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

by

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Construction of Mechanical Reasoning and Spatial Cognition

Thesis directed by Prof. Michael Eisenberg

The creative impulse in the human species is nowhere more evident than in children. From an early age they draw, paint, mold, paste, and build a dizzying array of physical objects to both establish their place within societal groups and please and amuse themselves. But this activity is also critical to the cognitive development of the child. From the ages of roughly seven to twelve, children are busy learning to reason logically and to organize thoughts coherently. Piaget calls this the concrete operational stage, where the child has learned to use symbols such as language but is unable yet to reason abstractly. In this stage children begin to truly understand how the world works, and to integrate this information into the knowledge stores that they will use for the rest of their lives. This stage is concrete because this knowledge construction occurs through the construction and manipulation of physical objects in the world.

This dissertation describes a computer aided design and manufacturing (CAD/CAM) system called MachineShop that was created to assist middle school-aged children in the design and construction of mechanical automata. By assisting children as they design mechanisms and then leveraging the power of computer controlled fabrication tools, children can create mechanical devices that they are not yet capable of making by more traditional means. Through this process children have been found to acquire enhanced visuospatial reasoning abilities, improved understandings of the nature of machines, and increased levels of confidence.

Dedication

Max Blauvelt guided and mediated my interactions with machines and mechanisms for nearly thirty years and, unbeknownst to either of us, set me on the path that has ultimately led here. This is for you Dad.

Climbin' a rope ladder over the wall,
I can be anything at all,
I know imagination's the only thing that can stop me.

11 Easy Steps, Keith Grimwood and Ezra Idlet

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There would have been nothing to report if it hadn't been for my six wonderful users: Abbie, Calum, Dylan, Frank, Iris, and Sam. You all rock!

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Chapter 1

Introduction

Civilizations have always depended on technology, but the world we live in relies on more kinds of technologies applied in more ways than would have been imaginable only a hundred years ago. Agriculture is mechanized, manufacturing automated, health care computerized. At times it seems that we have been been subsumed by our own creations. These ubiquitous and often indispensable elements of modern life are not Promethean; they are the result of human intellect and talent. Scientists have made discoveries about the working of the universe and engineers and technologists have applied that knowledge in ways that have fundamentally changed our lives.

Where do scientists and engineers come from? What is it that now separates those who create from those who consume? Why have we relinquished our understanding and control of such an important part of our lives to such a small subset of the population? This dissertation is motivated by these questions.

1.1 Motivating Problem

As recently as thirty or forty years ago, anyone with the desire to investigate the ways in which technology worked had ample opportunity. The trend had not yet begun to conceal the working parts of devices in sealed enclosures or to obfuscate their functions. The technology truly belonged to the users. While one might choose to have repairs done by someone else, it was common to purchase the parts and perform your own. Interacting with technology at such

a low level was informative and gaining skill and knowledge was easy. This held for children as well as adults and during much of the twentieth century children with desire learned to operate, maintain, and modify a wide assortment of common technology. And at that time, technology meant machines.

Two fundamental changes occurred to help put an end to these activities. The first was technological itself; the invention of the transistor. Before 1949, electronic devices could only be miniaturized to a limited extent. You could put a handle on a radio and call it portable, but you could never carry your record collection with you, or enjoy it while traveling. By the 1960s, a radio would fit in a pocket, and the smaller size to which electronic devices could be built saw them begin to take over from mechanical devices at a rapid pace. By the 1980s, transistors and the devices they spawned (like integrated circuits) had replaced mechanical timers in ovens, mechanical tuners in televisions, and mechanical engine controls in automobiles. These new devices prevented users from looking inside to see how they worked. Often the only way to repair them was by replacing them, a philosophy called planned obsolescence, and the second of the two changes. Products began to be manufactured with the specific intent that they would be replaced rather than repaired, thus providing larger profits for their makers and a population of users who knew less and less about how they worked. We, and our children in particular, have lost what was once our most common means of learning about technology. This loss is significant, since the ability to think and reason about machines can have an impact on our abilities to perform many important tasks.

1.1.1 Visuospatial Reasoning

The primary cognitive abilities associated with mechanical thinking are spatial cognition and mechanical reasoning, both of which fall into the more general category of visuospatial reasoning abilities. An individual's abilities to plan the route for a trip, arrange events chronologically, or determine if one animal is smarter than another all depend on her visuospatial reasoning skills. These same skills are also a prognosticator of how well she will do if she chooses to become a

scientist or engineer; the better her reasoning ability, the more likely she will not only succeed in a technical career, but that she will find satisfaction in it. With an increasing reliance on technology that the masses cannot understand, it has become crucial that as many people as possible not only understand technology, but can also guide its development. These people are scientists and engineers and the number who are graduating from universities in the United States is dwindling. This is hardly surprising if freshman have had diminished opportunities to gain the skills that will help them succeed. This research was motivated by a desire to expose children to mechanical systems through a very personal involvement with their design and construction and to see how the children changed as a result.

1.2 The Research Domain

The first step towards this goal was to find a domain and identify a process that would be effective for children to learn about machines. The domain needed to possess several important features that were established early in the research. First, the domain had to be one in which physical objects could be manipulated and examined. Second, the domain had to be authentic, with many and varied examples as well as a history and a reason for its existence. Third, the domain had to be interesting and one that could engage children intellectually and emotionally. Finally, the domain had to be accessible to children with enough variation in its elements that beginning builders could start off with simple mechanisms and work toward the more complex end of the domain as their abilities allowed. One domain that met all of these requirements was that of contemporary automata.

1.2.1 Automata

Automata are moving sculptures of people and/or animals whose motions repeat and are controlled by mechanical means. The history of mechanical automata goes back at least two thousands years to the Greeks. During that period the Alexandrian School of philosophers, physicians, mathematicians and engineers became a center for classical learning. Notable among the engi-

neers of this school was Hero of Alexandria. Hero designed automata to serve as examples for his papers on pneumatics and hydraulics. His designs contained many of the same elements seen in automata today; they were clever, told a story, and engaged and entertained viewers. They also featured some notable differences in that they were very large, often life-size, and the mechanisms that caused them to move were hidden from view.

Hero wasn't the only automatist working in Alexandria, but we know more about him as his surviving works became the technical foundation for the revival of the automata in the middle ages. Found mostly in water gardens and large cathedral of town square clocks in Europe, automata progressed from being water powered to operating through the use of clockwork mechanisms. As the clockmaker's art gave way to the more refined work of the watchmaker, automata also became more refined as they moved indoors. The eighteenth and nineteenth centuries were a golden age for automata and skilled artists like de Vaucanson and Jaquet-Droz created examples that were unparalleled in their beauty, detail, and actions. By World War One the days of automata were nearly done.

1.2.2 Contemporary Automata

By the latter half of the twentieth century automata were seen mostly as Victorian curiosities. But there was a small group of automatists who were reinventing the art and with the opening of Cabaret Mechanical Theatre in the United Kingdom automata started to enjoy a resurgence. Built in the style called *contemporary automata* these devices shared much with their ancestors; their motions were repeating and derived from sometimes complex mechanical arrangements, they told stories, and they were entertaining and engaging. But there were two key elements of this new style that were unique. First, their mechanisms were not hidden from view, but displayed prominently. This made the mechanical operation of the machines an integral part of the experience of viewers. Second, the stories that they told were whimsical, humorous, and sometimes just a little disturbing. There was a sense of playfulness in this style that had only rarely been seen and automata began to be reinstated into the public's consciousness.

1.2.3 Why are Contemporary Automata a Good Choice?

Contemporary automata meet all of the requirements specified in Section 1.2. In addition, they address the motivating problem in important ways. They offer children the opportunity to interact directly with their moving parts and to observe both the dynamic and static relationships between the parts. They range in complexity from very simple examples with one or two mechanical components, to intricate creations with mechanism wherever you look. Children see simple automata as something they can not only understand, but that they can build. The complex automata let children know that they can move beyond their early successes and continually find challenges and rewards in the domain. Most of all, contemporary automata are fun, something children understand the moment they first see one. This type of engagement makes the domain attractive to children and should hold their interest for a long time.

1.3 Why Create Computer Systems to Design and Build Automata?

The tradition of automata construction has been one in which a skilled craftsperson[1] has built each automaton by hand. The conventional meaning of the phrase "by hand" causes concern when thinking about activities for children. Even though the introduction of tools powered by water, steam, and electricity altered its definition only slightly, adding computers to craft isn't viewed as a benign change. McCullough [77] provides a more inclusive perspective when he suggests that "by hand" should be understood to mean that the craftsperson is in control of the craft process at all times. This gives us a guideline for how to incorporate computers and software into the craft of automata building, but still leaves the question of how this will benefit children who want to create automata.

[1] As Wrensch points out [133], trying to distinguish between craft and art is a particularly futile effort. The professional automatists mentioned later in this work are brilliant artists as well as skilled crafters. I have chosen to use craft throughout this work simply because an automatist shares his or her skill with tools with other pursuits that are more closely associated with craft.

1.3.1 Reduce Barriers to Entry

Although automata can be very simple, learning how to design and build them is not. Automatists need to know about how the mechanical components they will design will work together, how the materials they will choose behave when being shaped, formed, and used, and how the tools they will need are efficiently manipulated. Few children have even a small amount of this knowledge, and gaining it in traditional ways takes a long time. Computer systems can support new automatists as they acquire this knowledge by reducing, and in some cases eliminating, much of this need. By providing software tools to design components, the automatist can easily make them with a desired functionality without needing to know values for all of their descriptive parameters. By utilizing automated fabrication tools to create components, the automatist produce finished pieces that are of high quality and that can be made from a variety of materials.

1.3.2 Make Mechanical Reasoning Explicit

Computer systems can provide a means to explore mechanical systems in ways that would be hard to do in the real world. Changes to a cam's profile or the pitch of a gear's teeth can happen quickly with a computer system, but are slow and laborious processes when done traditionally. The behavior and look of an automaton can be played with and refined until they match exactly the automatist's goals. An automatist can ask "what if" questions and have empirical answers within minutes. This is not a substitute for manipulating physical objects. It is a means to manipulating more objects than might otherwise be possible.

1.3.3 What Do Beginning Automatists Currently Use?

The venues in which a computer system for automata creation would be found are now home to automata kits, and most beginning automatists get their starts by building these kits. Some kits contain all of the materials needed to build an automaton designed by a talented automatist. Most commonly the materials are wood or paper and only glue, paint, common tools,

and a little self-confidence are all that the builder needs to supply (see Section 3.4.1.1). Kits provide a good introduction. The builder has some assurance that the pieces will fit and function as expected, the instructions clearly lay out the assembly steps, the end result has a professional pedigree, and, particularly in the case of the paper kits, the price is reasonable. But the design activity and its associated learning opportunities are missing entirely.

Other kits (see Section 3.4.1.3) provide a variety of pre-made mechanical and decorative components and are intended to help automatists design automata. These kits are made from wood and plastic and are expected to be assembled and disassembled many times. The parts are robust and the operation reliable, but the finished automata are not as visually pleasing as those made from the single purpose kits nor are they intended to have any permanence. By building computer systems we can gain the advantages of both types of kits, and even a bit more.

1.4 Research Question

The preceding sections have given context to the issues and concerns that have shaped this research. They have described the domain in which this research was undertaken and explained what advantages a computer based approach might be expected to provide. They have also helped frame a research question to guide this research:

> **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?**

The chapters that follow will provide further understanding of the context and will strive to provide an answer to this question.

1.5 Research Approach

The research question separated the research into two logically connected components that benefited from being largely sequential. First it was necessary to design and implement not

only the software that had been initially envisioned, but also to leverage the power of one of the growing number of fabrication devices. For the software, a suitable programming language was chosen and hardware platforms on which the software would run were selected. A survey of contemporary automata was initiated to determine the most used and most useful subset of possible components. For each component, choices were made as to their base attributes and about how much and in what ways they should be modifiable by users. The major tools were created, altered, and combined in an iterative development cycle. File types and specifications were developed. Software to create fabrication files for the original laser cutter in our lab was built and then modified when that machine became irreparably horked.

As the software reached a useful level of maturity, planning began on the methodology for the user testing and evaluation. Based on nearly thirty years of personal experience both receiving and providing on-the-job type training, a plan for involving the young users in an apprentice-like series of activities was conceived and refined. The foundation for these activities was patterned after common engineering practice involving new design, modification of existing design, reuse, and prototyping. Support materials were created and a plan for documentation and assessment was developed.

At this point users were recruited and the testing began. The first user was the son of a graduate student at the university who arranged a meeting between his science teacher and several members of our research group. This meeting resulted in my being contacted by parents of four middle school students who were interested in the research. Of these four, only three participated. The fifth user to begin the testing was the daughter of another graduate student and within a few weeks of her involvement she convinced a friend to become the sixth and final user. The testing spanned a period of ten and a half months during which time user participation ranged from 13 weeks to 37 weeks.

1.6 Reader's Guide and Road Map

The dissertation is a work in three parts. The first part is concerned with mechanical thinking and its applications. It begins with Chapter 2 which examines the current state of research into visuospatial reasoning in general and mechanical reasoning and spatial cognition in particular. The importance of these abilities is presented and a set of evaluation metrics for use in the experiments are developed.

Chapter 3 reviews a variety of environments and tools that are of potential use in studying the acquisition of mechanical thinking in children. The relative merits of these are compared and their strengths and weaknesses discussed.

The second part examines the domain chosen for this research. Chapter 4 begins with a history of mechanical automata from antiquity to the present day. It describes the evolution automata have undergone and identifies the core elements that have remained constant for over two thousand years. It continues by discussing the features of automata construction that make it a reasonable choice for this research and concludes with a brief look at some ways in which contemporary automata are being used in education.

The third part looks at the experiments created to address the research question. Chapter 5 examines the MachineShop system in detail and discusses how its design will support children as they create automata. It describes the process by which a user's ideas are carried through to physical objects and details supplemental materials that were created to support that process.

Chapter 6 details the experimental method and its underlying foundations. It reports on the results of the user tests and examines them to see what they mean with respect to the research question.

Chapter 7 presents an abridged case study from the testing. One user is followed as he designs and builds two automata and the changes in his mechanical thinking, domain expertise, and self-confidence are discussed and illustrated.

Chapter 8 summarizes the conclusions reached from the user testing. It highlights the key

contributions of this work and presents directions for future research.

Chapter 2

Mechanical and Spatial Thinking: Concepts

What is it that makes thinking and reasoning about machines such a difficult task for so many people? There are many reasons, but three come readily to mind. First, the structure, composition, and behavior of machines do not easily lend themselves to being communicated in words, a situation that Wallace considers key:

> The work of the mechanician was, in large part, intellectual work. This was true in spite of the fact that he dealt with tangible objects and physical processes, not with symbols, and that some of what he did was done with dirty hands. The thinking of the mechanician in designing, building, and repairing tools and machinery had to be primarily visual and tactile, however, and this set it apart from those intellectual traditions that depended upon language, whether spoken or written. The product of the mechanician's thinking was a physical object, which virtually had to be seen to be understood; descriptions of machines, even in technical language, are notoriously ambiguous and extremely difficult to write, even with the aid of drawings and models. [127, page 237]

Second, over the last three or four decades, the opportunities to view the internal operation of machines have been significantly reduced, even as our exposure to machines has increased. Part of this has to do with the replacing of mechanical controls with electronics, but to a greater extent this has come about through a deliberate trend towards the machine as *black box*. We are free to observe the input and output states of a machine, but we no longer have access to the works, and can no longer observe the machine as it operates. Users are advised against breaking the seals of black box machines with threats of injury and voided warranties and by assurances that there is nothing to be gained by opening the case. Illich emphasizes this point:

> The nonspecialist is discouraged from figuring out what makes a watch tick, or a telephone ring, or an electric typewriter work, by being warned that it will break if he tries. He can be told how a transistor radio works but he cannot find out for himself. This type of design tends to reinforce a noninventive society in which the experts find it progressively easier to hide behind their expertise and beyond evaluation. [62, page 115]

Third is the marginalization of the master/apprentice model of instruction common during the two hundred years that saw mechanization and industrialization spread around the world. A young person (often a boy or young man owing to social norms) could apprentice to an older, experienced master in order to gain an intimate familiarity with the design and maintenance of machines and would be expected to pass along his knowledge to his own apprentices[1] . Denis Diderot in his article "Arts" in the *Encyclopédie* highlights the importance of applied knowledge:

> . . . every "art" [technique] has its speculative and its practical side. Its speculation is the theoretical knowledge of the principles of the technique; its practice is but the habitual and instinctive application of these principles. It is difficult if not impossible to make much progress in the application without theory; conversely, it is difficult to understand the theory without knowledge of the technique. In all techniques, there are specific circumstances relating to the material, instruments and their manipulation which only experience teaches. (quoted in [82, page 27])

Illich raises a genuine concern with respect to our general inability to think and reason about machines and our seeming indifference to that inability; we have become a noninventive society. We consume technology rather than create it. We use technology but we can no longer repair it when it fails, or adapt it to other purposes. We have lost our power over technology and consigned our technological choices to others. Understanding how mechanical thinking and reasoning occur and creating strategies to enhance them could go a long way toward letting us retake control.

[1] The sociological impacts of this form of *on-the-job training* were profound, but are beyond the scope of this discussion. I have concerned myself here only with the transfer of domain knowledge and skill in this working environment.

This chapter explores issues relating to thinking and reasoning about machines. It begins with a brief introduction to mechanical thinking[2] with an emphasis on why it is different than other types of thinking, why it is a valuable ability, and why its acquisition has become increasingly more difficult in the last few decades. This is followed by definitions of the terms *spatial cognition* and *mechanical reasoning* as they apply to mechanical thinking. It continues with a look at current research into, and models of, mechanical reasoning and looks at what, if anything, might be done to enhance the acquisition of mechanical reasoning in children. It then offers an argument for taking a *constructionist* approach to encouraging children to design and construct machines and situates the MachineShop system and research program within constructionism. It concludes by using the prior research into mechanical reasoning and constructionist education to identify methods by which changes in children's mechanical thinking might be observed during the assessment of the experiments described in Chapter 6.

2.1 Thinking and Reasoning About Machines

Wallace makes two crucial observations in his quote above. First, the work done by those who design, create, and maintain machines (*mechanicians*) is just as much intellectual work as that done by any other professional. Second, the realization of the mechanician's intellectual work in physical objects makes the work substantially different than intellectual work that produces answers, ideas, or other thoughts. The understanding of the mechanician is encapsulated in her machines and it is through those machines that other mechanicians can learn what she knows. The same is not true, for example, of a botanist. While her understanding might help her develop a hybrid plant strain with some desirable property, showing that plant to other botanists would have no effect on their ability to duplicate or extend her accomplishments.

In Wallace's analysis, the roles of the elements of thought and their grammars are reversed when comparing his two categories of thinking. In linguistic and mathematical thinking the syntax

[2] Mechanical thinking is used in this work to refer to understanding and reasoning about machines and not to its often used meaning of thinking in a mechanical fashion.

of thought is known a priori, and it is the words or phrases which, when taken together according to that syntax, give meaning to the thought. In mechanical thinking, the components available for use in a machine are previously known and it is in the order and structure of their composition that the meaning of the thought is revealed.

The former pattern of thought is the one that most people feel comfortable with and it is the pattern of education in most of its forms. The latter is rarely encountered and seldom taught. It is small wonder that many people find it foreign. But is this a situation with which we should be satisfied? Wallace and Illich clearly believe it is not and Section 2.2 will argue that when children are better able to think and reason about machines it benefits them in a variety of ways.

2.2 Visuospatial Reasoning

The ability to reason about machines falls into the broad arena of visuospatial reasoning. Tversky [123] places a variety of tasks in this category, some of which, at first glance, aren't obviously visuospatial. For example, she says that many abstract reasoning tasks such as chronologically situating two events or determining if a conclusion follows logically from its premises are visuospatial tasks and that they require the same abilities as running to catch a ball, stacking suitcases, designing a museum, or determining whether gears will mesh. This is true, she claims, because humans need to acquire spatial knowledge about the world and the things it contains in order to survive. Visuospatial reasoning becomes our first, and for many years primary, tool for accumulating this critical knowledge and its importance is reflected in the large number of spatial figures of speech that we routinely employ:

> . . . we feel close to some people and remote from others, we try to keep our spirits up, to perform at the peak of our powers, to avoid falling into depressions, pits, or quagmires; we enter fields that are wide open, struggling to stay on top of things and not get out of depth. [123, page 209]

The ability to reason visuospatially has been shown to affect an individual's success in a number of areas far beyond the realm of the vocational. Elementary school-aged children with

well developed spatial abilities tend to perform better when working with high-level mathematical concepts, particularly those that require problem solving in three dimensions [46]. When students enter college their spatial abilities are good indicators of the success they will experience in mathematics [106], the physical sciences [105], and engineering [100]. Certainly there is some evidence that admitting students to programs in engineering and the physical sciences based solely on their mathematical and verbal performance on standardized tests such as the Scholastic Aptitude Test (SAT) or the Graduate Record Examination (GRE) keeps many talented individuals from pursuing studies in these important fields [61].

Visuospatial reasoning comprises creating internal representations of objects, performing transformations on those representations, and making inferences based on the transformed representations. Representations are composed of static properties of objects such as color, shape, and texture, relations between objects and reference frames such as distance and direction, and dynamic properties of objects such as direction, path, speed, and manner of movement. Transformations are operations that either use the information contained in a representation or change it in some way. While the number of distinct visuospatial abilities as well as their distinctness are still open research topics [56, 16], three factors recur in the study of visuospatial reasoning [71]: spatial perception, spatial visualization, and mental rotation. Each plays a key role in the two components of mechanical thinking of salience to us here: spatial cognition and mechanical reasoning.

2.2.1 Spatial Cognition

Spatial cognition is concerned with the acquisition, organization, utilization, and revision of knowledge about objects and space. This ability serves us in many ways beyond simply navigating in our surroundings. It allows us to make sense of the visual stimuli our eyes send our brains, and to communicate that information using language [99], to make inferences and predictions about occurrences in the world [38], and is fundamental for a host of other basic and high-level cognitive tasks. With respect to mechanical thinking, spatial cognition establishes what can be

known about the relationships and dependencies among mechanical components in a machine and provides the information necessary to make inferences about causality in their motions. It allows an individual to map structure, form, and function from machine to diagrammatic representation and vice versa and it supports reasoning about the outcome of operations that the machine might perform. Spatial cognition provides the basic tools that are brought to bear on mechanical reasoning tasks.

