 1976.

[15] Ken Kahn. Helping Children Learn Hard Things: Computer Programming with Familiar Objects and Actions. In Allison Druin, editor, *The Design of Children's Technology*. Morgan Kaufman, San Francisco, CA, 1999.

[16] Clayton Lewis and John Rieman. *Task-Centered User Interface Design: A Practical Introduction*. Shareware, Boulder, CO, 1994.

[17] Alan Lightman and Roberta Brawer. *Origins: The Lives and Worlds of Modern Cosmologists*. Harvard University Press, Cambridge, MA, 1990.

[18] Aidan Lawrence Onn and Gary Alexander. *Cabaret Mechanical Movement: Understanding Movement and Making Automata*. Cabaret Mechanical Theatre, London, UK, 1998.

[19] Todd Oppenheimer. The Computer Delusion. *The Atlantic Monthly*, 280(1):45–62, July 1997.

[20] Seymour Papert. Situating Constructionism. In Idit Harel and Seymour Papert, editors, *Constructionism: Research Reports and Essays, 1985-1990*. Ablex Publishing, Norwood, NJ, 1991.

[21] Seymour Papert. *Mindstorms: Children, Computers, and Powerful Ideas*. Basic Books, second edition, 1993.

[22] Jean Piaget and Baerbel Inhelder. *The Psychology of the Child*. Basic Books, 1969.

[23] Derek J. de Solla Price. Automata and the Origins of Mechanism and Mechanistic Philosophy. *Technology and Culture*, 5(4):9–23, Spring 1964.

[24] Cindy Rader, Cathy Brand, and Clayton Lewis. Degrees of Comprehension: Children's Understanding of a Visual Programming Environment. In *Proceedings of CHI '97, Human Factors in Computing Systems*, 1997.

[25] Cindy Rader, Gina Cherry, Cathy Brand, Alex Repenning, and Clayton Lewis. Designing Mixed Textual and Iconic Programming Languages for Novice Users. In *Proceedings of 1998 IEEE Symposium on Visual Languages*, 1998.

[26] Alexander Repenning and Tamara Sumner. Agentsheets: A Medium for Creating Domain-Oriented Visual Programming Languages. *IEEE Computer*, 28(3):17–25, March 1995.

[27] Mitchel Resnick, Robbie Berg, and Michael Eisenberg. Beyond Black Boxes: Bringing Transparency and Aesthetics Back to Scientific Investigation. *The Journal of the Learning Sciences*, 9(1):7–30, January 2000.

[28] Marlene Scardamalia and Carl Bereiter. Higher Levels of Agency for Children in Knowledge Building: A Challenge for the Design of New Knowledge Media. *Journal of the Learning Sciences*, 1(1):37–68, 1991.

[29] David Canfield Smith and Allen Cypher. Making Programming Easier for Children. In Allison Druin, editor, *The Design of Children's Technology*. Morgan Kaufman, San Francisco, CA, 1999.

[30] David Canfield Smith, Allen Cypher, and Jim Spohrer. KidSim: Programming Agents without a Programming Language. *Communications of the ACM*, 37(7):54–67, July 1994.

[31] Cynthia Solomon. *Computer Environments for Children : A Reflection on Theories of Learning and Education*. MIT Press, Cambridge, MA, 1986.

[32] Cabaret Mechanical Theatre. *Cabaret Mechanical Video*, 1991.