For the purposes of this research, spatial cognition is understood to provide knowledge of the absolute positions of components within a machine and the relative positions between components. It underlies understanding of the transmission of motion from input to output, the identification of both permitted and forbidden motions based on component selection and placement, and the ability to locate and correct errors and malfunctions in a mechanism.

2.2.2 Mechanical Reasoning

Defining mechanical reasoning is not an easy task. It goes by many names (mechanical aptitude, mechanical ability, mechanical ingenuity, mechanical sense, and many others) and has equally many meanings. A survey of the literature shows these used somewhat interchangeably which further confounds efforts to present a consistent definition. As will be seen in the discussion which follows, there are two key abilities which are studied. The first of these, which is commonly termed mechanical reasoning, is the ability of an individual to perceive and understand the movement or function of mechanism (usually of simple design and composition) either from interacting with the mechanism or by observing the mechanism or an illustration of it [48, 57]. The second ability, which is sometimes called mechanical ability, is the ability of an individual to describe a mechanism that, when given some specified input, will produce a desired output [23, 51].

It seems reasonable that being able to infer the operation of a mechanism and being able to design a mechanism to achieve some desired function have a great deal of overlap. The teasing apart of these skills has resulted more from divergent research agendas than from any real differ-

ence in abilities. On this basis, mechanical reasoning will be used in the following chapters to include the ability to understand the functioning of a mechanism or machine (mechanical reasoning) as well as the ability to conceive of a mechanism or machine that is suitable for a specified purpose (mechanical ability).

2.3 Research in Mechanical Reasoning

While human societies have relied upon individuals who can create and understand machines for centuries, it has only been in the last one hundred years that concerted research has been undertaken to study how mechanical reasoning takes place. This section provides an overview of that one hundred years of research and describes the goals and conclusions reached.

2.3.1 Industrial and Vocational Psychology Research

The field of industrial psychology emerged early in the twentieth century [96]. While much of the work in this field formed the basis for studies in industrial processes and efficiency (the time and motion studies of Taylor for example [116]), it also gave rise to a body of research which would become vocational psychology. Vocational psychologists were (and are) interested in discovering which intellectual capacities predispose an individual to a certain occupation or set of occupations and in devising methods to identify those capacities in an individual. Vocational psychology arose concurrently with technologies that promoted mass production at one extreme and mechanization on much smaller scales than previously possible on the other. Given this parallel development, it was all but inevitable that vocational psychologists would become interested in the trades of the mechanician and engineer.

Researchers such as Cox [23] and Paterson [95] were interested in *mechanical aptitude* as a measure of potential success for individuals interested in careers as engineers, draftsmen, machinists, mechanics, ornamental ironworkers, and similar occupations. Cox sought evidence for a special *mechanical intelligence* which was separate from, and complementary to, Spearman's general intelligence quotient (*g*) [108]. His thesis presupposes the existence of this special intel-

ligence (which Cox calls *m*), and is primarily concerned with the development of tests to provide a measure of this aptitude and methods by which those measurements can be used to predict vocational success. In constructing his tests, Cox and Paterson built upon the work of other researchers in this nascent field, most notably that of Stenquist [110] who had devised some of the seminal tests for this purpose.

While assessments of this type were widely used to measure aptitude [3] towards a variety of occupations (including engineering and home economics [113]) into the latter part of the twentieth century, they are predominantly used now with occupations such as drafting, machining, and vehicle maintenance.

2.3.2 Cognitive Psychology Research

Cognitive psychologists began studying mechanical reasoning in earnest during the 1980s, drawn by questions of how the brain acquires, processes, and uses information about mechanisms and machines. This form of mechanical reasoning research has focused on a number of areas (presented here in approximately chronological order):

- The use of rules in the construction of mental models of mechanical reasoning
- Differences in the accuracy of reasoning between individuals and the sources of those differences
- The cognitive costs associated with individual components of mechanical reasoning tasks and their effects on working memory
- Inferring motion from static representations of mechanical systems
- Using text and diagrams in the construction of mental models
- The effects of animated diagrams on mechanical reasoning

[3] While there may exist some natural affinity to the domain of machines in individuals who perform well on these kinds of psychometric tests, much of what is revealed arguably reflects experience and familiarity.

- Differences in mechanical reasoning using diagrams and real machines
- The use of diagrams as external memory in mechanical reasoning

In early research, Hegarty, Just, and Morrison [51] presented subjects with diagrams of pulley systems and asked them to answer questions based on the diagrams. Figure 2.1 is typical of these problems.

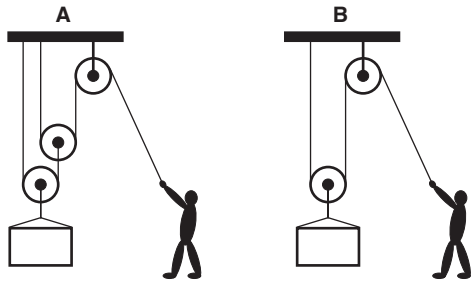


Figure 2.1: A diagram of a pulley system used to understand how test subjects reasoned in this domain. Subjects were asked to choose which pulley system would require the greatest effort in order to lift the weight; A, B, or C if there were no difference. (After Hegarty)

Their goal was to identify the rules subjects used to accomplish these tasks and to account for individual differences in performance [51]. A production system was created to simulate the performance of the subjects and the production rules were assessed by comparing the performance of the system with that of the subjects. Three abilities were identified to account for individual differences: distinguishing between relevant and irrelevant system attributes when creating rules, consistent use of rules, and the ability to combine information about multiple attributes into a single rule. They concluded that these rules and their application reflect an individual's understanding of the causal relationships between the attributes of the system and that this causal understanding of a mechanical system constitutes a mental model of the system. They further asserted that low-scoring subjects used only qualitative mental models while high-scoring subjects used both qualitative and quantitative models.

The three abilities identified by Hegarty and her colleagues relate directly to the visuospatial reasoning factors of spatial perception and spatial visualization mentioned in section 2.2.

Further research addressed the role of the third factor, mental rotation, in mechanical reasoning. The type of mental manipulation necessary to reason about the functioning of a mechanical system relies not on the individual's ability to rotate the mechanism as a unit, but the ability to mentally set the components of the mechanism in motion and observe their operation [48].

While predicting system behavior from static diagrams was shown to enhance subjects' understanding of the system [53], mental animation can reduce the accuracy of mechanical reasoning. Since these animations are carried out in working memory, the limits on the capacity of working memory can be exceeded as the number of system attributes increases [49], with the result that errors increase with a component's distance from the beginning of the causal chain due to the increased number of intermediate motions that must be stored in working memory, then retrieved and evaluated [54]. This is similar to what is seen in standard mental rotation studies where the time necessary to compare two shapes increases with the angular differences in their orientations [115]. The capacity of working memory also seems to be a factor in individual differences in that subjects who can combine attributes of the system by chunking [81] perform better than those who cannot.

With respect to mental models of mechanical systems, those constructed using text and diagrams have been shown to be superior to models constructed using either medium alone [50]. Diagrams serve as external memory aids in support of the text which frees up working memory while the text directs the inspection of the diagrams and the encoding of information in them. Diagrams become even more useful external memory aids when users are encouraged to annotate and embellish them [55]. Not surprisingly, it was found that when reasoning about the pulley systems used in all of this research that the best mental models were constructed during interactions with physical systems [35] where multiple visual viewpoints were available and tactile feedback of the system kinetics was available.

It should be noted that all of the cognitive research examined here has been based on systems of pulleys that, for the most part, were represented as textual descriptions and two-dimensional diagrams. This is not the only research of this kind however, and other researchers

do choose to study other kinds of systems including a few that are heterogeneous and more complex [57]. Hegarty and her colleagues [51] defend their choices by citing previous research on similar psychometric testing. They assert that this research shows that it is not essential to the validity of the tests to manipulate physical objects and that restricting experiments to pulley systems does not compromise the generality of the research. If all that we are interested in is the quality of the research methods this will suffice. But while much may be learned from text and diagrams, it seems likely that even more can be learned from real machines, particularly when those machines are authentic, heterogeneous collections of components rather than simplistic, homogeneous assemblages.

2.3.3 Educational Research and Practice

To complement the vocational and cognitive research agendas already mentioned, there is a third body of research and practice in which an individual's ability to reason about machines and mechanisms plays an important role; the classroom. The use of physical manipulatives in structured educational settings is not a new phenomenon [10, 104], but the purposes to which mechanical devices and components as *objects-to-think-with* [92] are used go far beyond anything that Froebel or Dewey might have imagined. Most elementary school children in the United States will see *simple machines*[4] in general science units dealing with force and mechanical advantage [22], and some research [78] has examined ways in which reasoning about simple machines can be enhanced in these settings. In mathematics classrooms children may encounter levers and pulleys for lessons in algebraic reasoning [84, 85], or they may use gears as aids in understanding mathematical theorems [5]. These have been the standard methods of using machines as manipulatives in education for many years. More recently though, curricula are once again including elements intended to teach children about technology, its design, construction, uses, and societal implications, and research and practice have turned to how best to structure this educational

[4] The five classic simple machines are the lever, inclined plane, wheel and axle, screw, and pulley. The wedge is sometimes included in this group, but is really a form of inclined plane according to my fifth grade teacher, Mrs. Barby.

focus.

One way to study children's notions about mechanisms is to look at how they assign roles to components in mechanisms as an indication of their understanding of the causal relationships between the components. Causal reasoning, as mentioned previously, is one of a number of abilities gathered under the umbrella of visuospatial reasoning and is an important constituent of generalizable abstract reasoning. Among approaches to studying causal reasoning is the *mechanism approach* which posits that causation relies on some sense of a force being transmitted from one component in the causal chain to another [1] just as forces are transmitted between the mechanical components in a machine. Lehrer and Schauble [69] have taken advantage of this proposition to examine how children reason about causality in compositions of gears with no purposeful function as well as in machines with which children are assumed to be familiar[5] . Their research showed important age related stages in children's abilities to discover, internalize, and communicate causal relationships between components and suggests approaches to structuring educational contexts to better support learning and reasoning about machines.

This desire to teach children about machines is not new. In the United States, technology education (formerly know as the *mechanical* or *industrial arts*) has a history going back over a century. Educational philosophers such as Dewey believed it to be an important area of knowledge, but all too often they felt that its study was not socially and culturally at the level of other educational subjects. This attitude is still prevalent and has hindered many attempts to mainstream technology education, particularly in the elementary grades [39]. This has not been helped by the "trivial and methodologically flawed" [63, page 29] research on technology education in the latter part of the twentieth century, and the very small amount of that research that was specific to elementary education [40]. Many current attempts work towards an understanding of technology through the process of designing technology that is conceived and developed by the

[5] The choices of crank driven eggbeater and bicycle are interesting. In the case of the eggbeater, it is probably rare that a child has encountered such a device without a motor until the testing session. And while bicycles are said to have *gears* they more correctly use *sprockets* to transmit power from the pedals to the rear wheel. Sprockets differ fundamentally from gears in the direction of rotation of connected components. Direction of rotation is one of the attributes of interest in this study.

children themselves. This process of providing design guidelines (providing the design process with constraints) to students, rather than design briefs (explicit courses of action), works to create a more authentic experience for students which in turn makes the skills and knowledge acquired more relevant and meaningful [59, 121]. Curricula of this type are being used in many places around the world (the United Kingdom [86] and New Zealand [64]for example) and in many state, provincial, and local school districts in North America.

2.4 Constructing Mechanical Reasoning

The correlation between visuospatial reasoning and success in a number of academic areas is compelling and it would seem that we would be doing children a service if we were able to design learning environments to stimulate and support the creation of this kind of reasoning. As an example, much has been learned about how mechanical reasoning occurs; the mental models that are constructed, the limits imposed by working memory, the discovery of causal relationships, and a host of other cognitive features. Other research has shown how this knowledge can be put to use in creating learning environments for technology education. But what about the *acquisition* of mechanical reasoning?

The common wisdom is that an individual's visuospatial abilities are constrained by aptitude and little research exists that runs counter to that claim. In one notable exception, Brinkmann showed that the spatial visualization test scores of students participating in a carefully crafted course of programmed instruction were significantly higher than either their pre-instruction test scores or the post-instruction test scores of a control group [8]. While these results are encouraging, the students were unhappy with the programmed instruction technique and it might have proven difficult to get these students to volunteer for another course of instruction to determine if their scores could be raised even further. The work described herein uses another educational technique that has proven itself to be more agreeable and engaging to its users; constructionism.

2.4.1 Constructivism and Constructionism

Constructivism is a psychological theory of learning which has its roots in the works of Vygotsky and Piaget [94]. Piaget's contributions to this theory are sometimes termed *cognitive constructivism* while Vygotsky's are termed *social constructivism* [20]. In the Piagetian view, the learner constructs knowledge internally from a series of experiences with the implication that the role of the teacher is to provide rich environments for exploration. In contrast, the Vygotskian view places emphasis on learning that is situated in particular contexts and socially mediated. This implies that the while the learner still constructs knowledge, teachers and peers play a key role in the mediation of that process. Both views are strongly related by their central tenet of experience in learning.

Constructionism can be seen as an effort to meld the two facets of constructivism and to extend the resultant. It's principles come from the work of Papert who explains it simply:

> Constructio*n*ism—the N word as opposed to the V word—shares constructivism's connotation of learning as "building knowledge structures" irrespective of the circumstances of the learning. It then adds the idea that this happens especially felicitously in a context where the learner is consciously engaged in constructing a public entity, whether it's a sand castle on the beach or a theory of the universe [91, page 1].

Both constructionism and constructivism place the emphasis of knowledge construction with the learner, putting them at odds with the instructionist view that knowledge can be handed down from some authoritative source (such as a teacher) and then fully integrated by the individual with her existing knowledge. Papert addresses this dichotomy in his observation that while there exists a word for the art of teaching (*pedagogy*) there is no word in popular usage that describes the art of learning[6] [93]. Constructionist learning environments that are computational [65], physical [112], and combinations of both [103] show much promise for work in this area and suggest that, in many educational activities, constructionist methods provide greater potential

[6] Papert proposes the word *mathetic* to mean the art of learning from the Greek *mathmatikos* meaning "disposed to learn".

for enhanced learning outcomes.

2.4.2 A Constructionist Approach to Mechanical Thinking

The current work takes a constructionist approach to mechanical thinking and the acquisition and enhancement of mechanical thinking and reasoning. By placing the user in a position where she must create a "public entity", in this case a small machine of her own design, the domain becomes a much richer environment in which to work and her path toward knowledge construction becomes far less structured than an instructional activity would have allowed. With little epistemological data available concerning how children design and construct machines and even less pedagogy, it was necessary to rely heavily on previous constructionist research and prior experience to deconstruct this domain in order to develop an environment suitable for study.

The first step was to choose a mechanical domain that would be authentic and rich in character while being small and well defined and would allow for the creation of physical objects that children would find within their abilities. To this end a number of types of small mechanisms were evaluated. Some proved overly simple or superficial and were not thought compelling enough to maintain children's interest over consecutive projects. Others which looked initially promising were later discovered to contain some feature or features that rendered them unsuitable from an intellectual or mechanical standpoint. In one instance, some considerable time was spent in trying to devise solutions to mechanical issues with a family of objects only to discover that the were really only of interest when combined together into larger aggregates. The search finally settled on mechanical automata and in particular that subset described as contemporary automata. Chapter 4 explores these devices in detail and discusses the reasons that they were selected for this study.

The second step was to create a methodology for design and construction that would support novices as they explored the domain. The end result combined a number of features from both the craft apprenticeship and modern engineering traditions. Craft apprenticeship showed the value of having novice designers working alongside a researcher with a significant level of

domain knowledge and experience. This would provide the novice with a primary source of information and a guide in new and unfamiliar areas of the domain. To keep novices engaged and involved, some traditional features were eschewed. For example, an important area of inquiry was to examine the changes that occurred in children's mechanical reasoning as they worked from their initial concepts through to realized machines. This was simply not done in the craft tradition where it was customary for apprentices to work on projects that were envisioned and supervised by their masters. This meant that much of an apprentice's involvement with any project was repetitive and menial. While this was necessary to encourage the acquisition of manual abilities and aesthetic sensibilities, it meant that it was many years before an apprentice would be allowed to work on his own creations. Borrowed from current engineering practice were features such as the use of hierarchical decomposition of the intended movements during the design phase, the use of iterative prototyping for design refinement (including changes to the design requirements), and the reuse and modification of existing design elements. This approach is believed to provide both sufficient freedom for the users to create without being overly constrained while offering an adequate level of assurance that designs could, and would, be brought to completion. The application of these principles is presented in Chapter 6.

The third step was to design the tools that children would need to support their work in this domain and several key issues needed to be addressed in the requirements of this support system:

(1) The system must be usable by children.

(2) The system should support users with varying amounts of domain knowledge and skills.

(3) The system should reduce the complexity of difficult tasks (such as component fabrication) in order to keep users focused on more engaging tasks.

(4) The system should support multiple styles of use and allow for variety in workflow

(5) The system should be integrated into the environment in such a way as to allow users to work holistically.

The system that resulted from the implementation of these requirements is presented in Chapter 5.

2.5 Changes in Mechanical Thinking

The cognitive, vocational, and educational research into mechanical reasoning suggest a number of phenomena whose manifestation would suggest that changes in mechanical thinking have occurred. When viewed through the filter of constructionist educational activities it is possible to identify several criteria, qualitative in nature, that could be used to evaluate the efficacy of educational methods whose focus is the acquisition and enhancement of mechanical thinking in children. Some of these, such as causal inference, have been explicitly targeted in the research literature [69], while others such as discrimination and integration (Section 2.5.4) have not. They all provide indications of an individual's ability to think and reason mechanically and those that follow were considered important metrics for evaluating the user testing for MachineShop (described in Chapter 6).

2.5.1 Changes in the Use of Domain Specific Language

These occurrences can be of two types, both with a continuum of possible observations. The first is a change in the correct use of terminology. When dealing with individual components, for example, this continuum would proceed from the use of abstract terms ("thing", "star", "doohickie") to the use of generic category names ("cam", "gear", "lever") to specific identifiers ("three-lobed snail cam", "a set of pinwheel gears with a two-to-one ratio"). It would also be expected that there would be occasions where unfamiliar objects would be placed into familiar categories using identifiable similarity measures or that new objects might be referred to using some combination of previously acquired terms combined in a novel fashion.

The second is a change in the ability to describe and discuss mechanical components, assemblies, and complete machines with increasingly sophisticated technical language. This ranges from the proper user of terms to the ability to describe some aspect of a machine in a concise and logical manner, to the ability to discuss mechanical processes in the abstract. While this is the more sophisticated of these two facets, it would be expected to see it arise more or less concurrently with increases in terminology proficiency.

2.5.2 Changes in the Use of External Representations

External representations serve key roles in the design process. With the design of automata they take two primary forms: drawings and artifacts. Tversky calls drawings "... an integral part of the dialogue a designer conducts with him or herself during design." [122] and argues that they reflect conceptualizations rather than perceptions of reality. She further contends that they use a small number of elements to map the important attributes of a domain and that the elements used and the order in which they are drawn reveal the manner in which the domain is schematized. Kavakli has investigated the how the use of sketching compares in novice and expert designers [74]. While users will not become expert automata designers during the course of this research, changes in the number of drawings created and the information they contain would indicate changes in reasoning.

The same should be true for physical artifacts, which Chandrasekaran calls kinesthetic representations [17]. The information gained from manipulating objects complements that found in drawings, particularly when dealing with the structural or dynamical properties of the object (Suwa and Tversky refer to this as functional information [114]) which may be difficult to represent statically or in two-dimensions. Observing how the use of artifacts changes over the course of the experiments would also be expected to reflect how reasoning is changing.

2.5.3 Changes in Mappings from Structure to Motion

The shape of a component in a mechanism is its most readily identifiable feature and would be the expected manner in which novices would refer to it. These descriptions rely on static representations of components that only become interesting when placed in motion. Changes in the ability to describe the mappings that exist between the static features of a component and the behaviors it exhibits when moving reflect associated changes in reasoning.

2.5.4 Changes in Discrimination and Integration Skills

One of the most difficult tasks in mechanical thinking is being able to look at a new collection of components and determine the function of the assembly. This process has two parts and successful causal reasoning depends on both. The first is discrimination; the ability to look at a mechanism and determine what role each component plays in the operation of the whole. The second is integration; the ability to see not only how the combination of individual component behaviors work together to produce the observed function of the mechanism, but also to see how changes or rearrangements would affect that function. This skill is also important in the design of new mechanisms with a predefined behavior.

2.5.5 Changes in the Ability to Deal with Complexity

The complexity level of mechanisms and machines can range from the very simple to the virtually incomprehensible. As the ability to think mechanically increases, it should be possible for an individual to make sense of increasingly more complex mechanisms.

2.5.6 Changes in Design Abilities

Increased ability to think mechanically would present itself in an individual's approach to designing new mechanisms in a number of ways. Changes made during the design of a single machine during the iterative design/prototype/evaluate cycle would provide evidence. Making

incremental changes to the current design during this process would reflect changes in understanding at a very fine scale while making radical changes (replacing one component with one of another type for example) would show either deep understanding of function or a lack of understanding depending on whether the modifications move the design toward or away from the intended goal.

Changes in reasoning across subsequent designs would be seen in the time necessary to refine the design, the willingness to undertake the design of more complex machines and the number and nature of sketches and notes created during the design process. This would also be seen in reduced time spent in fabrication and construction from entering those phases with improved designs.

2.5.7 Changes in Confidence Levels

Working at or beyond the limits of their abilities can be a frustrating experience for children. Failure, or the likelihood of failure, can lead children to conclude that they are incompetent, a condition they often believe cannot be modified by learning or practice [31]. Because children have little or no experience working with machines, spending extended periods of time working in this domain can easily frustrate them. But increased confidence should be evident in the ways in which work in the domain is approached. Maintained interest over the extended time frames necessary to create unique machines, self-directed investigation of the domain, excitement during the conceptual phase, the desire to build on previous accomplishments and to reach into untried territory, a sense of playfulness during the process, and satisfaction with the results of the long hours are all indicative of increased confidence which is itself an indication of positive changes in mechanical thinking.

2.6 Summary

Thinking and reasoning about machines is difficult for many people for a number of reasons. First, descriptions of machines and their functions are not easily conveyed in words, the

medium of many other disciplines. Second, even as technology has become more ubiquitous, it has simultaneously become less accessible to scrutiny and comprehension, particularly for children. Third, the work of creating and caring for machines has become trivialized to such an extent in society that the study of machines is not included in substantive ways in mainstream educational curricula. This is unfortunate, as the kinds of visuospatial reasoning fostered by designing, constructing, and maintaining machines and mechanical devices are important in any number of human endeavors, many with no apparent connection to the work of the mechanician.

Research into how individuals reason about machines falls broadly into three categories. Those interested in industrial and vocational psychology seek to identify traits and predispositions that will indicate success in mechanical occupations. Those interested in the cognitive underpinnings of mechanical reasoning attempt to create models of how mechanical thinking is handled by the brain in order to better understand the workings of the human mind. Those interested in children's education use machines to support learning in science and mathematics and to help children develop abstract reasoning abilities, but only attempt to teach children *about* machines in mostly traditional ways which isolate their study. Constructionism offers an alternative approach to learning that has the construction of artifacts as a core feature and constructionist methods were fundamental in structuring the research that will be described in subsequent chapters. Constructionism and cognitive research have also suggested ways in which changes in mechanical thinking and reasoning might be revealed. Several of these have been chosen for inclusion in the assessment of the experiments that are reported later in this work and provide a qualitative counterpoint to the quantitative assessment of method and product.

The discussion of mechanical and spatial thinking begun here continues in Chapter 3 which looks at a variety of tools that have potential as starting points or key elements in constructionist environments designed to help children learn about machines and acquire and enhance their mechanical reasoning and spatial cognition in the process.

Chapter 3

Mechanical and Spatial Thinking: Tools

Chapter 2 shows the nature of the problems faced when trying to support children's learning about mechanical systems and suggests some metrics that can be applied to gauge the effectiveness of any tool we may wish to give children to assist them during the design process. These tools fall generally into two categories: collections of physical pieces that can be combined into objects and software applications that can be used to create virtual objects for later realization as physical objects. Tools in the first category intuitively seem well suited to the task. Physical manipulation of the components provides the opportunity to experience the physical and mechanical properties of mechanisms in a very intimate way. Knowledge gained during the construction of mechanisms, even prototypes, is easily transferred to subsequent mechanisms.

The use of software tools to aid in the design process might seem to have less value. The friction observed as two gears mesh with each other or the interference problems encountered when adding components may not be evident in a virtual assembly. Where a designer might rummage through a box of parts examining and fitting candidate components to a mechanism in progress, the user of design software might not know about all of the components available. A list of difficulties inherent in using software to design mechanisms, especially for children, could go on and on. But software applications can provide significant benefits to children as they create automata when they support the designers' learning in relevant ways.

This chapter presents a representative sample of software applications and construction kits that have been, and could be used to explore mechanical systems. Some of these are aimed

at adult users, while a few specifically target children. In some cases, adult tools have been used by children in the design and construction of contemporary automata and this will be noted when they are examined. The chapter begins with a look at software for designing and evaluating mechanical and physical systems. This is followed by a survey of several popular construction kits that emphasize and encourage the exploration of mechanical systems. The chapter concludes with an overview of both software and construction kits that specifically target the contemporary automata domain.

3.1 Design Software for Children

The landscape of software applications that focus on the design of mechanisms and are intended for children to use is incredibly barren. There are a number of excellent drawing programs for children (KidPix is one example), but these really aren't good choices for creating mechanisms for the same reason that Adobe Illustrator isn't used to create assembly drawings for automobiles. The software that is available for children falls into two general categories: programs that can be used to design objects which can then be constructed and programs that can be used to design purely virtual objects. The former is often limited in the type and complexity of machines that can be built, while the latter can suffer from their inability to be observed and analyzed in the real world. This space of design software is the one for which the MachineShop software was created and the example programs examined here provided much guidance during its development.

3.1.1 LEGO CAD and Derivative Software

In 1997, CyberToys created a program called LEGO CAD for LEGO Dacta (the educational arm of LEGO Group) and Autodesk (makers of AutoCAD) [24]. Written in Macromedia Director and running on Macintosh (systems 7 and 8) and Windows (95 or 98) computers, it was conceived as a tool for teaching children about simple machines (in the sense of machines that were not complicated rather than the traditional meaning of the phrase). LEGO CAD could render 63 (or 68; the documentation contains conflicting values) different LEGO parts; both traditional bricks

and beams as well as several gears, axles, hubs, chains and other moving pieces found in LEGO Technic kits. These components in particular allowed children to create interesting mechanical objects that could exhibit a wide variety of behaviors. LEGO CAD stored models of each of these elements rather than images and rendered them on the fly as most CAD programs do. Machines built in LEGO CAD looked amazingly like the illustrations that are seen in the directions that accompany LEGO kits (Figure 3.1) and children could then use these pictures as guides when building physical instances of the machines.

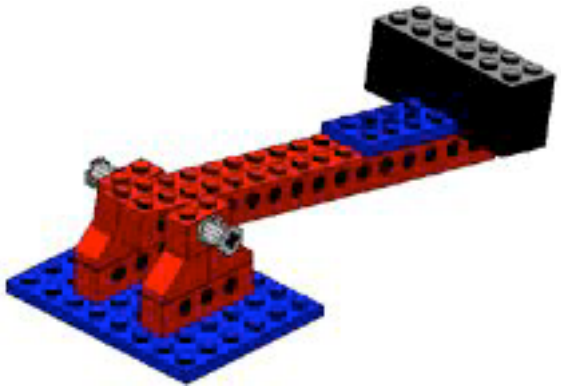


Figure 3.1: Using familiar LEGO elements, children could create simple machines using the LEGO CAD program. These virtual machines could then be assembled from LEGO components and physically manipulated.

LEGO CAD was a surprisingly sophisticated program for its time although it had several shortcomings. The choice of Macromedia Director meant that the program didn't behave quite the same on Windows computers as it did on Macintosh computers. For example, the quality of displayed images was of a higher quality when viewed on a Macintosh than when viewed on a Windows computer. The interface to the software required users to manipulate elements in a 3-dimensional space using the mouse which is a difficult task for a child. Each piece had several attachment points at which it would snap to attachment points on mating pieces. When a piece had a number of these points, it could be difficult to get the desired points to connect, frustrating users. The developers eventually made available a number of work-arounds to make the process easier. And while 63 or 68 pieces may seem like a significant number, it is, in fact,

a very small percentage of the inventory of physical LEGO components available. Users had no mechanism available to them to create additional pieces so were limited to creating within the boundaries established both by the software developers and by LEGO (this is discussed further in Section 3.3.1).

Despite the stated desires of the developers to enhance, expand, and optimize the program, newer versions failed to appear and LEGO CAD is no longer available. But the concepts of virtual LEGO constructions first seen in LEGO CAD still exist in new software from LEGO Group and the open source community. While these tools are not specifically designed for children they are included here because they live in the LEGO domain.

3.1.1.1 LEGO Digital Designer

In August 2005, LEGO Group released a design environment for LEGO constructions called LEGO Factory [68]. Designers use a freely available software application called LEGO Digital Designer to create 3-dimensional models and building instructions using components chosen from a number of palettes. When finished, users can upload their designs and, if they wish, order the bricks necessary to build their designs. The software clearly shows its LEGO CAD heritage. Users place components into a 3-dimensional view and attachment points are used to connect components (Figure 3.2).

LEGO Digital Designer has a number of features desirable in a design tool for children. By imposing constraints on manipulation and placement of components it helps a new user become productive in a reasonable period of time. The file formats for completed models, while encoded in a binary format and thus not meaningful without the software, are intended to be exchanged and modified by users which should help to create and support communities of practice. The software runs on both Windows and Macintosh computers, making it accessible to a larger audience than if it had been written for just one platform.

LEGO Digital Designer also falls short in some desirable areas. The 3-dimensional interface sometimes makes it difficult to determine one component's relationship to other components or

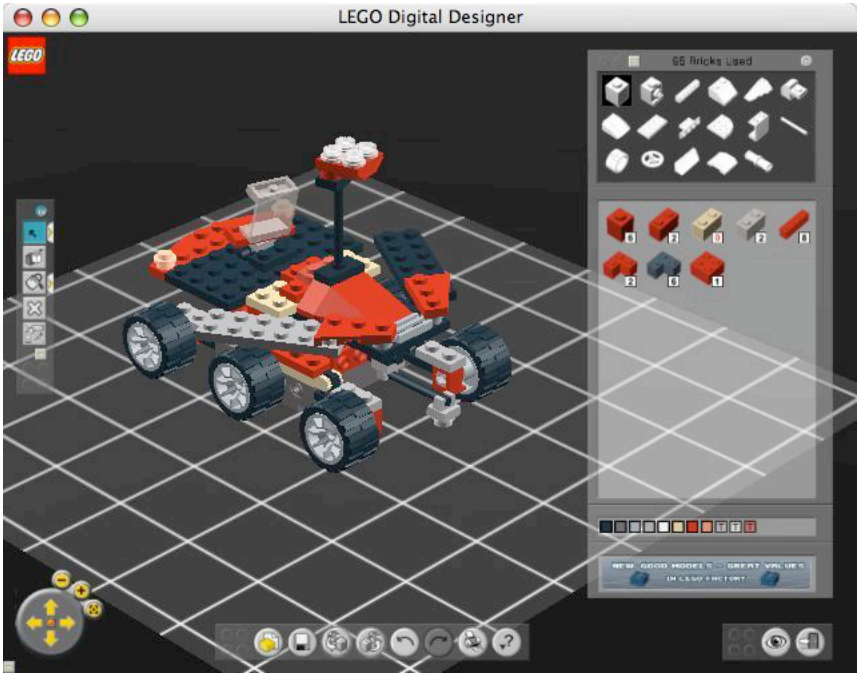


Figure 3.2: A Mars rover model in LEGO Digital Designer. The palette of components is at the right, file controls are at bottom, view manipulation controls at the lower left, and component manipulation tools are at the left. Model designed by 9 year old *npartist* (real name not given). Image courtesy the LEGO Group.

the base working surface. The control icons are not always meaningful and a new user must rely on descriptive text supplied by placing the cursor over a control and waiting. While LEGO Digital Designer has about 180 components available to users (almost three times as many as LEGO CAD), the majority are blocks and bricks and the number of mechanical components is actually smaller than provided by LEGO CAD. This limits users to doing little more than attaching wheels and tires to their models. There are currently no gears, pulleys, or other motion transmitting pieces available in the software making even simple machines impossible to design.

3.1.1.2 LDraw and the Open Source Community

LDraw is an open source CAD program and file format created by James Jessiman and originally intended to generate images of parts to catalog his LEGO collection. Written in 1995, it predates LEGO CAD by two years but does not have the official status enjoyed by LEGO CAD.

Unlike LEGO CAD, the open file format has allowed thousands of adult LEGO users to create both their own files for components but also CAD and viewer programs to work with those files as well as high quality rendering engines to create photo-realistic images of virtual models. Software exists for Macintosh (BrickDraw3D, BrickSmith), Linux (LDGLite), and Windows (MLCad, LeoCAD) computers and is available without charge. A large user community has grown up around these tools [67, 72].

What sets LDraw based programs apart from those produced for LEGO Group is that the needs of the community directly drive development. Any user has the ability to create files for any LEGO component that exists or that can be imagined which can, theoretically, eliminate one of the major shortcomings in the official LEGO products. The community has an oversight process for new part files that helps to assure that files are of consistently high quality and that components described by those files will work together like the physical components do. The LDraw libraries also include a growing number of pieces found in LEGO Technic kits which are especially appropriate for designing mechanisms.

3.1.2 The Incredible Machine

In the Incredible Machine (in all of its incarnations) the user is faced with a series of puzzles which can only be solved by creating machines (*contraptions* as they are called in the game) in the style of Rube Goldberg. Through captivating animation and physics modeling, users must attach various mechanical, optical, electrical, and fluid components together in order to achieve the goal of the puzzle.

A simple puzzle is shown in Figure 3.3. On the left, the user must use the pulley and rope provided to connect the two levers in such a way that when the soccer ball (right) is dropped, the basketball will end up in the left hand box and the soccer ball will end up in the right hand box. This is a simple pulley problem in the style of Hegarty [52] with the addition of two levers of the first order to make it interesting. The solution appears on the right.

It's not often possible to make realistic mechanisms with the Incredible Machine, and du-

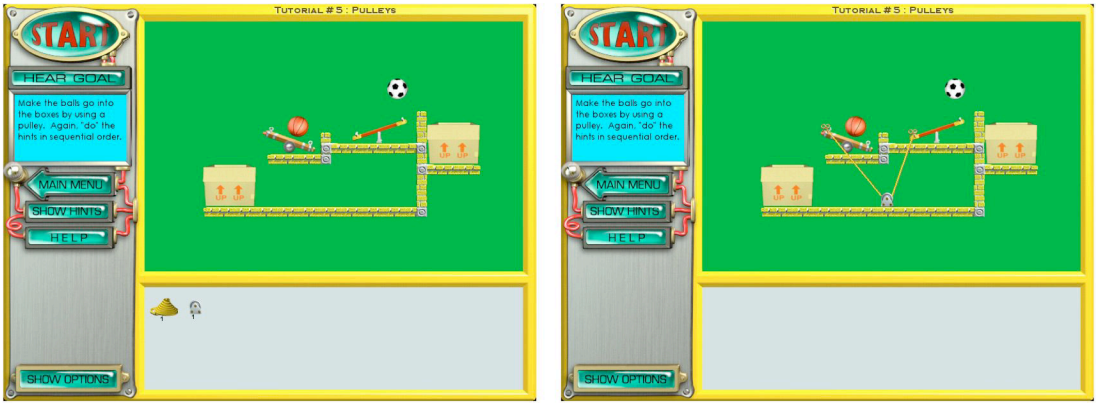


Figure 3.3: In this Incredible Machine puzzle, the user must connect both levers with the rope and pulley (bottom panel) in such a way that each ball ends up in one of the cardboard boxes. The initial puzzle is shown on the left and a solution is shown on the right.

plicating game contraptions in the real world would be next to impossible. But the variety and ultimate complexity of the machines which are created provides the user with opportunities to experiment and learn that are not seen in other tools. The user can place, rearrange, and test combinations to not only complete the puzzle, but to see how those changes affect the operation of the machine. There are no penalties assessed for wrong solutions so the humorous and intriguing nature of this game encourages users to play and to learn. This has great value in learning to reason about mechanisms and would be a desirable addition to software more appropriate for building physical machines.

3.2 Design Software for Adults

While good tools for their intended purposes, none of the tools just described would make good choices for children to use for designing and building automata. Those that do support the construction of physical objects are limited in the kinds and styles of mechanical components that are available for building mechanisms. At the other extreme, being able to design with a large number of components is of little help when there is no adequate way to translate the virtual designs to physical mechanisms. For these reasons students who do build automata as part of

their education are rarely given these tools, even though in other domains or for other activities those software applications can be very useful. The software tools most often used by children to design mechanisms are full-featured applications created for adult engineers and designers such as the ones described in this section.

These tools offer their users the ability to create an almost limitless variety of mechanisms and, in many cases, can help users turn their designs into physical objects. Many of these tools provide sophisticated simulation environments in which the physical properties of material and component can be precisely determined before fabrication. But this power comes at a high price for children. The interfaces are often created with the understanding that users will already be familiar with the domain and the software's approach to the domain. Even for the initiated, the learning curves can be quite steep. Most of these tools are very expensive and require high-end computers to run on, both of which are large obstacles for children, their parents, and their schools. Most of these applications are general purpose and the tools they provide for the creation of simple mechanisms may be difficult to locate, difficult to use, or both. Even a task successfully completed once may be nearly impossible to repeat if the sequence of steps can't be remembered from one use to another. Still, in many cases, there is nothing better available and even a cumbersome tool is better than no tool at all.

3.2.1 AutoCAD

While many proprietary drafting systems had been developed by large engineering and manufacturing firms to link their mainframe computers to their flatbed plotters, AutoCAD was among the first CAD/CAM programs to be released for use by smaller firms and individuals. Created by Autodesk and first made available in December 1982, it quickly gained a following in companies who were keen to to realize the benefits it provided both in the research and development and production phases of product development. While AutoCAD was designed to work in ways that were easy for the compass and triangle crowd to embrace, its real power came from its built-in LISP [109] macro language. For the first time, small engineering firms could automate

many of the repetitive drawing and design tasks that had previously been very labor intensive.

The massive feature set of AutoCAD makes it a powerful tool for industry and any survey of contemporary automata will not reveal a single instance that could not be designed with AutoCAD or fabricated from files that AutoCAD could produce. But the hundreds of commands and tools and the thousands of ways in which they can be combined make it a very difficult program to learn[1] and a poor choice for children to use. Still, with the help of an adult knowledgeable in both mechanical design and the use of the software, AutoCAD could be a useful tool for a child.

3.2.2 Pro/DESKTOP

Pro/DESKTOP is a 3-dimensional design tool from Parametric Technology that allows users to perform solid modeling parametrically. It found widespread acceptance in industry, sometimes being used alongside its larger CAD/CAM sibling Pro/ENGINEER, but often as the sole CAD/CAM tool in many companies. While not specifically designed for education, Parametric Technology saw this as an opportunity to expand their user base. In 1999, to begin the process, they donated an unlimited license for Pro/DESKTOP to the entire public school system in the United Kingdom for use in the Design and Technology (D&T) component of the curriculum.

This windfall was not all boon, however. D&T teachers found themselves in the position of needing to integrate a tool designed for industry into their classrooms. Most teachers were unfamiliar with Pro/DESKTOP and were forced to make do with whatever training they could receive. While older students had an easier time working with the software, younger students struggled and teachers were forced to find simpler roles for its use. When students in years 5 and 6 are making moving toys or automata [25, 26] they often make use of Pro/DESKTOP, especially when their school owns one or more machine tools that can produce components from the computer files the children create.

D&T teachers almost universally find Pro/DESKTOP to be poorly suited to the purposes

[1] The author spent six years as a draftsman working with AutoCAD before returning to university and this statement is based on that experience.

for which it is used but can find no better alternatives. To make matters worse, at the time this is being written Parametric Technology is in the process of retiring Pro/DESKTOP since most of its functionality has been gradually incorporated into Pro/ENGINEER. What this means for D&T education remains to be seen, but what is clear is that there is still no tool truly appropriate for these teachers to use.

3.2.3 Working Model

Working Model differs from AutoCAD and Pro/DESKTOP in that its purpose isn't to design mechanisms, but rather to understand them. Working Model is a Computer Aided Engineering (CAE) program in which simulations can be run and the data from those simulations analyzed. For the most part CAD/CAM systems are designed to work with components and assemblies at rest and are not particularly well suited to examining those components or assemblies in motion. Working Model allows the user to import 2-dimensional CAD drawings in the standard Drawing Exchange Format (DXF) which can be written by most CAD programs. The user is then able to set those drawings in motion and specify parameters dealing with the simulation environment such as speed, direction, and coefficients of friction. The simulation not only allows the user to watch the mechanism in action, but also provides a variety of output values for such things as force, torque, and acceleration.

Since automata are dynamic objects there are advantages to seeing them move during the design phase, and Working Model provides an environment in which to do this. But do we need simulation, or would simple animation be sufficient? Defining the correct parameters for a simulation and arriving at appropriate values for them can make the initial setup of simulations difficult. Simulations also suffer from difficulties in defining the boundary of the model; deciding what is internal to the simulated environment and what is external to it [133].

3.3 Construction Kits

Construction kits are collections of components that are designed to be combined with one another, creating larger assemblies. While the term has become common (software construction kits, homepage construction kits, language construction kits), it is used here to mean sets of physical objects which, when attached or connected together, can be used to create larger objects with more complex structure. It can be argued that these kinds of kits are descended from the *gifts* created by Friedrich Froebel for use in his kindergartens [10] of the early nineteenth century. Certainly he was the first to use this kind of play activity to facilitate learning. As previously mentioned, the use of physical components to construct mechanisms has much to recommend it.

When a child holds, moves, attaches, removes, rotates, inverts, or engages in any other action with a piece she is building knowledge about the process, the domain, and the materials in ways that cannot be duplicated with a computer. This knowledge becomes intimate and its acquisition personal. The things she learns building one structure or mechanism will assist her in building the next. This type of experiential learning begins in infancy and children (and many adults) continue to learn this way. Construction kits take advantage of children's love of building to make the learning all but invisible.

There have been scores of construction kits available to children since Froebel's time. This section will focus on a handful of examples from the last 100 years, all of which could be used to construct the types of mechanisms found in contemporary automata.

3.3.1 LEGO

LEGO Group makes what are arguably the most popular and successful construction kits ever created. The familiar plastic bricks were created in 1958 and incorporated design ideas that LEGO had been using since 1949 in their Automatic Binding Bricks. The building components that LEGO makes are so ubiquitous that rarely does any one refer to them as LEGO bricks, but simply as LEGOs. For the construction of automata this is a distinct advantage. LEGO components are

familiar to many children who need no instruction in their use. This frees them to create stories for their automata to tell and to explore possible mechanisms to help tell those stories.

Because of their popularity, LEGO has segmented their products into families (with some overlap). The bricks, beams, and plates used most often comprise the LEGO System. The mechanical components such as axles, gears, and pulleys along with the special beams and bricks to support them comprise Technic. And the computer controlled robotics sets (which borrow components from both System and Technic) are called Mindstorms.

3.3.1.1 LEGO System

LEGO System contains the pieces that are most familiar such as bricks, beams, and plates. The variety of pieces available is considerable and they can be used to build anything from a simple house to a full size automobile (Figure 3.4). Hundreds of kits have been released but one of the major draws of System is the availability of large quantities of pieces that have no specific end result in mind allowing the builder to create whatever she wishes. With respect to designing and building automata, System components are primarily of interest for the support roles they can fill. Since all LEGO components are designed to work together, these pieces can be used in structural supports for mechanism components, as general framework components, and as tableau elements and decoration.

3.3.1.2 LEGO Technic

LEGO Technic sets first appeared in 1977 and were originally called Expert Builder. What differentiated these kits from System is the inclusion of parts specifically designed to provide motion to the static models previously available. Technic kits have overwhelmingly consisted of parts to build vehicles of one description or another. Large collections of parts are not available as they are with System although a number of components can be ordered. The types of mechanisms that can be created with Technic components can come very close to those used in automata. LEGO has created a variety of gears and shafts that can be used directly.

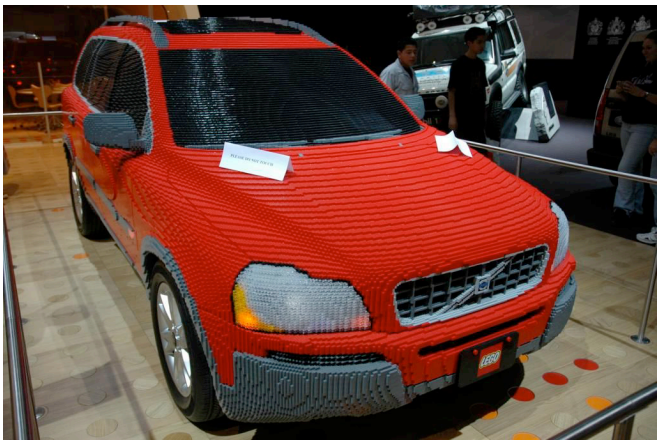


Figure 3.4: A full size replica of a Volvo XC-90 automobile made from LEGO bricks on display at an auto show.



Figure 3.5: A selection of Technic gears and pulleys that can be ordered from LEGO. Note that several of the gears have holes where connectors can be added to create cranks. Drawing courtesy the LEGO Group.

Some of the gears (Figure 3.5) have holes near their edges in which connectors can be added to make cranks, the closest Technic comes to having cams. In addition, the novel beams and connectors used in Technic kits can be used to create levers and cranks. These features make Technic a valuable prototyping environment for automata although several factors make it less

than perfect for final construction. The most serious is the limited selection of parts available[2] . LEGO has decided what sizes and ratios the gears will have, which, in turn, fixes the distances at which shafts and other components can be placed, defining the sizes at which mechanisms can be built.

3.3.2 K'NEX



Figure 3.6: The K'NEX gear and crank set can be used to create a number of machines in addition to those shown in the instruction booklet. From left, a Ferris Wheel, an eggbeater, and a bicycle built following supplied plans. Photo courtesy K'NEX.

K'NEX also markets a wide variety of construction kits. The building style is quite different from LEGO in that, rather than assembling bricks and beams into solid shapes, plastic rods of various lengths are snapped together using connector pieces. These connectors allow rods to be connected at angles which are multiples of 45° in the plane of the connector and at right angles to the plane of the connector. Rods and connectors are color coded indicating the length of rods and the maximum angles that connectors can support. Constructions in K'NEX are based

[2] This is a drawback to a greater or lesser extent with all construction kits. One goal of the MachineShop system is to allow users to design custom parts to fit their exact needs rather than working around the parts that are available.

on right isosceles triangles and to make this possible, the lengths of successive rods (taking into account the additional length the connectors add) are at a ratio of $1:\sqrt{2}$. These triangles are what gives K'NEX models their structural strength. K'NEX owes much of its style to a much older toy, Tinkertoys [111], but has expanded Tinkertoys capabilities and eliminated many of its shortcomings. K'NEX constructions have a more open feeling than do those made with LEGO and, because there can be significant distances between adjacent pieces, they can be quite large.

Like Technic, K'NEX makes pieces for building machines. Levers, pulleys, wheels, gears, and cranks are all available for inclusion in models (see Figure 3.6) and these can also be useful prototyping tools. In some cases, gears for instance, K'NEX provides more variety than Technic.

3.3.3 Metal Construction Toys

Metal construction toys first appeared early in the twentieth century with the introduction of the Meccano Construction Toy System in England in 1901, with Erector Sets following in the United States in 1913 [43]. While Meccano and Erector are arguably the two most successful and well known metal construction toys, they had many imitators and competitors throughout their lives. Temsi, Marklin Metall, Ami-Lac, Stokys, Stabil, Mignon, and Eitech in Europe, Exacto in South America, Steel Tec in Asia, and American Model Builder, Constructioneer, and Metalcraft in the United States all built (or build) similar toys. These systems share a number of common features. They utilize standard systems of reusable metal parts, including perforated strips, girders, wheels, rods, brackets, pulleys, sprockets, gears, electrical parts, motors, and other specialized parts that are attached to one another with screws and nuts. Most systems contain the necessary components for the construction of mechanisms. A #10 Erector set from 1932 is shown in Figure 3.7.

The components in these systems and the building styles they support mirror the explosions in mechanical and civil engineering at the turn of the twentieth century. Skyscrapers and bridges, trucks and automobiles, even the pinnacle of steam power both for transportation and industry are easily modeled with these toys. A.C. Gilbert seems to have been inspired to create



Figure 3.7: An original Erector set from 1932. Erector sets carried number designations and this #10 set was the largest made at that time. Note the variety of wheels, gears, pulleys, and shafts for making moving models. Erector and other metal construction toys are highly prized collector items. The set shown here sold at auction in October, 2005 for $19,200 US [19]. Photo courtesy Chicago Antiques Guide.

Erector after seeing the catenary towers for the electrification of the New York, New Haven, and Hartford Railroad being constructed from steel girders [128]. This style of construction kit lends itself well to the design and construction of mechanisms and machines both in the variety of ready to use mechanical components and the ease with which frameworks to support and align mechanisms can be constructed.

As with all of the other construction kits mentioned here, metal construction toys are not without flaws. Primary among these is the ease with which the connecting screws and nuts can become lost and the difficulties younger children have in manipulating them. Many times the pieces, beams in particular, are easily bent but not so easily straightened. And a specific drawback

for using these kinds of kits for automata is the virtual impossibility of constructing reasonable looking people and animals with components designed to simulate cranes and Ferris wheels.

3.4 Automata Software, Kits, and Resources

The previous sections have reviewed a number of software applications and physical constructions kits that have been or could be used to design and create the mechanisms for automata and, in the process, affect the mechanical reasoning and spatial cognition of the builders. But in all cases these artifacts are general purpose tools for working with mechanisms and machines of many types, not specifically automata. Since automata are the research domain detailed herein, this section will focus on tools which aid the builder in creating contemporary automata (Section 4.1.4). In a number of these examples the intended audience is school aged children, just as MachineShop. It is important to note that all of the examples presented here come from countries with design and technology components in local or national curricula and that little imagination is necessary to see how these would be used to address classroom needs. It also bears mentioning that all of these were assessed as to their strengths and weaknesses and those assessments were used to guide the design of the MachineShop system.

3.4.1 Cabaret Mechanical Theatre

England's Cabaret Mechanical Theatre could be considered the nucleus of the contemporary automata revival [120]. In addition to providing a gallery for the exhibition of automata[3] Cabaret Mechanical Theatre early on offered the works of its artists for sale to the public. The shop soon expanded its offerings to include automata kits (both card and wood) as well as posters, books, and videos to aid neophyte automatists. When design and technology was added to the national curriculum in the United Kingdom, the proprietors, Sue Jackson and Sarah Alexander, found themselves besieged by requests from teachers for help with the new subject matter and a

[3] Sadly, Cabaret Mechanical Theatre no longer occupies the marvelous space in Covent Garden, London that it did for nearly two decades. The collection currently has no permanent home although representative selections do appear from time to time in traveling or temporary exhibitions.

number of new products joined their automata kits.

3.4.1.1 Automata Kits

Over the years Cabaret Mechanical Theatre has offered a number of wooden and card automata kits designed by several of the artists whose work is found in the Cabaret Mechanical Theatre collection. The wooden kits are comprised of pre-cut wooden pieces with card, string, and other necessary bits along with simple instructions. These kits range from the very simple to the moderately difficult. The card kits have the pieces brightly printed on stiff card stock with dowels and other parts included. Unlike the pre-cut pieces in the wooden kits, the card pieces must be cut out by the builder before assembly can begin so even the simplest of the card kits is more difficult than the simpler wooden kits. Both kinds of kits require the builder to be able to fit, assemble, and attach pieces as described in the instructions. Building kits such as these is a perfect way to learn many of the necessary skills required to build (but not necessarily design) automata. Since the builder is completing the assembly of a proven design from a master automatist, careful construction (especially with the card kits) will almost always lead to a properly functioning automaton. Figure 3.8 shows an example of an automaton built from a fairly difficult card cutout kit.

The downside of using kits is that little of the design process of the automaton can be discovered during construction. The mechanism and its attachments to the figure or figures of the automaton carry with them none of the design decisions or discarded alternatives that determined what pieces would become the kit. To better understand mechanisms, it is important that the builder be involved in those decisions in order to gain the analytic and comparative skills that are necessary for good design.

3.4.1.2 Cabaret Mechanical Movement

To provide assistance to novice automata designers, Cabaret Mechanical Theatre published a book designed to help new automatists understand the kinds of movement found in automata,



Figure 3.8: This nefarious feline plies his trade smuggling a shipment of canned tuna in his rowboat. Card cutout kit designed by Keith Newstead. Photo courtesy Cabaret Mechanical Theatre.

learn how components such as cams, gears, and levers can be combined in mechanisms to provide those movements, and how to go about the task of building an automaton [90]. This book is a valuable reference and source of ideas for anyone building automata although younger builders will benefit from having a more experienced builder direct them to the key points in the beginning.

3.4.1.3 Designing Kits

To fill the need for an intermediate product between the design oriented *Cabaret Mechanical Movement* and the construction oriented wooden and card kits, Cabaret Mechanical Theatre

created the first of their hands-on kits to help new builders, primarily children, create their own original automata in 1999. This kit was refined in 2002 and a revised version of that kit was introduced in 2005 (Figure 3.9). These kits are a good way for complete novices to gain some experience in both the design and construction of automata. Four movements are supplied to followers by a single-lobed snail cam, a three-lobed triangular cam, a disk, and a crank-slider (see Section 5.1.3.1 for explanations of these components). The builder must choose which of these movements are appropriate for her automaton and attach the necessary pieces which will create the people, animals, or other storytelling elements of the automata.



Figure 3.9: Nearly one hundred pieces can be assembled to make a variety of automata with this Designing Automata kit from Cabaret Mechanical Theatre. Mechanisms are limited to those using cams or a crank-slider. Photo courtesy Cabaret Mechanical Theatre.

This ability to rapidly create an automaton comes at the price of variety in the designs.

While there are a great number of automata that can be built using this kit, focusing on only one kind of mechanical component, the cam, is a serious limiting factor. The alternative would be to add other types of components to the kit, but this could then complicate the process and make the kit less useful for its intended purpose.

3.4.1.4 Interactive CD ROM

To provide opportunities for younger children to experience building automata, Cabaret Mechanical Theatre produced an interactive, animated CD ROM aimed at children from five to eight years old. Children using the CD can assemble and embellish an automaton using virtual representations of physical pieces from the Designing Automata kit. The CD has a number of frustrating issues. First, it provides even less of an opportunity to experiment with a variety of mechanisms than does the kit. Second, when adding a piece to the mechanism, it is often unclear exactly where the user need to place it in order for it to be added correctly. Finally, this is not an activity that children should be expected to return to again and again such as could reasonably be expected with the Designing Automata kit or the *Cabaret Mechanical Movement* book.

3.4.2 Flying Pig

Flying Pig is another company in the United Kingdom devoted to the design and creation of contemporary automata [37]. Although primarily existing to sell its line of card cutout automata kits, its website has a number of useful links on mechanisms and their motion, the proper selection and use of tools for building automata, building tips, photos of automata, and a forum for builders to ask questions and exchange ideas. This is one of number of websites (see Appendix D) that automatists of any skill level will find useful.

3.4.3 Software 4 Teachers

Software 4 Teachers is an organization in the United Kingdom that makes a useful product for builders of automata [107]. Their interactive CD ROM entitled *Automata* contains a wealth

of valuable information. The disc is divided into five sections, each dealing with a set of topics. The first section provides an introduction to automata, spends some time addressing the process of designing, looks at basic properties of movements, and briefly discusses the support structures needed for an automaton. Sections two and three present an introduction to mechanical components showing familiar examples, explaining how best to fabricate them, and showing them used in automata. Section four deals with getting the components to move as they should and spends a little time talking about "the bit on top". Section five introduces the tools necessary for fabrication and explains how to use them safely. This material is presented through photographs and short video clips supported by textual and audio descriptions. The user is free to explore the material as she chooses using the navigational windows.

3.4.4 MouseWorks

MouseWorks Canada markets a number of wooden automata kits using simple mechanisms. They also sell a book on automata construction [76]. The first half of the book deals with designing and constructing automata and includes sections on tools, materials, and fixtures. It then presents a number of historically important automata before spending the remainder of the book providing instructions for constructing a number of sample automata. The book is an amalgamation of information readily available elsewhere with some of the illustrations remarkably similar to those in *Cabaret Mechanical Movement* (compare the figures at [76, page 2-4] with those at [90, pp. 53–55]). While the example automata building instructions are good for those learning the craft, the rest of the book is of varying usefulness.

3.5 Summary

The purpose of the MachineShop system is to support children as they design and construct mechanisms for use in contemporary automata. Other software applications can (and often are) used for this same purpose. Of those applications written for children to use in designing mechanisms, some put an emphasis on virtual simulation of the real world and challenge users

to create machines which, though whimsical, could never be built. Others are tightly coupled to some physical construction system (LEGO bricks and components for example) and require users to create with only the components available in the system. No software currently exists that will allow children both a high degree of freedom when designing mechanisms and give them some confidence that those mechanisms can be built to function as intended. While professional CAD/CAM systems can allow that freedom and confidence, they can also be openly hostile and antagonistic to naïve users who can struggle with overly rich feature sets, nonintuitive workflow, and intimidating user interfaces. But in many cases they are the only real option available and children are taught to accomplish only the tasks that they need to accomplish and nothing more. Chapter 5 will examine the ways in which the MachineShop software provides professional power to children.

Software is not the only way to design and experiment with mechanisms. Machines can be built in structured ways using a variety of construction toys or kits. The choice of appropriate construction kits for building the kinds of mechanisms found in automata is a difficult one. Each brand or type of kit has its own strengths and weaknesses and, at least for children, familiarity is often a deciding factor. No construction kit available has the variety of mechanism components that are found in any significant sample of contemporary automata which puts limits on the automata that can be constructed.

Because the design and construction of automata has found a place in some curricula, most notably in the United Kingdom, a number of products are now available that are automata specific. Kits made from wood or heavy card can be assembled to provide construction experience. Software, videos, and books present the problems and solutions of design so that builders can create unique designs. Construction kits whose parts can be used again and again to create any number of automata are now available and a significant number of websites designed to both sell these products and to provide resources to further enhance a new builder's learning have also appeared. This emphasis on contemporary automata will be described in greater detail in Chapter 4.

Chapter 4

Automata as a Domain for Exploring Mechanical Reasoning and Spatial Cognition

Chapter 3 described a number of software applications and construction kits with which mechanical and spatial thinking could be explored. Those examples that provide the most freedom with respect to design lend themselves to a variety of mechanical domains without favoring any. While this can be desirable for designing in the real world, the absence of limits on the types of objects that can be designed and their complexity would make asking reasonable questions about mechanical and spatial thinking difficult and would provide no easily manageable context for examining and comparing the disparate objects that could be created. This makes it necessary to select a single domain which can be defined and constrained in such a way as to allow significant freedom in the design of mechanisms while still allowing the products to be similar in important fundamental ways. For this research the domain that I have chosen is mechanical automata, specifically automata of the style known as *contemporary automata*.

What is an automaton? This simple question is surprisingly difficult to answer. Webster defines automaton (automata in the plural) as "a machine or control mechanism designed to follow automatically a predetermined sequence of operations or respond to encoded instructions" [79]. Bailly offers a nineteenth century definition: "a machine which has the form of an organised being and contains within itself a mechanism capable of creating movement and simulating life" [4, page 13]. Peppé [97] suggests that definitions are of little value since each automaton is unique mechanically and in its artistic aspirations. Bailly (echoing Peppé) points out that no capsule description gets at the essential quality of automata; their power to fascinate and engage.

Still, automata are so far removed from the experiences of most of us that a concise description is warranted. For the purposes of this research an automaton is a moving sculpture of people and/or animals whose motions repeat and are controlled by mechanical means.

This chapter will first provide a brief and incomplete history of automata leading up to the contemporary automata which comprise the research domain for this work with an emphasis on the pairing of cutting edge technologies and automata throughout history. This is followed by a discussion of the reasons that the design and construction of automata was chosen for this research. Next two automata are presented to provide examples of the domain. The chapter concludes with a discussion of current uses of automata in education.

4.1 A Brief History of Automata

The history of automata is intimately woven into humankind's desire to understand and comment on our existence. From the first representations of daily life painted on cave walls, we have wanted to understand and reflect on the world around us. Two-dimensional representations spawned those in three dimensions. Static representations became dynamic and the desire to do more than model became a quest to understand and mimic nature. That, of course, required technology beyond that currently available and the simulation of life as captured in automata took advantage of many breakthrough technologies.

4.1.1 Automata in Antiquity

Moving and articulated statues can be considered the progenitors not only of automata but also of mechanical toys and puppets. These statues and busts were found in many cultures and served both iconic and prophetic functions, making them anything but everyday objects. Precisely when these moving figures found their way into the secular world is unknown, but early writings suggest that the direct line to automata as we know them may have been in place as early as the third century BCE at Alexandria[18].

Around this time the Alexandrian School was formed by a group of philosophers, physicians, mathematicians, and engineers and it became the most important and productive center of learning in the Classical world. The power of water, steam, and compressed air were harnessed for a variety of purposes religious, secular, and military. Notable among the engineers in Alexandria were Ctesibius [117] and Philon [125] (both in the third century BCE) and Hero [118].

Ctesibius of Alexandria was a prolific inventor [1] who also spent considerable effort refining the water clock (clepsydra). Some of these refinements included using floats to actuate mechanisms, and in at least one case a clock of his design used a moving human figure to indicate the time.

Philon (or Philo) of Byzantium's work focused primarily on the military use of machines. Interestingly, he saw war machines as a single component of military strategy and his work also included topics such as besieging and defending towns, constructing forts and seaports, and general topics in strategy. His work would not be considered in the context of automata if not for a single volume of his nine volume treatise *Mechanica* which was entitled *On Automatic Theatres*. These devices were miniature theaters in which stories were told through the actions of automated figures and settings [80]. While this volume has been lost, Hero builds on this work in his own descriptions of automatic theaters.

Much of what we know about the mechanical knowledge and technology of ancient Greece comes from the work of Hero (or Heron) of Alexandria. Exact dates for Hero are hard to determine, but Drachmann places him in the first century CE [28]. Hero wrote extensively on geometry, surveying, optics and mechanics. Five complete works survive: *Pneumatica* and *Automata* in Greek and *Mechanica*, *Metrica*, and *Dioptra* in Arabic. Other writings survive in fragments while many have been lost. Hero described and expanded on the work of others (most notably Ctesibius and Philon) as well as describing his own discoveries and inventions. Hero described how the power of water, wind, and steam could be used to (among other things) automate the opening

[1] Ctesibius has been called the "Edison of the Alexandrian School". Among his inventions were the suction pump (which is still used today in many applications including fire engines) and the hydraulis, the first musical instrument to be played using a keyboard and the ancestor of the pipe organ.

of temple doors, power sound effect machines and automatic theaters, and provide sound and movement to automata. In the *Pneumatica* he uses many examples of automata to illustrate his technical discussions.

With the destruction of the Library of Alexandria and the fall of Rome, both in the fifth century CE, Byzantium and the Arab world became the repository of most of the remaining learning from the Classical period. It was from Byzantium that this knowledge would make its way to Europe at the end of the Dark Ages.

4.1.2 Automata come to Europe

With the beginning of the Renaissance in the thirteenth and fourteenth centuries there was a rediscovery of the ancient classical texts and a desire to apply this knowledge to the arts and sciences. Water clocks were fitted with mechanisms to chime bells or to activate rope driven human and animal figures (called jacquemarts or jacks). These clocks gave way to weight-driven mechanical clocks which featured not only jacks but often a variety of astronomical and holy day displays, calendars, and sometimes even a dial for telling the time [101]. As clock mechanisms grew more advanced, so did the automation of the jacks. Rope movements were replaced by sophisticated collections of strings which in turn were replaced by arrangements of gears and cams. These mechanical clocks were immensely popular and were added to cathedrals and town squares across Europe for the next three hundred years, becoming a part of everyday life.

Another mostly independent line from water clocks to automata can be found in water works and water gardens. Expensive to build and maintain, they were toys of the nobility. Some were elaborate complexes of grottos connected by vaulted galleries. Fed by water from nearby rivers or lakes they often contained large, multi-level fountains. The water also powered organs and mechanisms to animate tableaus, often of a mythological nature [7]. These application of the hydraulic and pneumatic devices and processes of the Greeks coincided with a number of translations of Hero's *Pneumatica*, first into Latin, then into Italian and English. Some of these translations acquired beautiful illustrations to show the translator's impression of what these de-

vices should look like. One example appears in Figure 4.1.

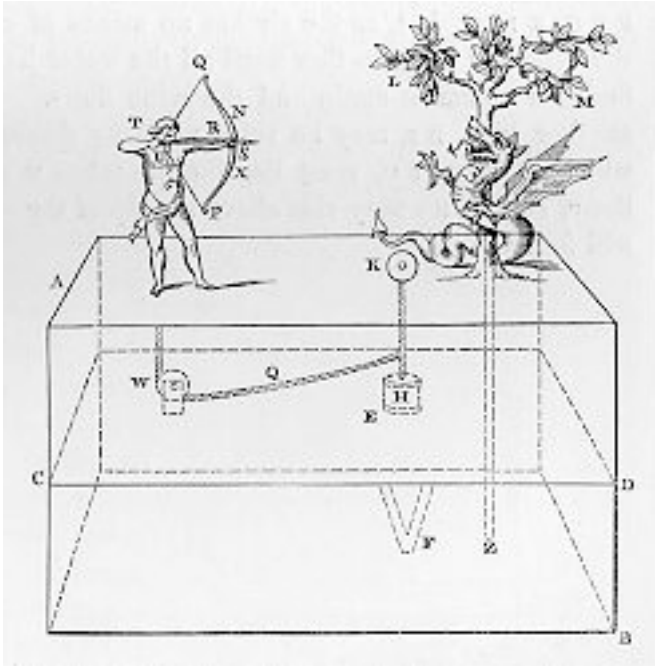


Figure 4.1: On an Apple being lifted, Hercules shoots a Dragon which then hisses. When an observer raises the apple (K) from the platform, Hercules fires his arrow at the dragon. Originally described by Hero of Alexandria in his *Pneumatica*. Illustration from Woodcroft [132, Section 40].

4.1.3 The Golden Age of Automata

Clockwork evolved into the watchmaker's art in the sixteenth century. Portable clocks using spring driven movements rather than weights were followed by early pocket watches in the seventeenth century. Also around this time the pinned cylinder (familiar to anyone who has examined a music box movement) was applied to the control of organ pipes for the automated playing of music. These developments were not lost on automata makers who adopted and refined these mechanisms. The new precision with which mechanical components could be created allowed for more robust and lifelike movements to be imparted to automata. The new spring driven movements meant that the size of automata could be reduced to make them more approachable and even portable; an attribute not previously associated with automata. Clever watchmakers started

building automata to showcase their skills in novel ways.

The eighteenth and nineteenth centuries can truly be called the Golden Age of Automata. This period saw some of the most beautiful and complex automata ever created and in many cases the technology was elevated to art. Galleries were rented, exhibitions were mounted, and the paying public flocked to be amazed and astounded. Many talented makers found prominence during this period. Notable among them were Jacques de Vaucanson and Pierre Jaquet-Droz.

Jacques de Vaucanson (1709-1782) "...is unquestionably the most important inventor in the history of automata ..." [7, page 36]. Vaucanson initially became interested in creating a "moving anatomy" which, for a variety of reasons, he never completed. In 1735 he had the idea to raise money by creating several machines that could excite the public's curiosity. By 1738 he had completed two life-sized musicians. The first, a flute player could play eleven different tunes by forcing air from its lips and moving its fingers over the holes in the flute. The second played twenty tunes on a three holed pipe in the same manner while accompanying itself on the tambour [60] (Figure 4.2).

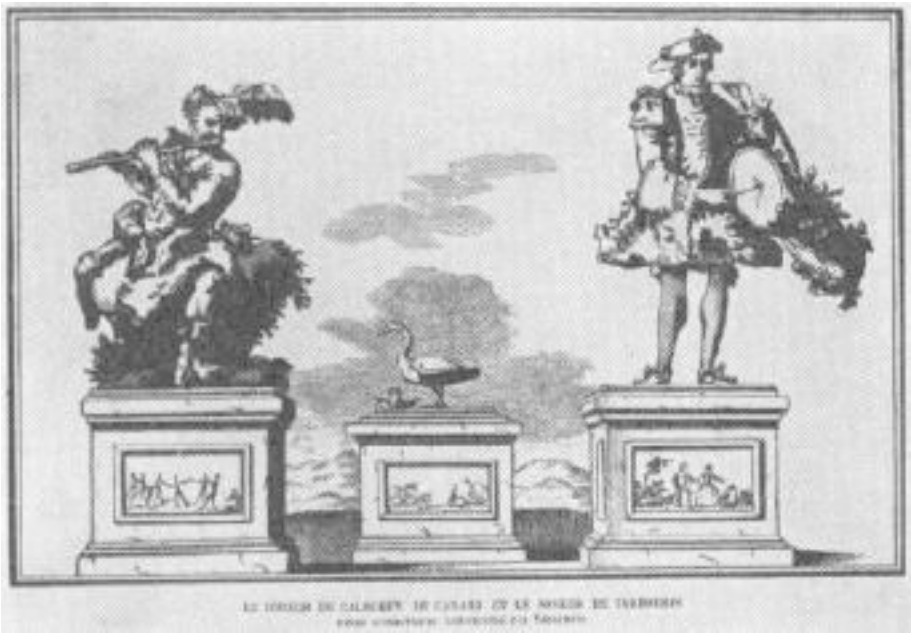


Figure 4.2: Three Automata by Vaucanson. In this wood cut, Vaucanson's famous duck is flanked by his equally well known flutist (left) and tambourist (right).

Vaucanson then went on to best himself by creating and exhibiting a life-sized duck. His prospectus declared it to be "An artificial duck made of gilded copper who drinks, eats, quacks, splashes about on the water, and digests his food like a living duck" [18, page 233]. This is arguably the most famous automaton ever created. The mechanisms which controlled the actions of this and other automata of this period were very complex, made use of the newest technologies available and were finely crafted. Vaucanson was not very forthcoming with details of how the duck worked leading to much speculation as to the mechanism. Figure 4.3 shows one guess as well as a photo purported to be that of the actual mechanism which was housed entirely in the pedestal.

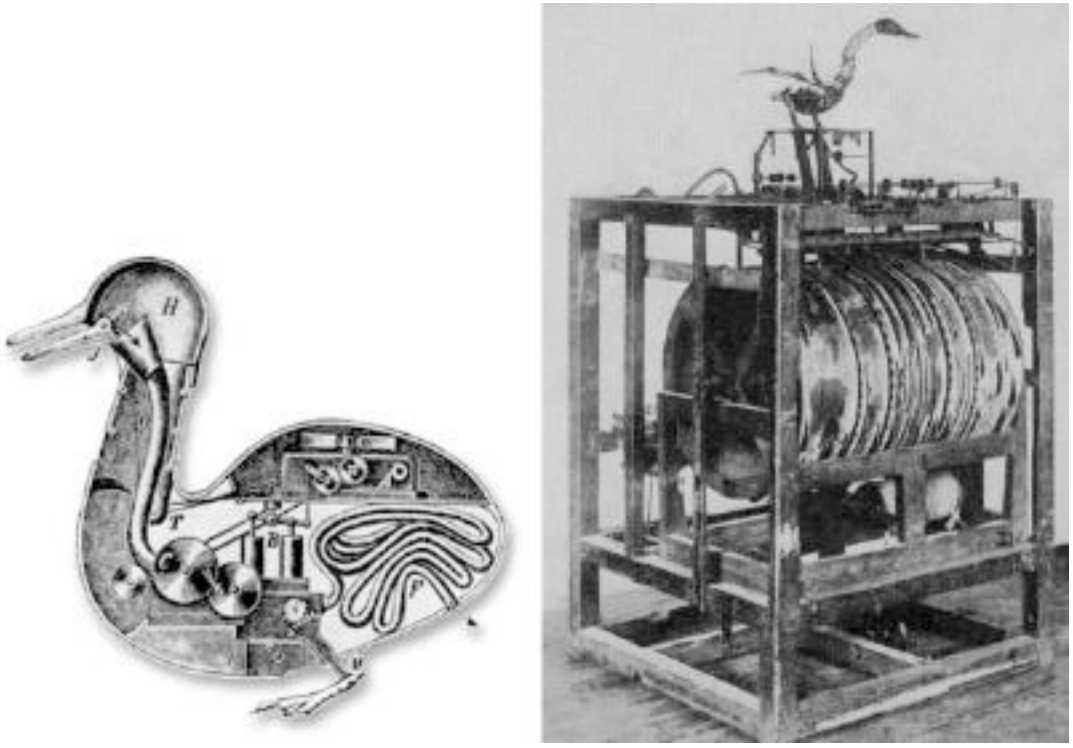


Figure 4.3: On the left, a contemporary woodcut speculation on the internal workings of Vaucanson's duck. On the right a photograph of the actual mechanism for the duck taken in the mid-nineteenth century and claimed to be of the original.

Pierre Jaquet-Droz (1721-1790) and his son Henri-Louis (1752-1791) brought their expertise and skill as watchmakers to the building of automata. Unlike the automata of Vaucanson,

there are at least three Jaquet-Droz automata still extant in the Museum in Neuchâtel Switzerland [18]. The *Musician* plays a harpsichord by pressing her fingers to the keys and her general body and facial movements are meant to suggest that she is somewhat self-conscious of the attention being paid her. The *Writer* sits behind a mahogany table and, with the appropriate changes to his mechanism, can write any text of up to forty letters in length using a quill pen. The *Draughtsman* uses a pencil to produce any one of four drawings: Louis XV, King George III and Queen Charlotte of England, cupid riding in a butterfly drawn chariot, and a dog on which he also writes "my bow-wow" in English. A hidden bellows allows him to blow the pencil dust from his drawings. These automata are shown in Figure 4.4.



Figure 4.4: Three Automata by Jaquet-Droz. The *Musician* flanked by the *Draughtsman* on the left and the *Writer* on the right. These automata are now preserved in the Museum of Art and History in Neuchâtel, Switzerland. Photo: Musée d'Art et d'Histoire, Neuchâtel.

The automata of Jaquet-Droz followed those of Vaucanson by about forty years and differ in several ways that show how much the craft had changed in such a short period of time. Where the human figures of Vaucanson had been adult in size and appearance, the figures of the Jaquet-Droz automata are those of children. Perhaps one reason for this is the different emotional response that a viewer has to a talented and precocious child. Another reason may be to emphasize the

degree to which the mechanisms had been miniaturized. Where Vaucanson had placed his figures on pedestals which contained the mechanism, the Jaquet-Droz automata have their mechanisms enclosed in their bodies. This trend would continue up until the popularity of automata faded early in the twentieth century. There were, to be sure, artists who would keep the tradition alive to a limited extent, but with the death of Carl Fabergé (perhaps the last of the great craftsmen [7]) in 1920, the Golden Age was over.

4.1.4 The Contemporary Automata Period

By the turn of the twentieth century, the industrialization of Europe and North America had shifted the focus of new technologies into the production of goods. Clockwork mechanisms were replaced by steam, internal combustion, and electricity. It was often more important to produce objects quickly and cheaply and automata suffered the same fate as many other products. Cheap wind-up toys and banks became their legacy. The quality of these later devices was often only good enough so that they didn't break until they had been briefly used. Cheap materials and mass production made the fine automata of only a century before little but a memory.

But the creation of automata was not a lost art. In the late 1970s a small number of European artists started making automata in a totally new style; one called *contemporary automata*. Where previously the goal of automata had been to inspire wonder, reverence, or awe, these new automata have a decidedly humorous intent. Where previously automata had been made as life-like in appearance and motion as possible, the new trend is often cartoonish or abstract. Where previously automata had hidden their mechanisms from view, these new automata are often brazen in offering their movements as part of the overall viewing experience. And where previously automata had been operated by mechanical, hydraulic, or pneumatic means, these new automata are, for the largest part, hand cranked by the viewer. These differences may at first seem subtle, but they have a profound impact on the viewer, making the experience more intimate and personal.

One central force in this rebirth was Cabaret Mechanical Theatre in England [14]. Here

artists such as Peter Markey, Paul Spooner, Keith Newstead, Tim Hunkin, and Ron Fuller were able to present their work to the public much as Vaucanson and the Jaquet-Droz had done two hundred years earlier. This public space introduced thousands to automata in an entertaining and educational way. Figure 4.5 illustrates this style. Using many of the same types of components as were used by Vaucanson (cams, gears, levers, even a bellows), Paul Spooner is telling a story; the milk is better because it belongs to someone else. And in addition to amusing us, he is also giving us the chance to see all of the intricacy of the automaton by exposing the mechanism to our view.



Figure 4.5: Cat Drinking Someone Else's Milk by Paul Spooner. The cat nervously looks from left to right to avoid being caught as it laps up the milk. Photo: Cabaret Mechanical Theatre.

4.2 What Makes the Design and Construction of Automata an Appropriate Task?

As mentioned early in this chapter, there are a number of domains and approaches which could lend themselves to research on the acquisition of mechanical reasoning and spatial cognition. Why then choose the design and construction of contemporary automata? Before answering

this question it is important to ask a related question. When learning about mechanisms, why design and construct physical objects at all? It could be argued that sophisticated simulation programs running on fast computers could provide children with the opportunity to explore far beyond the bounds of what they are physically able to create. After all, much of engineering education has abandoned construction for simulation. But that seems to shortchange children who no longer have the opportunities to observe and interact with machines that were available to children as recently as thirty years ago. Many of the common machines that children now encounter day-to-day no longer have mechanisms in the traditional sense, being primarily electronic. And of those which do have mechanical elements, they are often enclosed and sealed so as to prevent them from being observed and understood. It seems evident that the exposure to and understanding of machines is critical to gaining the ability to reason mechanically and that exposure can no longer be obtained in daily experience. Building machines seems to be indicated in this case.

To support this assertion, there exists a body of historical and educational practice. Historically, the design, construction, and maintenance of machines has been a skill passed down from master to apprentice for centuries. By doing at the elbow of a skilled craftsperson, a novice gains both the knowledge and the understanding that leads to proficiency. It was perhaps the success of this traditional model that led Fredrich Froebel to invent Kindergarten. He believed that engaging with the world through practical work and the direct use of materials allowed understanding to unfold. This led directly to the creation of the *gifts* (play materials) and *occupations* (activities) that were the core of his educational method [10]. Piaget claimed that cognitive development is facilitated by placing learners in situations or activities that require them to interpret events in terms of their existing cognitive structures (*assimilation*) and to change those structures to better makes sense of those events (*accommodation*) in a process he called *adaptation* [41]. Papert cites his early experiences with gears and his use of that knowledge as a foundation for mathematical learning as an instance of Piaget's notion of assimilation [92] and he argues that learning is greatly facilitated when the learner is engaged in the creation of some *thing* [91]. Designing and building automata is very much in keeping with these schools of practice and exhibits several

attributes that makes it particularly attractive.

4.2.1 Automata Tell a Story

Turning the crank on an automaton does more than set it in motion. The viewer is told a story through the actions of the character or characters. The story is rarely involved, but when done properly can carry all of the impact of a well written and illustrated cartoon. This is because, in many instances, automata and cartoons (especially single panel cartoons) share a similar sensibility; extract the essence of the story and tell it as economically as possible. The story telling aspect of contemporary automata provides much of their initial appeal and, when done correctly, that appeal continues. Like all good stories it begs to be shared, making automata a focal point of social interaction.

4.2.2 Separation of Story and Mechanism

Contemporary automata can be divided into two units: the story components (the figures and supporting story elements) and the mechanism. While the telling of the story is in large part due to the design and function of the mechanism, from a pedagogical standpoint they can be viewed separately. This allows a designer to come to the process with an idea for the story to be told and to develop a mechanism that will provide the desired behavior that will tell that story. That allows for the study of mechanism design, mechanical reasoning, and spatial cognition in a more purely mechanical setting. A set of actions and dependences are defined that are necessary to tell the story and those become the constraints on the design of the mechanism.

4.2.3 Domain Knowledge and Constraints

Compared to some other domains, the mechanisms in contemporary automata are relatively simple and often composed of only a handful of components. This provides opportunities to explore both the properties of individual component families (such as cams) and the interactions between components in a mechanism, allowing domain knowledge to be constructed both

from the bottom-up and from the top-down. When mechanisms are assembled it is rare that individual components are tightly placed or hidden from view which provides the ability to fully examine components before, during, and after assembly.

The mechanisms in these automata also lend themselves to the kind of constraints necessary for this type of research. Constraints can be placed on the design and construction of these mechanisms that allow a more direct focus on mechanical reasoning during the design and construction phases while placing minimal restrictions on the behaviors of the resulting mechanisms. This occurs primarily by limiting the number of component families offered and by restricting the number and types of members of those families. Careful selection of components can still allow the knowledge gained to be applicable to a large number of mechanical systems in other domains. Additionally, the very nature of contemporary automata provides a number of very useful constraints. First, as already mentioned, these mechanisms are most often composed of a small number and type of components. Second, in very many cases contemporary automata are small enough in size to be easily held and manipulated by children, but still large enough to be constructed without difficulty and operated reliably. Third, the materials from which contemporary automata can be made are ones that many children will already be familiar with. And fourth, in most automata, the mechanism moves at a relatively slow speed requiring less precision in its fabrication and assembly and more readily allowing it to be observed and analyzed.

4.2.4 Unexpected Results

Designing and building contemporary automata is not an exact science. Unlike high precision mechanical systems, there is rarely any attempt made to simulate the operation of an automata before building a prototype. This can lead to a number of unexpected results, not all of them bad. Paul Spooner mentions that unexpected friction at the hip joints in his automaton *Press-up Anubis* (Figure 4.6) allowed the shoulders to precede the hips as Anubis lowers his body which he finds more pleasing than what he had originally anticipated [120].

Unexpected negative results are rarely critical problems. Because of the relatively simple



Figure 4.6: Press-up Anubis. As Anubis pushes up, his body straightens but when it moves back down, friction at the hip joint allows the shoulders to touch the table first. Built by Paul Spooner and Matt Smith. Photo: Fourteen Balls Toy Company.

mechanisms involved, diagnosis of problems and the creation of solutions is a more straightforward process than many other domains would allow. The failed results become excellent learning opportunities for the user and provide yet another means by which reasoning about the mechanism can be done.

4.3 Contemporary Automata

What is it that distinguishes contemporary automata from other categories of automatically moving figures? There are five principal features that are evident in contemporary automata. Not every contemporary automaton may have all of these features, but these do help us establish some subjective guidelines.

(1) Contemporary automata interact with viewers in an intimate way. These automata are not exhibited to large audiences, but are viewed by one or a few individuals at a time.

The viewer is responsible for setting the automaton in motion and determining how long, and in some cases how fast, the automaton will operate. The power source for that automaton is often supplied by having the viewer turn a crank or otherwise provide some mechanical input. The viewer may be able to lift and hold the automaton and to view it from many angles. In essence the viewer does not observe the automaton's actions but participates in them.

(2) The mechanisms found in contemporary automata are commonly simple, being constructed from a small number of components whose type and function can be discerned without extended study. The viewer no longer needs to be an engineer or mechanist to understand the workings of the automaton and understand how the design of the mechanism contributes to the experience of viewing.

(3) The mechanisms found in contemporary automata are commonly exposed to the viewer. Traditional automata conceal the mechanisms in the bodies of the automata or in the base or clock to which they are attached. Viewers were allowed to marvel at the motions, but not allowed to see how it was done. Contemporary automata take a holistic view that all of the parts are important to the viewer's experience.

(4) The figures and scenes presented in contemporary automata are caricatures of life rather than exact copies. Rather than the perfectly life-like motions and appearances sought as ideals in traditional automata, contemporary automata embrace cartoon-like motions and appearances which engage the viewer in the same ways that print and animated cartoons do.

(5) Where traditional automata were created to inspire reverence, awe, and wonder in their viewers, contemporary automata are generally humorous and playful. The humor is sometimes dark but the maker establishes an emotional link with the viewer through the automaton that doesn't exist in other types of automata.

To illustrate these principles, two examples are briefly presented here. One was designed by a professional automata maker and constructed from a kit while the other is the work of a skilled novice.

4.3.1 The Camel Simulator

This automaton (Figure 4.7) was designed by Paul Spooner and built from a kit. It depicts Anubis, the the Egyptian god of the dead, practicing for the fast getaways necessary when his customers got wind of the poor quality and pricey funerals he had sold them.



Figure 4.7: Practicing fast getaways was a critical survival skill for the ancient flim-flam undertaker. Here Anubis, Egyptian god of the dead, stays in tip-top shape. Built from a wooden kit designed by Paul Spooner.

The mechanism consists of three cams (see Section 5.1.3.1 for a description) attached to the crank via a single shaft. Two of the cams are eccentric cams with ring followers to move the camel's head and tail. The remaining cam is a three-lobed snail cam that lifts and drops the camel's hump. The lobes on the snail cam are not evenly spaced, but are designed to produce a galloping

rhythm in the motion of the hump. Anubis' body articulates at four locations: his heels articulate at the camel's neck, his legs articulate at the hips, his hands articulate at the reigns, and his arms articulate at the shoulders. This creates a quadrilateral (legs, torso, arms, camel's neck) that can move at each corner.As the camel's hump rises, so does Anubis' torso. When the hump falls, Anubis follows along. While the motion of the head and tail comes about because the eccentric cams pull them down as well as well as push them up, the downward motion of the hump and Anubis' torso results strictly from gravity.

4.3.2 Celia the Sea Lion

Celia (Figure 4.8) is the prototypical pinniped made good; she balances on her pedestal while spinning the ball and moving her flippers.

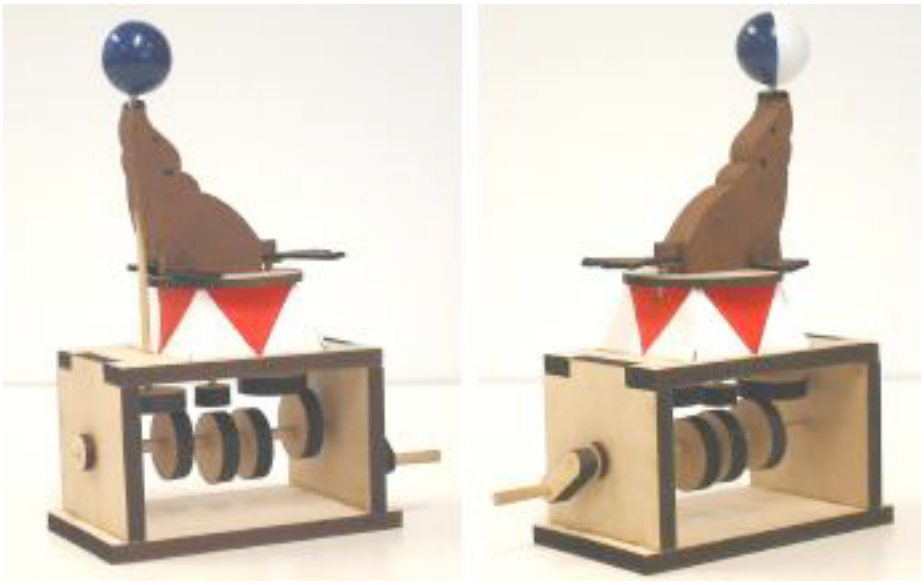


Figure 4.8: Balanced on her pedestal, Celia keeps the ball spinning on her nose while constantly moving both her front and back flippers. The mechanism is based on one created by Peter Markey and used in his *Angry Cat*.

The mechanism consists of three cams and one disk attached to the crank via a single shaft. The disk rotates another disk attached to a second shaft set perpendicular to the the first. This causes the ball to rotate continuously as long as the crank is turned. The first eccentric

cam moves its follower up and down. This follower moves a lever hidden inside the body that is attached to the front flippers, causing them move. The remaining two eccentric cams are arranges symmetrically at opposite ends of perpendicular disk. Because of this placement, a continuous turning of the cams causes the disk to turn back and forth. This causes the tail flippers to move from side to side.

4.4 Automata in Education

The use of automata is not a new idea. For example, in both Canada and the United States automata are used as students study basic science, mechanics, and mathematics. In the UK, the National Curriculum [87] has included a Design and Technology (D&T) component since 1995. During Key Stage 2 (ages 7-11) all students must make a mechanical toy with the goals of increasing their building skills and learning about how motion can be controlled. While the standards call for the design and construction of a simple toy with a cam mechanism [25], many teachers take this opportunity to engage the children in designing somewhat more complex mechanisms that might also include gears or levers. In many instances, the resultant artifacts exhibit many of the attributes of contemporary automata.

The mechanical toy unit has much in common with the research described here. A number of the challenges by both students and teachers have helped shape the MachineShop system (Sections 5.1 and 5.2) and the experimental method (Section 6.1). Among these are:

- Information about mechanisms of the type under study is not abundant. In many cases students bring no prior knowledge of machines to their first design and the lack of ancillary materials to provide examples and explanations makes the process more difficult.

- With the software design tools available to students even the creation of simple mechanisms is quite challenging. The same CAD/CAM (computer aided design and computer aided manufacturing) tools used in higher grade levels are also used in the mechanical

toy unit. Younger students are not a target audience for these tools and their interfaces and feature sets make them a poor choice for this activity.

- The time limit set for completion of the unit restricts the amount of time available to students to experiment and refine their designs. In some cases students are only given one work session in which to develop an idea and produce preliminary drawings. And as the unit progresses little or no time is available to iteratively prototype and improve.

- Children at this age are still learning to use tools and to understand the properties of the materials that they are working with. To expect them to be able to produce mechanical components with any degree of precision is Panglossian.

It might seem that these issues would make the mechanical toy unit frustrating for the students and that the results would not be very interesting. Nothing could be further from the truth. One can wonder, however, what the results might be like if these issues were addressed.

4.5 Summary

Automata are moving sculptures of people or animals with repeating motions controlled by mechanisms. The ancestry of the machines that we identify as automata goes back over 2000 years and we find descriptions of automata in the writings of members of the Alexandrian School as far back as the third century BCE. Powered by steam, wind, and water, these early automata were used for religious purposes, as entertainment, and to illustrate many of the latest technological advances; a role they would play throughout most of their life. Much of what the Greeks knew lay dormant or was lost during the Dark Ages, but by the thirteenth century CE a large portion of that knowledge was being rediscovered in Europe. Water clocks gained automated figures and eventually were made obsolete by the weight-driven clock mechanism of the town square. Water gardens with elaborate automata adorned great palaces, and the ancient writings of the Greeks were translated and studied. The spring replaced weights in clockwork allowing the mechanisms for automata to become smaller and more intricate. Automata building was raised to high art.

The late twentieth century found two primary schools of automata building: the traditional and the contemporary. Contemporary automata differ from traditional automata in a number of ways mostly dealing with aesthetics and the connections between automata and viewers. Contemporary automata provide a good domain in which to study the acquisition of mechanical reasoning and spatial cognition because children find them interesting, because the mechanisms are simple and easily studied, because the amount of knowledge and skill necessary to design and make simple automata is small, and because designing and building automata gets directly to many of the core components of designing and building any mechanical system.

While automata have been and are being used in education settings, they often are relegated to the role of educational manipulative in the teaching of important concepts. In the UK the creation of a mechanical toy or automata is a required exercise with the goals of increasing a student's ability to make physical artifacts and as an introduction to controlling mechanisms. This task is not without its difficulties, and the design of the MachineShop system reflects a desire to address some of these problems. This is more fully discussed in Chapter 5.

Chapter 5

The MachineShop System

The design and construction of automata can be intimidating for the adult novice and even more daunting for a child. Appropriate tools and knowledge support materials can make the process of both building and learning easier and improve the quality of the user's experience. By extension, this increases the likelihood that a user will continue to create automata, with the increased probability that her skill and understanding will both increase. The MachineShop system was created to fill this role by providing users with a collection of core and supplemental tools to support this task.

This chapter begins with an overview of the MachineShop software, a discussion of its constituent parts and their functions, and an examination of the files the software creates and uses. This is followed by an introduction to recent advances in affordable computer controlled machine tools and output devices with an emphasis on carbon-dioxide laser cutters of the type used in this research. Examples of how MachineShop can work with other devices are also provided. The chapter concludes with a description of the supplemental materials created and appropriated to support users as they make their own automata.

5.1 The MachineShop Software

MachineShop was created to provide children aged 11 to 13 years with a computer-aided design and computer-aided manufacturing (CAD/CAM) tool that they could use to make the mechanical components needed to construct their own contemporary automata. Commercial design

tools (see Section 3.2) are too complex, feature laden, and general purpose for children to use in specialized domains such as automata design. This is frustrating for children and causes them to spend too much of their time with the software trying to discover and remember the steps necessary to do what they want. The intent with MachineShop was to create a tool specific to the task that supported users as they acquired domain knowledge and mechanical reasoning skills through the process of building.

This section details the current form of the MachineShop software and how it focuses on supporting users as they create automata. It discusses the major challenges that have been faced in the creation of the software and how they have been addressed through both design decisions and domain constraints.

5.1.1 High Level Considerations

To insure that MachineShop would meet the needs of its intended users A set of six core metrics were derived empirically and they were then used to guide the initial design choices for the MachineShop software.

(1) The purpose of the MachineShop system is to support the activities that children do as they design and build contemporary automata. This support should be as extensive as possible while keeping the system simple to learn and easy to use.

(2) Children have access to computers that come from a variety of manufacturers. These computers are of varying ages and capabilities, and use an assortment of operating systems. This means that software has to be created for as many of these platforms as possible in ways that do not make unwarranted computational demands on hardware that is one, two, or even three generations old.

(3) Because the software will be used for the creation of physical objects, users should be able to create and manipulate these objects in as natural a way as possible.

(4) The interface should present information to the user in a consistent and meaningful fashion. Where controls are duplicated from one tool to another they should be, as much as possible, in the same locations. Information should be presented in appropriate forms and multiple forms should be used when needed. These multiple forms should be placed near each other so that the user may take advantage of them without spending time trying to locate them.

(5) The version of the MachineShop software that was used for the research described in this document should be considered only the initial version. It should be extensible by anyone who cares to obtain the source code and modify it.

(6) The MachineShop software should be available to anyone without cost.

Most of these constraints can be addressed by the appropriate choice of a programming language and supporting libraries in which to write the software.

(1) The language must have a compiler, interpreter, or runtime environment for each hardware and operating system combination on which the software will be expected to run and all executable files created and libraries used must be free from licensing arrangements that would restrict the use of the software or impose fees for its use.

(2) The underlying structure of the language and its libraries should map logically to the problem domain.

(3) The language must have a freely available set of graphical libraries for both the creation of the user interface and the display of the graphical information needed by the user.

(4) The language should be one that is easily learned and has a large user community to enable persons other than the original author to make changes to the software in order to fill evolving needs.

(5) Implementations of the language should be available at no cost for a wide variety of hardware and operating system combinations.

These requirements led to the choice of Java (in particular the Java 2 standard edition) for the creation of the MachineShop software. A Java Virtual Machine (JVM) is freely available for almost every platform that a child might have access to. It has a library of graphical interface components (Swing) as well as libraries for 2-D and 3-D graphics that can be easily and freely obtained. The Java language has a large (and growing) user community and can be obtained for developing on many platforms without cost. Everything that the MachineShop software should need to do could be done in Java without the need for commercial extensions to the language or paying licensing fees.

The interface design choices were developed using the methods of Task Centered Design [70] and recent work on the cognitive aspects of using figures and animations to support text based learning [13]. Because the intended users of MachineShop are children, particular care was taken to make the interface accessible and meaningful to that population.

A survey of almost one hundred sample automata was conducted with the goal of finding the best initial capabilities for the software in the areas of supported tasks and mechanism creation. Although the mechanisms in these automata form a continuum from very simple to very complex, they do have much in common both in process and in mechanical composition. The construction of an automaton can be divided into three tasks. First, an idea is refined into a workable form. Second, a mechanism is devised and tuned to provide the desired behavior. Finally, the automaton is fabricated, assembled, and decorated. Not all of these tasks need software support but identifying the ones that do, especially with the intended user community in mind, suggests three tasks in which the software should assist the user.

- The software should assist the user in acquiring knowledge about mechanisms and movement.

- The software should assist the user in designing components that provide the behaviors the user wants.
- The software should assist the user in combining components into mechanisms that preserve the individual behaviors of components and combine them into the desired behavior for any given automaton.

To this list is added the task of providing persistent storage of component and mechanism designs; something that is not commonly done by automatists. These are the four tasks the MachineShop software supports (Figure 5.1).



Figure 5.1: When the MachineShop software is launched the user is asked to select which of the four core tasks she wants to undertake.

The types of components seen during the survey presented some surprises. Even with the unique nature of the automata examined and the differences in the complexity of their mech-

anisms, cams, levers and cranks, and gears comprise the overwhelming majority of mechanical components and are often found combined into more complex assemblies. The MachineShop software needs to support the creation of a wide range of these basic components and allow for the future addition of new component types.

5.1.2 Exploring Movement

To help users understand how mechanisms work the MachineShop software includes a *movement explorer*. Figure 5.2 shows the interface to this tool.

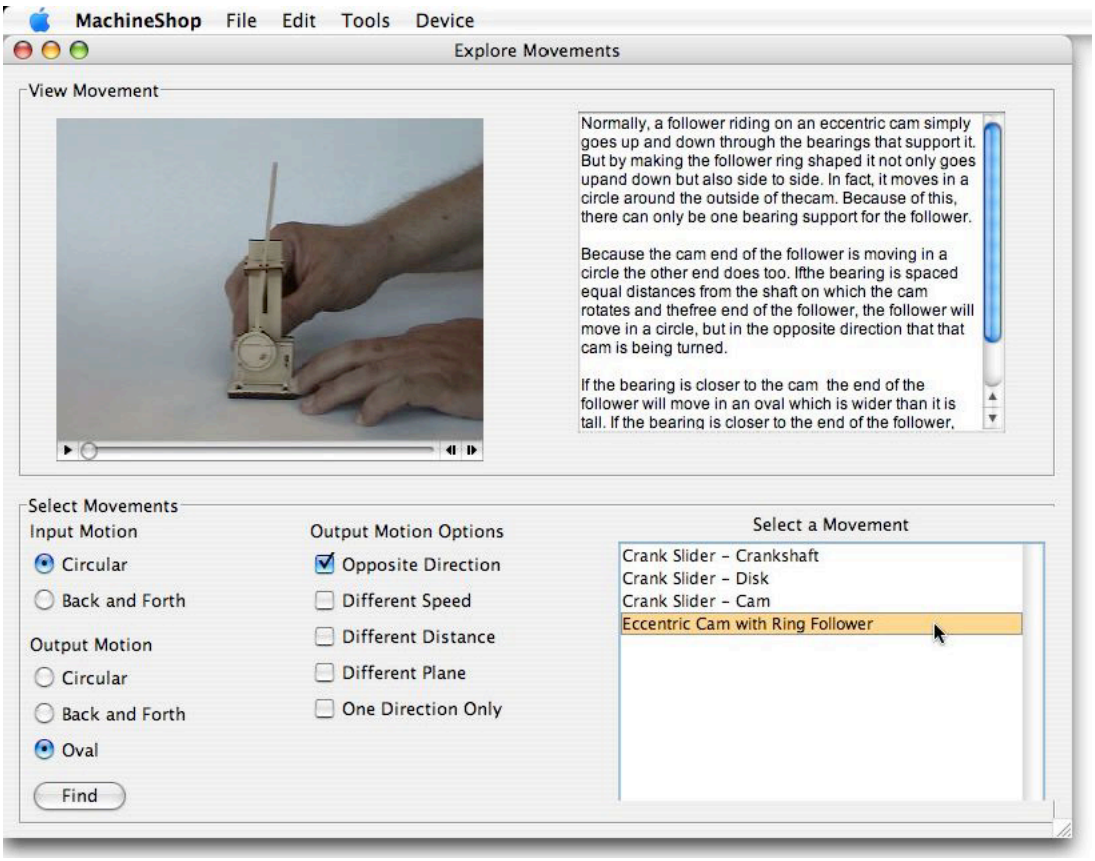


Figure 5.2: To help users understand the behaviors of the components which can be designed and built in MachineShop, the movement explorer provides examples and explanations.

Most children today have no knowledge about how machines work in contrast to their counterparts of half a century ago. As recently as the mid-twentieth century many common devices

used mechanisms that could be easily examined, but the move over the last three or four decades has been to sealed units with “no user serviceable parts” inside. Simple mechanisms (with the exception of bicycles) are no longer common to children’s experience, leaving them with no base knowledge about machines on which to build. To successfully build automata this situation needs remediation.

One approach is to show children examples of automata. This is a worthwhile approach, and has value for deepening their understanding of what automata are and can be (see Section 6.1.1). But it can be hard for children to understand how the individual components of a mechanism function together, or which piece or pieces of an automaton’s motion a particular component contributes to when presented with a finished machine. A better approach is to provide children with examples of simple mechanisms that are composed of only one or two components and allow them to experience these movements in isolation. Once the behavior of individual components is understood, combining them into new mechanisms and decomposing existing mechanisms becomes an easier task. Not every child who works with MachineShop will have access to examples of this kind and even those who do will be unlikely to have examples of many of the mechanisms that can be made with the tool. To mitigate this situation, the software incorporates a tool for this purpose called the *movement explorer*. Figure 5.2 shows the interface to this tool.

The window is divided into four sections. Initially, only the lower left section is available for the user to interact with. These controls allow the user to think about the kinds of motions in which she is interested without requiring any knowledge of the behaviors of the components that might provide it. She needs to think about the kind of input motion she wants (rotational or translational), the general type of output motion she desires, and any special properties she wishes the output motion to have. For instance she may want circular input and output motions, but to have the output rotate in the opposite direction of the input or at a different speed. Once she has made her choices, she clicks the **Find** button and is presented with a list of movements in the lower right of the window that meet her criteria. If none exist, a dialog box appears to inform

her that there are no example movements currently in the database that match her choices.

Any entry she chooses from this list has two corresponding elements that appear in the upper section of the window. A short video of the movement appears on the left while a textual description of the movement appears on the right. The user can watch the video clip while comparing what she sees to the description given for the movement and can move back and forth between them as she finds necessary.

5.1.3 Component Editors

Once a user has determined which components are required for a particular mechanism, she needs to design them. This task is more than just making a component of a particular type and requires that the user accurately choose the parameters that will define the operation, behavior, and suitability of each component so that the desired mechanism behavior is achieved. To assist in this process, MachineShop provides an editor for each family of components that the software can create: cams, gears, and levers. Within each of these editors the user has the ability to either precisely define a component's parameters in a "bottom up" design process or to define a component's behavior in a "top down" design. These design styles can be used interchangeably as it seems most natural in any given circumstance.

Each editor is presented using a standard layout (see Figure 5.5 for one example). The window is divided into three areas and the functionality of each is repeated from editor to editor. In the upper section of the window are the representations of the behavior and motions of the component or component collection being designed. Below that are the controls needed to define basic parameters for the components and to specify the materials from which they will be fabricated. At the right side of the window is a visual representation of the components as they are currently defined that can be animated so that their movement can be observed.

To keep the user interface consistent across editors, a number of controls in the lower panel are repeated in each editor. Choosing the diameter of the shaft or shafts for components as well as picking a material and thickness from which to make the components are shared. The row

of buttons below these controls are also shared and allow the user to load a previously saved file into the editor, save a file to the library for reuse or sharing, create a fabrication file for use with a computer controlled output device (see Section 5.2), or to send the component's profile to a laser or inkjet printer.

5.1.3.1 Cams

Cams are one of the most intriguing of the components found in contemporary automata. At their most basic, they turn rotary motion into translational or oscillating motions of the devices that move along their outer edges. These devices, known as cam followers or simply followers, can either be the terminus for the cam's motion or can be used to transfer the cam's motion to other components[1] .

A lobe has three primary features: lift, dwell, and shape. Lift is simply the change in distance between the cam center and the minimum and maximum distances on the perimeter for the lobe. Dwell, sometimes called duration, is the rotational angle through which the lobe acts on the follower. Shape is the profile of the perimeter of the cam and varies from one type to another. Both lift and dwell are user defined parameters in Machineshop unlike shape which the software produces as a function of the cam type. A cam can have more than one lobe and the follower will move through a complete cycle once for each lobe on the cam. Figure 5.3 shows the lift and dwell of one lobe of a five lobed snail cam. Note that in this example the dwell and lift of each lobe are not the same.

Cams come in a variety of types and supply a corresponding variety of motions and behaviors to their mechanisms. Surveying existing contemporary automata showed that the cams most commonly used fall broadly into two types; eccentric cams and snail cams (see Figure 5.4. Eccentric cams have a circular profile but have their shaft offset from the disk center. This provides a smooth and regular movement to the follower effectively creating a single lobe with a lift of twice

[1] Strictly speaking, a cam is protuberance on the edge of a circular disk. MachineShop uses the more common term lobe for these deviations from the circular, and refers to the composition of lobe and disk as a cam.

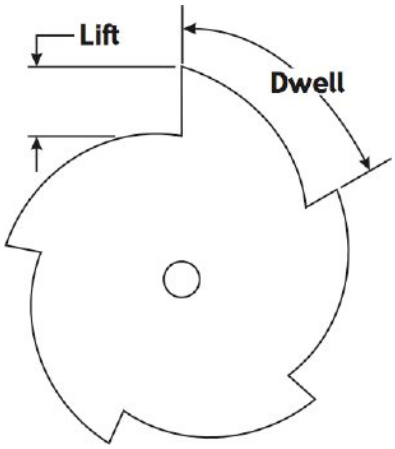


Figure 5.3: The lift of a lobe is the distance the cam follower moves relative to the rotational axis of the cam. The angular period over which this change takes place is the dwell.

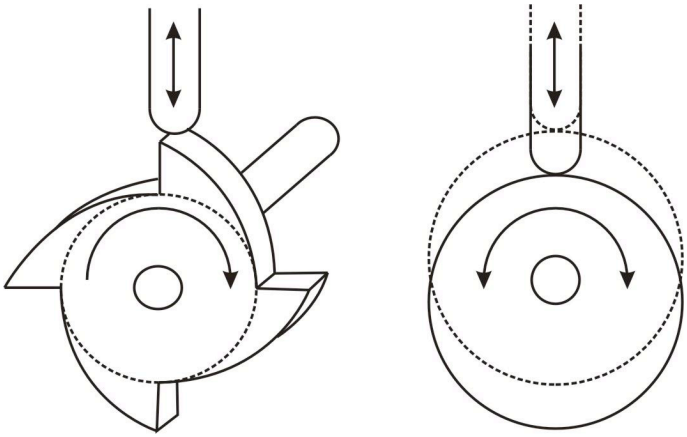


Figure 5.4: The snail cam (left) lifts its follower gently before letting it return rapidly to its starting position. The eccentric cam (right) moves its follower up and down with a smooth motion. Note that the snail cam can turn in one direction only while the eccentric cam can turn in either direction.

the shaft offset and a duration of 360 degrees. Snail cams (named for the snail shell like profile of the single-lobed instance) give their followers a gradual rise in lift followed by a rapid return to their original location. In contemporary automata mechanisms cams are commonly used to create a back-and-forth or up-and-down motion in one or more of the tableau elements such as the camel's head, hump, and tail in Spooner's *Camel Simulator* (Figure 4.7).

Figure 5.5 shows the interface for the cam editor during the process of designing a three-

lobed snail cam. In the upper panel, the user is presented with a motion profile that the cam follower will follow for the current cam. She may alter this profile by using the mouse to move any of the squares at the inflection points of the graph. This allows her to design top down, creating the path the follower must take while the software creates a cam profile that will deliver that motion.

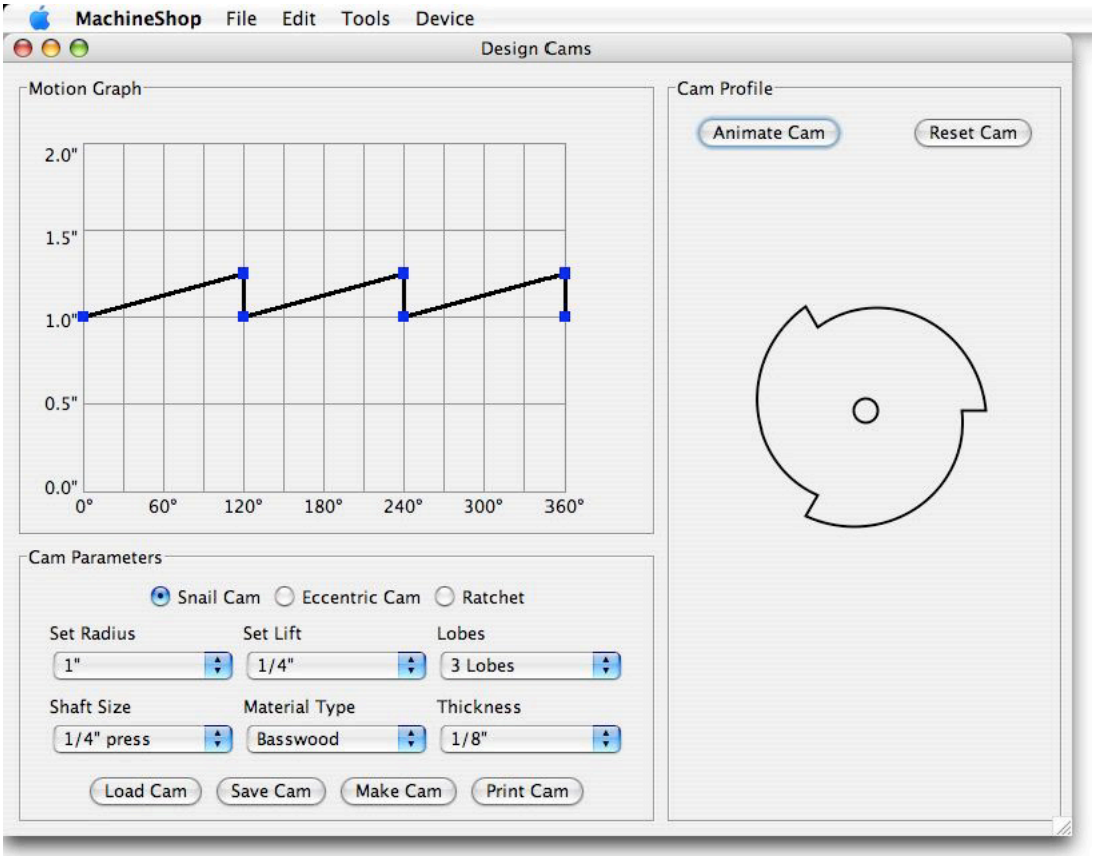


Figure 5.5: The cam editor presents the user with controls to set the parameters of the cam (lower left), a graphical display of the cam follower's motion that can be changed by dragging with the mouse (upper left), and the profile of the current cam (right). The cam profile can be animated to simulate the motion of the finished cam.

The lower panel contains controls that allow the user to set parameters directly to define the cam. Here the user can choose the base radius of the cam, the number of lobes (except in the case of eccentric cams) and the default lift for all lobes. Once these are chosen, the user may still independently modify the lift and dwell of each lobe in the upper panel.

The right hand panel shows the cam profile that will provide the follower motion shown in the graph in the upper panel. This profile cannot be directly manipulated by the user, but responds in real time to changes to the graph. At any time while the user is changing the graph, the current cam profile and a gray representation of the changes being applied to the graph are shown in this panel so that the user may see how her changes are affecting the cam's profile. When she finishes modifying the graph (by releasing the mouse button) the new profile is displayed. At any time the user may also animate the cam profile causing it to turn so that she can see the motion that the current profile will produce.

In addition to designing snail cams, the user may also design eccentric cams and ratchets. Eccentric cams (Figure C.7) are circular disks with their shaft holes offset from the disk center. The effective lift of an eccentric cam is therefore twice this offset (once above and once below the center) and the dwell is 360 degrees. Eccentric cams can have two different types of followers, each of which produces a different final motion. By using a rod follower as shown in Figure 5.4, an eccentric cam produces a smooth back and forth motion at the other end of the follower. By using a ring follower as shown in Figure C.7, an eccentric cam can be used as a crank-slider that produces an elliptical motion, opposite in direction to the rotation of the cam, at the far end of the follower. The software has the option of producing an appropriately sized ring follower for any eccentric cam the user may create.

While not technically a cam, MachineShop also allows users to create ratchets which share many physical similarities with snail cams and are included with cams for that reason. Ratchets are most commonly used to constrain rotation to one direction only or to supply intermittent linear motion from rotational motion. The interface for ratchet design is shown in Figure C.8.

5.1.3.2 Gears

Gears transfer rotary motion from one location to another. In the process, it is possible to change the speed, force and direction of rotation by the appropriate choice of the number of and ratios between the gears. A gear set with an even number of gear axes (since multiple gears can

exist on the same axis) will have the output (driven) gear rotate in the opposite direction to the input (drive) gear. A gear set with an odd number of gear axes will have the output gear rotate in the same direction as the input gear. The ratio between the sizes of the input and output gears in any gear pair determines both the change in rotational speed and the change in force that will occur in that pair. When the input gear is smaller than the output gear, the input gear will rotate more than one complete revolution for every complete revolution of the output gear. At the same time, the effort applied to the input gear will be amplified at the output gear. Both of these occur as functions of the gear ratio of the pair.

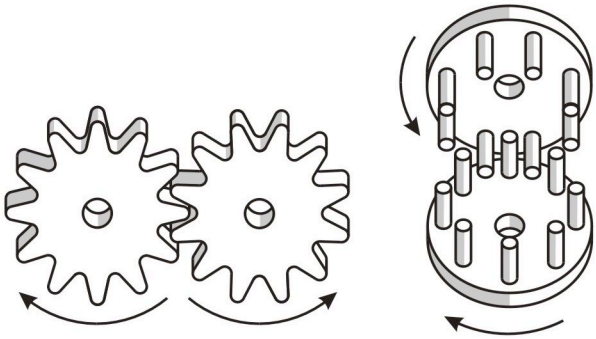


Figure 5.6: Spur gears (left) keep the axes of rotation parallel. Pinwheel gears (right) allow the axes of rotation to be 90 degrees apart. Note that the rotation direction of meshed gears in both types are in opposite directions.

Because the teeth of one gear mesh with the teeth of another, this rotational transfer is accomplished without slippage. Frictional losses of effort are an important concern in gear design and over time have been addressed primarily in the areas of tooth profile and angle and mesh properties between gears. To maximize the efficiency of gears, designers in the real world must deal with a large number of parameters [2] when creating gears [11, 29].

Like cams, gears come in a wide variety of styles to suit the numerous functions for which they are used. In the contemporary automata surveyed, the gears most commonly found were of the spur and pinwheel varieties (Figure 5.6). Spur gears keep the rotation axes parallel but allow

[2] No less than 58 parameters are defined as necessary for designing gears in [6].

them to be separated by some distance. Pinwheel gears move the rotational axis of the output gear 90 degrees from that of the input gear.

MachineShop allows the user to create gear sets composed of either two (pinwheel and spur gears) or three gears (spur gears only), in various ratios. It is of interest to note that gears are the one component currently implemented in MachineShop that exist only in sets. Since rotary motion is transferred from one gear to another, it makes no sense to think of a single gear in the context of a mechanism. The gears in MachineShop have been simplified such that there are only three user specified parameters: the number of gears in the gear set, the spacing between the input and output shafts (for spur gears) or the size of the larger gear (for spur gears), and the ratio between the input gear's size and the output gear's size. There are, of course, other parameters that must be known in order to create gears in MachineShop; diametral pitch and tooth profile for example. These values are currently established by the software and are not directly available to the users.

Figure 5.7 shows the interface for the gear editor during the process of designing a gear set of three spur gears. In the upper panel, the user is shown a representation of the gear set presenting its important properties. The relative sizes of the gears are shown, each with an arrow. The direction of rotation of a gear is indicated by the direction of its arrow, while the relative lengths of the arrows indicate the amount each gear moves relative to the amount its neighbor moves. The thickness of the arrow indicates relative force or effort in the same fashion. Unlike this panel in the cam (Section 5.1.3.1) and lever (Section 5.1.3.3) editors, the user cannot manipulate the gears directly. This decision was made because gears require an integer number of teeth. This limits the gear sizes available to a discrete number rather than the virtually unlimited sizes available to the other components. While the user could have been permitted to change the size of individual gears in one tooth increments with the resultant non-integer ratios, it was decided that most of what a user would want to do could be done within these constraints.

The lower panel contains controls that allow the user to set the parameters that define the properties of the gear set. Here the user can choose the number of gears that she wants (currently

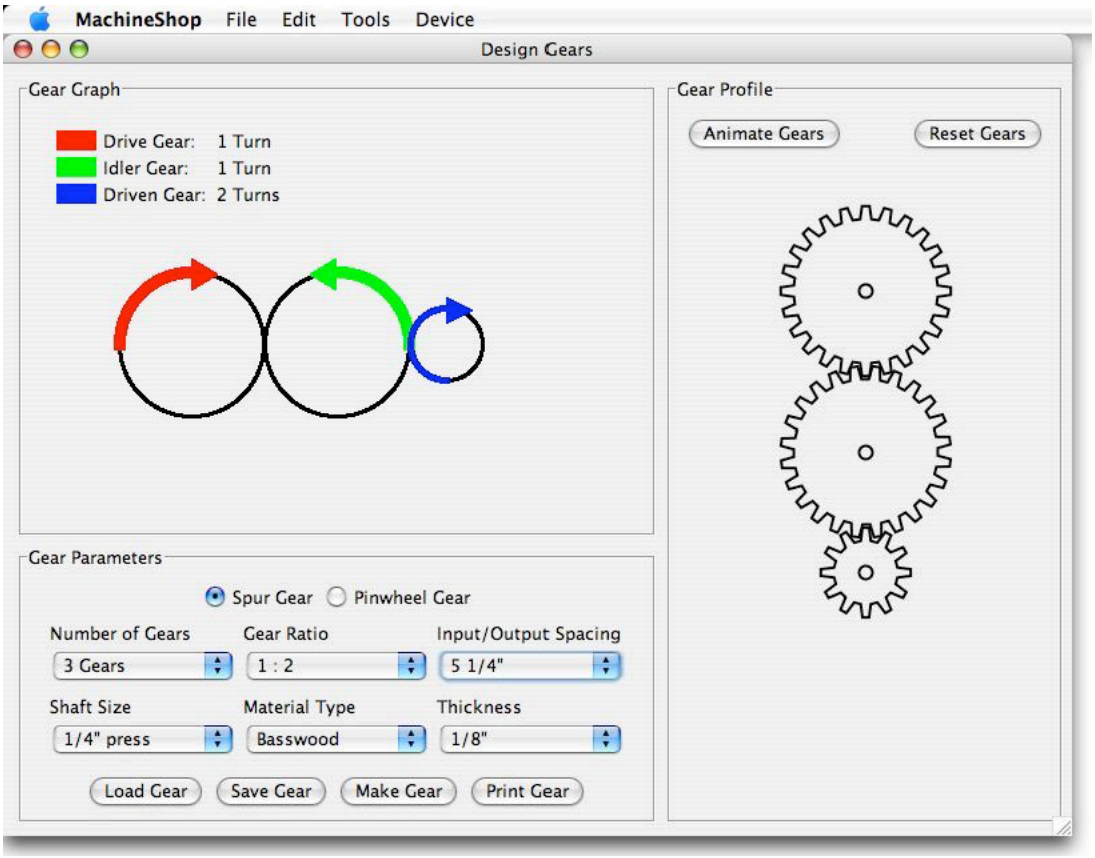


Figure 5.7: The gear editor presents the user with controls to set the parameters of the gear set (lower left), a symbolic representation of the direction, speed, and force delivered by each gear in the set (upper left), and the profiles of each gear in the current gear set (right). The gear profiles can be animated to simulate the motion of the finished gears.

only spur gear sets can contain 3 gears), the ratio between the input and output gears with respect to their sizes, speeds, and power, as well as the distance between the input and output shafts (spur gears) and the sizes of the gears (pinwheel gears). The decision to limit the number of gears in a set was deliberate. By choosing to provide only two or three gears in a set, MachineShop avoids presenting a confusing number of options to the novice user while still supporting more advanced users who can create more complex gear arrangements by combining smaller sets.

The right hand panel shows the profiles of the gears that compose the current gear set. The input gear is shown at the top with the output gear at the bottom. As the user changes parameters for the gear set with the controls, the profile is updated to reflect these changes. The user can also

animate the gear profiles to see what the motion of the gear set will be. The display of pinwheel gear profiles presented a special challenge since the faces of the gears are not located in the same plane. The profile display presents the gears in their actual orientation showing one gear face on and the other edge on (see Figure C.10).

5.1.3.3 Levers

Levers are arguably the oldest machines known to man and are one member of the set of devices known as simple machines [98]. The earliest purposes to which levers were put was in the amplification of forces in order to move heavy loads. In order to do this, the lever must have a fulcrum, or pivot point, upon which it can move. Levers are divided into to three classes or orders based on the relationships between the location of the force applied, the location of the work done, and the location of the fulcrum (see Figure 5.8).

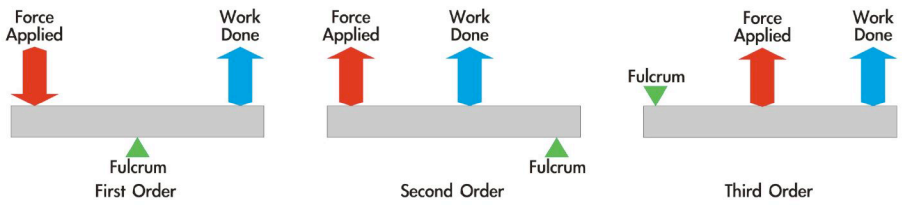


Figure 5.8: Levers are categorized according to the locations of their applied force, work done, and fulcrum. Examples of each order are a see-saw (first order), a wheelbarrow (second order), and a fishing rod (third order).

A lever of the first order has its fulcrum located between the location of the applied force and the location of the work done. A see-saw is an example of a lever of the first order. A lever of the second order has its location of the work done located between the location of the applied force and the fulcrum. A wheelbarrow is an example of a lever of the second order. A lever of the third order has the location of its applied force located between the location of the work done and the fulcrum. A fishing rod is an example of a lever of the third order.

Levers serve a wide variety of functions in the mechanisms of contemporary automata and are seen more frequently than either cams or gears. Levers are used to transfer linear motion from

one location to another, reversing its direction in the process. Many times this transfer of motion results in a change of distance travelled between the input and the output. Levers are used as cam followers, as pawls to constrain the rotation of ratchets, and as cranks that act as the interface between the viewer's hand and the mechanism.

Figure 5.9 shows the interface for the lever editor during the process of designing a lever of the first order. In the upper panel, the user is presented with a schematic representation of the lever along with its force and effort. She may relocate the locations where the force is applied, the work is done, or the lever pivots on the fulcrum by dragging any of the colored squares with the mouse. She can also choose to design a lever of another order by selecting the appropriate button in this panel.

The lower panel contains controls that allow the user to set parameters directly to define the lever. The user can choose a length and width for the lever and set the location of the fulcrum. The user can move back and forth between these controls and direct manipulation of the lever in the upper panel to create any lever she may desire. This panel also contains the controls that allow the user to select which type of component she wants to design.

The right hand panel shows the profile of the lever that matches the settings in the upper and lower panels. The profile in this panel cannot be directly manipulated but responds in real time to changes made in the upper panel. At any time that the user is changing the force, effort, or fulcrum locations or modifying the length of the lever in the upper panel, a gray profile representing the changes being applied appears over the current profile so that the user can determine how the changes she is making will affect the shape of the lever. When she releases the mouse button this new profile replaces the existing profile in the panel. At any time she may also animate the lever to see how it will move when used in a mechanism.

In addition to levers, this editor also allows users to design and create cranks and pawls (see Figure C.13). Cranks are levers with the location of either their applied force or returned effort coincidental with the location of their fulcrum. As commonly used in contemporary automata, the user applies force to the crank at some distance from the shaft that acts as both fulcrum and

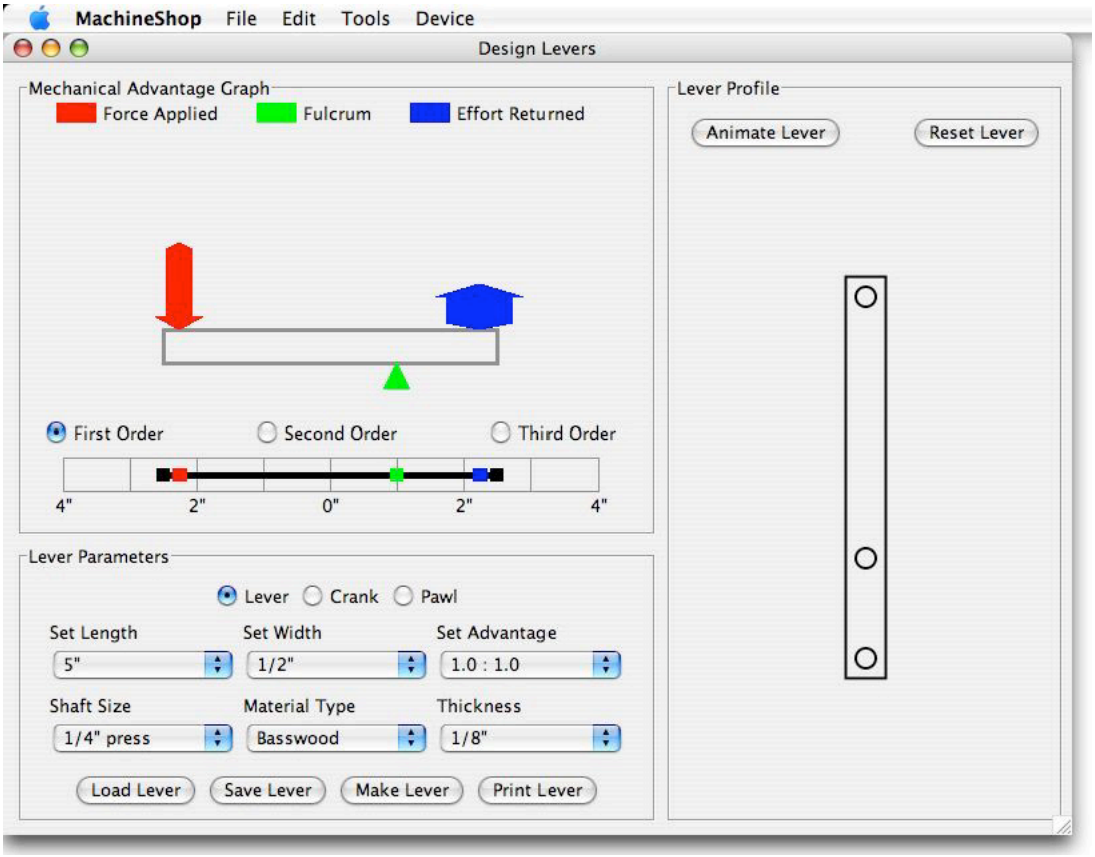


Figure 5.9: The lever editor presents the user with controls to set the parameters of the lever (lower left), a symbolic representation of the lever that can be changed by dragging with the mouse (upper left), and the profile of the current lever (right). The lever profile can be animated to simulate the motion of the finished lever.

source of the effort applied to the rest of the mechanism. Pawls are physically similar to cranks, but are used with ratchets (Section 5.1.3.1) to constrain rotary motion to one direction only.

5.1.4 Browsing Libraries of Components and Mechanisms

While the component editing tools in MachineShop allow users to quickly and accurately design the mechanical components that they require, doing so for each and every automaton that the user builds is a waste of effort. Additionally, it is desirable for users to be able to share their designs with each other so that either duplicate or derivative copies can be easily made. MachineShop has the ability to store and retrieve both the mechanisms that a user creates as well

as the individual components that comprise those mechanisms. Browsers allow users to visually examine each entry in the libraries, delete library entries, or load them into the appropriate editor. Users add components to the component library by using the **Save** button in that component's editor. Users can also load components from the library by using the **Load** button in the editor, bypassing the browser when the component's name is known.

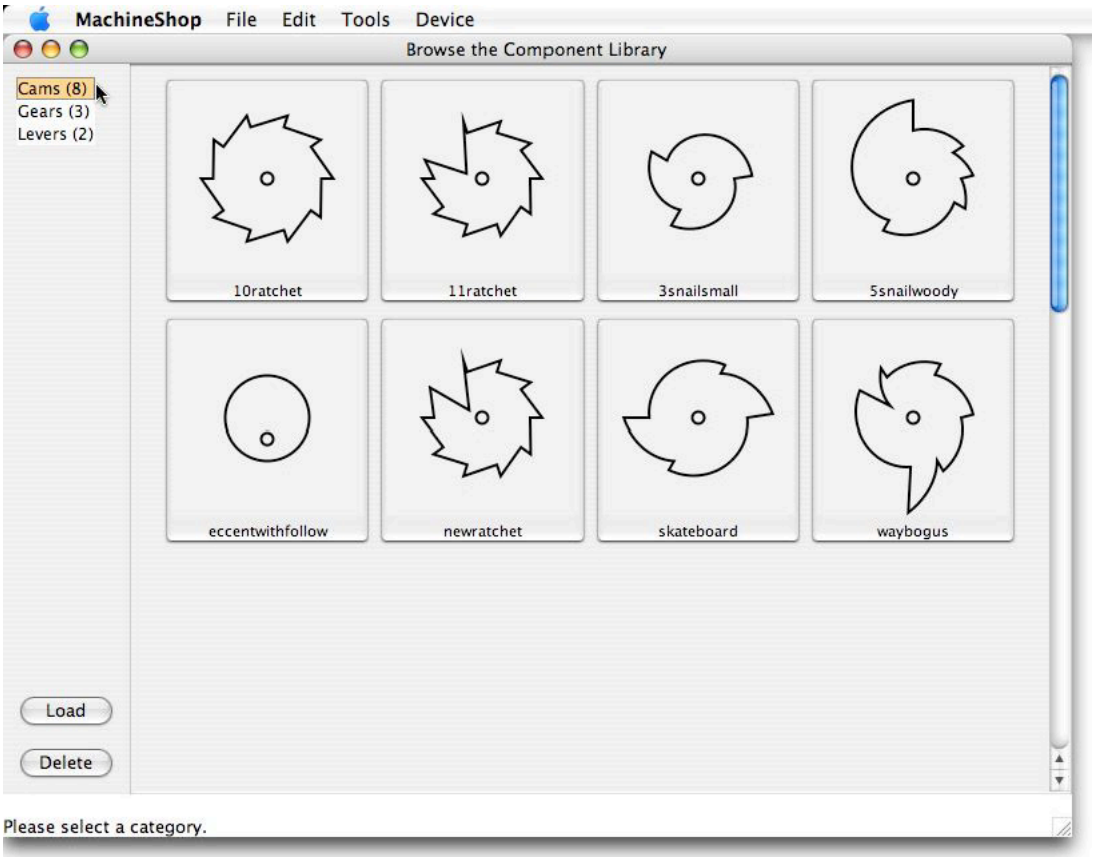


Figure 5.10: The component browser allows the user to quickly view all components saved in the library. By selecting from the component types (upper left) she is presented with images of the profile of all components of that type. If she wishes, she can select a component from this window and delete it, or she can load the component which will start the editor with the component ready to edit or fabricate.

Figure 5.10 shows the interface for the component browser while looking at previously created and saved cams. The left panel contains a list of the types of components stored in the library; currently cams, gears, and levers. When additional component editors are added to the

software they will have corresponding entries in this panel. The right hand panel contains small images of each component of the currently selected type that exist in the library. The user selects a component from this collection by clicking on it with the mouse. Once selected, she can choose to load the component into the appropriate editor or to delete it permanently from the library using the buttons in the left panel. She can, at any time, choose another component of the current type or choose to view components of another type.

Like components, mechanisms can be saved to and loaded from the library in the assembly tool (Section 5.1.5) or selected using the browser. Mechanisms are saved as assemblies of components with each component's description included in the mechanism's file. This method simplifies the reading and writing of mechanism files and allows users to not only learn about the mechanism, but also about its constituent components by reading the file.

5.1.5 Designing Mechanisms

The mechanisms that can be designed and created in MachineShop are more than just collections of components. Every mechanism also includes the shafts and bearing surfaces on and in which the components move, the support structures that hold the components in their relative positions and maintain alignment between them, and often other structures or pieces as well. Having a virtual space in which to fit components to create mechanisms can help users understand and visualize both the relationships between components and the relationship of a component to the mechanism and how those relationships affect the proper functioning of the mechanism. Designing a tool of this type for children to use is especially challenging. Conceptually, designing a case to hold mechanical components exposes many more variables than does designing a component. Where at most a handful of components can provide some desired mechanical behavior, an almost limitless variety of structural frameworks can be created to support those components. The software designer must proceed carefully when constraining those choices to avoid severely limiting users' creativity.

These choices affect what can be made and how it can be made in a variety of ways. For ex-

ample, looking at a variety of contemporary automata shows that most have structural frameworks which are some variation on a cube[3] . By restricting frameworks in MachineShop to be similarly constructed, the software can be greatly simplified and the user can be gently guided in making her mechanisms in empirically proven styles. Little seems to be lost by not allowing spherical or octahedral structures.

The structural framework of a mechanism exists primarily to allow the moving components of the mechanism to perform as the designer intended. But the outer framework is seldom sufficient to accomplish this task and very often must be augmented with additional structural members whose purpose is to allow free movement of components and to keep the components properly aligned, oriented, and located. These pieces are in turn aligned, oriented, and located by the structural framework of the mechanism. Intrinsic in the proper operation of the moving components are a number of mechanical requirements beyond the functional characteristics that the designer has selected.

Shafts with or about which components move need to be supported in at least two places and the greater the distance between these supports the greater will be the stability of the component. Holes in which shafts fit or turn must be appropriately sized. Cam followers need to be supported in two places and their performance is also affected by the distance between those supports. Components which operate in sets, like gears, need to maintain an optimum spacing regardless of their orientation within the mechanism. While important, much of this should not be forced on the user and can be dealt with by the software without the user needing to know about it. This allows the user the opportunity to acquire this knowledge while building mechanisms rather than needing the knowledge before mechanisms can be built.

The mechanism assembly tool has been the most complicated of all of the tools in the MachineShop software. It has been written, discarded, rewritten, and discarded numerous times. It seemed that every time a strategy had been devised for its creation, results from the user test-

[3] Few, if any, contemporary automata have frameworks that are truly cubes. Most are stretched or shrunk in some dimension and often one or more sides are missing or abbreviated to provide a view into the interior of the mechanism.

ing would reveal serious flaws with whatever approach was being used at the time and a new incarnation would need to be started. The incomplete version that exists at the time of this writing incorporates the lessons learned from the user tests (Section 6.2.5) as well as guidance from current cognitive theory (Section 2.3) and practices gleaned from the work of designers of contemporary automata. The issues that have arisen with respect to the design of the assembly tool that need to be addressed fall into two categories: conceptual and implementational.

The conceptual issues reflect concerns of overwhelming users with details of the domain and determining how best the software can take on less central, but still necessary, tasks to make the design of mechanisms less complicated. Foremost among these issues are:

- How much of the knowledge required to design and construct properly functioning mechanisms should a user need to know to successfully work in the domain? Will the user have opportunities to expand her understanding of the full range of knowledge?

- At what level or levels should the software support the assembly task? What advantages or disadvantages would the user have if static displays of the assembly were replaced with animated displays? Would anything be gained from simulating and modeling the physics of the operation of a mechanism?

- How much freedom in manipulating pieces in the virtual assembly should a user have? Should the distances a piece can be moved or the locations a piece can be placed be limited in some way or should the user have total freedom? Should pieces that are part of a logical group be constrained to move together when appropriate or should each piece be allowed to move independently?

The implementational issues concern making such a potentially complex tool available to the intended user audience. Among these issues are

- Since the mechanism assembly tool is one of a suite of tools, there should be as much consistency in the choice and placement of controls and information displays between

this and other tools as possible.

- Views of the mechanism should be displayed in appropriate forms. This may mean 2-dimensional views, 3-dimensional views, or some combination of the two.

- Manipulation of the components and structural elements in these views should be as simple and easy to learn as possible. It should be difficult to inadvertently rotate an object when attempting to move it. It should be easy to select and manipulate the desired object without interference from neighboring objects.

With respect to the conceptual issues it makes sense to insulate the user from some of the finer details of mechanism design. Other tools in the software already do this; the gear editor determines many of the important parameters transparently to the user for example. As previously mentioned, the sizes, features, and numbers of the support elements for components are very important, but asking the user to worry about these additional pieces would likely confound the design process by doubling or tripling the number of pieces the user would be responsible for creating correctly. MachineShop will add file specific data for default support elements when the user saves a component to the library or makes a fabrication file. Some components (cranks or pawls for example) will not have their own support pieces but will rely on other components' pieces for support.

Other issues can and will be addressed in the mechanism assembly tool interface shown in Figure 5.11. The window is divided into four panels, one more than in the component editors but with a similar logical grouping. While the implementation has only just begun, the following describes the intended functionality. The upper left panel contains a two-dimensional orthographic view of the mechanism in its current state. The user selects the view she wants from the six possible views (front, back, top, bottom, right, or left) using the pull down menu at the top of the panel. This panel is where the work of arranging and aligning the pieces of the mechanism is done using the mouse to select and move them. By providing a single view of the mechanism the user is not given the task of integrating multiple views [30]. Further, by restricting all of the ma-

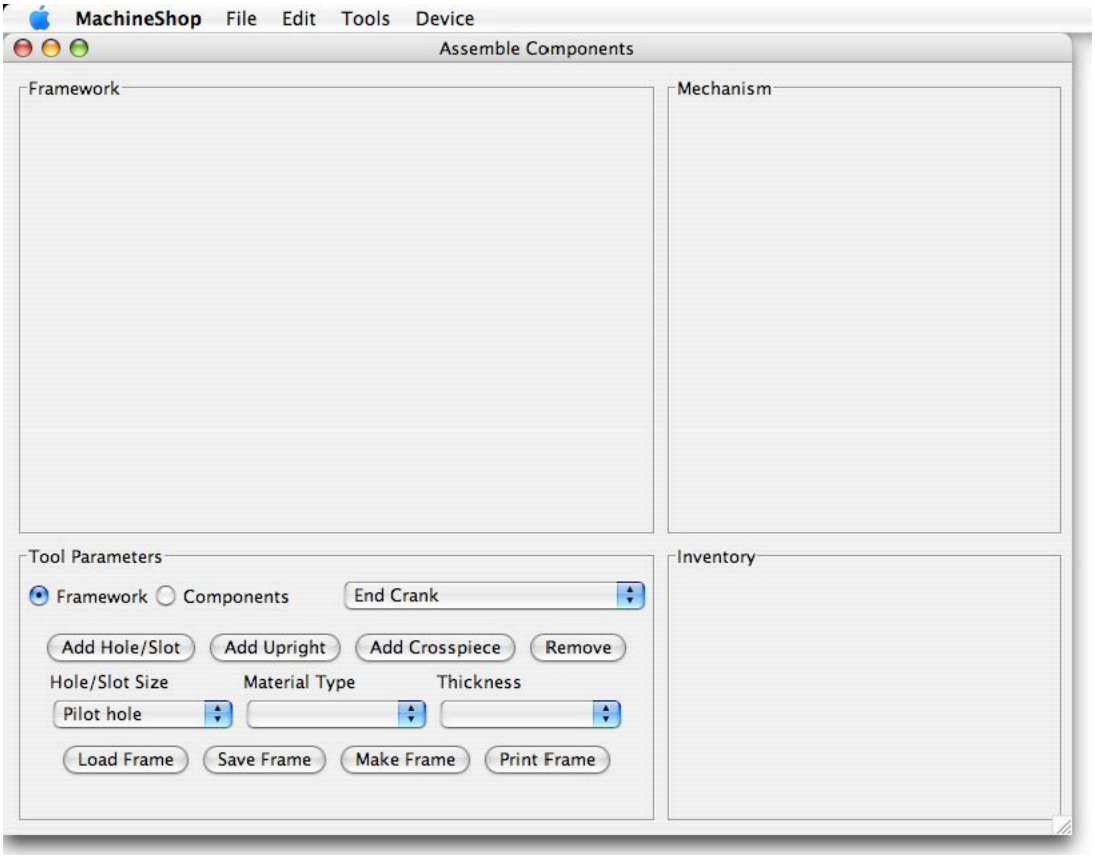


Figure 5.11: The mechanism assembly tool presents the user with controls to work with both components and structural elements of the mechanism (lower left), a user selectable view from any of the orthographic projections for the mechanism where components and structural elements can be placed with the mouse (upper left), an oblique (3-D) view of the mechanism (upper right), and an inventory of components for the mechanism (lower right). This figure shows the current, incomplete state of the tool with provisions made for adding the necessary functionality.

nipulation of the mechanism to a two-dimensional view, any ambiguity as to direction or distance is significantly reduced [36]. The upper right panel contains a three-dimensional oblique view of the mechanism as it is currently configured. Changes made in the two-dimensional view will be reflected here as they are made. The initial implementation of this panel will not provide the ability to animate the mechanism as can be done with components in the editors (Section 5.1.3).

The lower left panel contains the controls that allow the user to choose which category of pieces to work with and to set or change the properties of those pieces. When the **Framework** button is selected, the user can choose between framework types for this mechanism. She can

also choose to add a new support element to the framework, remove an element selected in the upper view, or change the orientation of the selected element in the framework. She can select the material type and thickness for any element and she can set or change the size of any existing holes or slots or add new holes or slots to the selected element. When the **Components** button is selected, she has a similar set of controls for adding, deleting, and positioning components. By separating the tasks of working with the structural members from working with the components, the number of controls immediately available to the user is reduced and each task becomes more structured. The lower right hand panel contains an itemized listing of the components included in the mechanism and corresponds to the components that will be included in the mechanism file when the current assembly is saved to the library. Adding a component to this inventory puts its profile in a default location of the two-dimensional view, ready for placement. Selecting a component in the list allows it to be removed from the assembly or loaded into its editor for manipulation.

Choosing between the component and framework categories not only changes the set of controls that the user has access to, it also affects the two-dimensional mechanism display. Pieces which belong to the selected category are displayed as solid objects while pieces of the other category are shown as wire frame outlines to make it more obvious which task the user is engaged in. But even with these differentiations there are still dependencies between the components and the structure. For example, since components and their supports share shafts, moving a component in a direction perpendicular to the axis of its shaft will cause its supports to also move. Moving a component along its shaft will force any supports that it contacts to move as well.

Little is known about how a tool such as this will be used or what effect it will have on users' understanding of the domain or mechanical reasoning. Children designing automata with MachineShop seem to have fundamentally different needs than mechanical engineers designing water treatment plants with AutoCAD. It seems prudent, therefore, to simplify as much as is reasonable until data are available to guide further development. For this reason the three-dimensional view will not allow for the mechanism to be animated, movement and placement of mechanism pieces

will be constrained to a grid, and any necessary spatial relationships between components and supports will be enforced. Further testing will indicate the efficacy of these choices.

5.1.6 File Types

Among the early design constraints for the MachineShop software were two that dealt with what appropriate file types might best support the goals established for the system. First, the software should make the design of components as transparent as possible to the user. This meant that whatever file encoding method was used by the component editors and libraries, it had to be human readable so that users could not only make sense of a component's file by looking at it but that these files could be easily exchanged. Second, the software would use one or more machine tools (section 5.2.1) to fabricate the mechanical components that the users would design. This meant that the software needed to be able to convert the profiles and parameters for components into forms that these machines could use.

To address the first constraint it was decided that files for the editors and libraries needed to be in some text format, using words and numbers that would make sense to the users. Because the intended users were children, the initial desire was files that could be read almost like text. This proved impossible as the parsers and generators necessary were not easily implemented and would not scale well. Pursuing this path would have made adding new component types and extensions to the software that relied on reading these files a potentially arduous task. A compromise position was to store these files in Extensible Markup Language (XML) format [119]. XML has become a standard encoding format for many large software companies over the last few years and a wide variety of tools are available for reading and working with files in the XML format. While XML files are not prose, they can be encoded in text and the ability to create meaningful tags goes a long way toward simplifying the reading and understanding of these files. For each component type tags were created that represent each property that the editor uses to define the component. These tags are then assigned the values given those properties by the editor.

Dealing with computer controlled output devices was a trickier proposition. These ma-

chines vary widely in the file formats that they will accept and it was necessary to consider carefully the types of machine tools that might be available to the intended target audience (see Section 5.2 for a discussion of this point) and the corresponding file encodings that they would accept. Many of these devices expect input in some vector format so the software was designed in such a way that component profiles could be easily saved as vectors. The first device that MachineShop was used with was a carbon-dioxide (CO_2) laser cutter that took its input from files encoded in the Hewlett-Packard Graphics Language (HPGL). Developed by Hewlett-Packard as the printer control language for their family of pen plotters, vector based HPGL became the standard control language for most plotters made by all manufacturers. Many commercial CAD and graphics programs can both write and read HPGL making it an appropriate format for many different tools.

5.2 Output Devices

While the software is a major constituent of the MachineShop system, much of the system's ability to bring the complicated undertaking of automata design and construction within a child's capabilities lies in the ways in which it supports the fabrication of mechanical components after they have been designed. Throughout the history of automata, the tools used to make the pieces needed have been used by skilled practitioners. These skills were often the result of years spent learning the craft as an apprentice. Even when this knowledge was codified in books and schools were established to train workers in these areas, true mastery was still the result of years of practice. While MachineShop can support users as they learn to use hand and power tools during the fabrication of automata, one of its major strengths lies in its capacity to minimize the necessity of mastering tools and materials while still producing high quality automata. This is due in large part to the abundance of machine tools which can be controlled programatically by computers.

5.2.1 The Landscape of Computer Controlled Machine Tools

Controlling machinery programatically is nothing new. The Jacquard loom of the early nineteenth century [34] and the census tabulating machines developed by Herman Hollerith [3]

both used punch cards to control the operation of the machines. Punched paper tape was used in Alexander Bain's automatic telegraph (later perfected by Thomas Edison) [2] which in turn spawned the teletype. Computer Numeric Control (CNC) was developed at the MIT Servomechanisms Laboratory in the late 1940s [130] and also used paper tape to transfer programs to machine tools such as lathes and mills. The holes in the tape controlled the actions of servo-motors which in turn controlled all aspects of the machining from tool selection to material or tool speed to tool depth. This advance allowed repeatable fabrication of objects with more precision than was possible any other way. Adapting a machine to use CNC was costly however, and even after manufacturers began selling tools already equipped for CNC, these machines were found only in large production machine shops.

But the microcomputer revolution of the 1980s changed things. CNC machines no longer read paper tapes, but were controlled by a small computers reading files written in G-Code [73] from floppy diskettes. By the mid-1990s smaller lathes, mills, and other machines equipped to use CNC were becoming available to small shops and hobbyists. It was also around this time that a variety of new fabrication tools were developed. The following list, while not exhaustive, shows how computers have changed the face of manufacturing.

- Shaping tools. Lathes (which create cylindrical objects by cutting material from blocks of spinning metal) and mills (which can create objects of arbitrary shapes by applying spinning cutting tools to stationary material) were the earliest of the modern breed and, in most cases, continue to use programs written in G-Code just as they did half a century ago. Routers have joined these tools and are used for decorative embellishment of wooden products like furniture and for tasks such as prototyping printed circuit boards.

- Cutting tools. For decades, repetitive production cutting of plate steel had been accomplished by first creating a reduced scale pattern of the shape to be cut and then using a pantograph with an acetylene cutting torch attached to create the full size pieces. CNC

allowed this crude form of automation to be significantly refined, eliminating both the time consuming tasks of creating the pattern and the tedious hand control of the pantograph. While these are still in use in many places, plasma torches are replacing acetylene where metals other than steel need to be cut (plasma torches can cut stainless steel, aluminum, titanium, and other metals) and where the smoother cuts produced by the plasma torch significantly reduce cleanup of the cuts. New technologies have also been applied to automated cutting in tools like high pressure water jet cutters and a variety of laser cutters. These new tools further expand the range of materials that can be precisely and repeatedly cut to wood, plastics, stone, and many others. Even cutting with knives has been automated in tools such as sign cutters and inkjet printer/cutters.

- Rapid prototyping tools. This relatively recent class of machines differs radically from those previously described. Rapid prototyping machines (sometimes called 3D printers) create objects by building them up from base materials in powder, string, or liquid forms rather than removing or cutting material from existing stock. These machines either deposit the material in the desired areas one thin layer at a time (deposition printing) or use lasers to solidify liquid in a tank (stereolithography).

The availability of these types of tools has profound implications for designers of software like MachineShop. The place where we stand today is reminiscent of where software designers were two decades ago when color printers were first becoming available. Those printers were expensive and there were few ways in which people could obtain some advantage from their use. But astute software developers started writing applications that could use color printers in ways that users found desirable. As an increasing number of people started using these applications, the demand for access to color printers rose. As supply increased, prices dropped. More people now had access to color printers and more software was written to take advantage of them. This spiral continues to this day and it is often the case that the purchase of a new computer will include a free or very low-priced color printer.

This same process is occurring with respect to computer controlled machine tools. A variety of expensive tools are currently available but the number of people who have applications for these tools is still small. MachineShop and other programs that take advantage of these tools can provide increased demand for these tools. Economies of scale will reduce prices and manufacturers will be able to add features to these lower cost machines, increasing their desirability. This is not speculation; it has been happening over the last decade. A laser cutter that cost $10,000 US six years ago can now be replaced by one with twice the power and three times the features for that same $10,000. While stereolithography machines still command prices of $250,000 US (and more), deposition printer prices have dropped to the point that several manufacturers offer machines for less than $20,000 US. These machines are still expensive, but they are quickly coming into the price range where a high school could buy one for use in shop classes or a community center could buy one for use in its after-school programs. Even hobbyists can acquire these devices with some carbon-dioxide laser cutters selling for as little as $5,000 US.

From the beginning, a key design consideration for MachineShop was that it would leverage as many members of this growing family of output devices as made sense. While the only tools that it has used so far have been laser cutters, the components that it creates can be fabricated by most of the tools listed here. The necessary classes to convert the software's internal representations to appropriate fabrication file encodings would not be difficult to create.

5.2.2 The Kern Laser

The first machine to be used with the MachineShop software was purchased from Kern Electronics. This device (Figure 5.12) had been used as a research test bed by the company and we were able to obtain it used for $10,000 US.

Despite its low power (10 watts), this was a laser cutter of industrial design. The laser sat on heavy steel framework with the horizontal beam being directed downwards by a 45° mirror to be focused on the workpiece by a lens. A jet of air supplied by an external air compressor was directed down on the workpiece, collinear with the laser beam. The laser itself was cooled by



Figure 5.12: The initial installation of the Kern CO_2 laser cutter in the lab. The laser is the black box at the top with the control cables and chilled water hoses exiting on the right. The air compressor that supplies air to the beam is located on the shelf below the laser and the water chiller sits on the floor beneath the compressor. The optics are attached to the left end of the laser and focus the beam down on the workpiece sitting on top of the moving table. The exhaust hose to the blower can be seen attached to the left of the moving table. The lead screw which moves the table in the X-axis can be seen on the table base plate while the Y-axis screw is visible to the right of the material support box. Not seen here is the computer which controls the table and the laser.

recirculating water from an external chiller. The workpiece was placed on a 12" x 24" aluminum box with a honeycombed top and vent through which smoke and cutting debris were drawn by an external fan. The box itself was supported on a 24" x 48" steel plate and was moved under the laser beam by two servo motors turning lead screws, one in the X-axis and one in the Y-axis. The servo motors were controlled by an EISA card inside the dedicated computer that also controlled the power level of the laser.

The laser came with proprietary software to control all aspects of the cutting process. This software could read fabrication files written in HPGL (Section 5.1.6) and in many ways the process of cutting with this laser was similar to using a pen plotter driven by HPGL. For example, the cutting table moved in two orthogonal directions as does the pen holder on a plotter. The

software took this one step further and defined eight *pens*, each of which corresponded to a power setting for the laser and a speed for the movement of the table. Pen plotters typically have carousels that hold eight pens and from which the plotter can retrieve and replace them during plotting.

This implementation of HPGL made creating plot files in the software an easy task. The Java 2D libraries use vectors to display component profiles and provide methods to convert those profiles to lists of points. These lists are converted to HPGL commands to move and locate the laser beam. It was also possible to establish a table of pen settings (power and speed values) and map material types and thicknesses to pen numbers. With the Kern laser the software could create fabrication files that set all of the necessary parameters for cutting without operator intervention.

But the Kern laser had its shortcomings as well. It was time consuming to set up and difficult to keep aligned. The exhaust fan, air compressor, and water chiller combined to make it very noisy to operate. The laser itself was a low-power unit which sometimes required multiple cutting passes to completely cut through thicker or harder materials. And, being used, it could no longer operate at its original ten watts which further exacerbated the problem. Despite all this, the laser helped guide the development of the software and produced many parts before finally succumbing to age and use. The cost of replacing the failed laser tube was more than the original cost of the system, making it prudent to explore options which had become available since the initial purchase.

5.2.3 The VersaLaser

The second output device used with the MachineShop software was a VersaLaser, model VL-300, manufactured by Universal Laser Systems (Figure 5.13) and was purchased after the Kern laser had failed. This design is one of the first intended for desktop use, and is targeted at small companies who make plaques and trophies. The laser is a 30 watt CO_2 unit and, in addition to etching and cutting wood, plastic, paper, cardboard, cloth and leather, it can etch on cylindrical objects with a rotary workpiece holder. The cost of this machine was $16,000 US but it is far more

capable than the machine it replaced.



Figure 5.13: The VersaLaser installed in the lab. The laser tube is mounted to the rear of the cabinet seen here and is air cooled. The moving optics are located under the clear safety lid. The tank at the left contains compressed nitrogen that is used to clear the kerf and reduce instances of flaming when cutting wood. The exhaust fan remains from the Kern laser and exhausts smoke and fumes into the lab's ventilation system. The computer that controls the laser is seen at right. Compare this installation to that in Figure 5.12 to see the kinds of changes that have occurred in these devices in only a 5 year period.

The VersaLaser uses an air cooled laser tube that eliminates the need for chilled water while providing three times the output power of the Kern unit. The workpiece support, the optics, and the laser are all contained in a single unit which occupies only about half the footprint of the Kern laser. Compressed nitrogen is used to clear the kerf and reduce the chances of flaming which can happen when cutting very thick or hard materials that require high power settings and slow speeds. The smoke and fumes are exhausted into the lab's ventilator using the fan that we had previously acquired. The computer which controls the laser sits to its right on the same desk.

Programatically, there are some differences between the Kern laser and the VersaLaser. Because the intended audience of the VersaLaser is not necessarily technical, or one that has a

background in manufacturing, the VersaLaser uses a printer driver similar to what would be used by any other printer attached to the computer. Rather than using a dedicated software application to control the laser as the Kern laser did, this printer driver can present the VersaLaser to many programs just as if it were a laser or inkjet printer. This adds a step to the fabrication process by requiring that the fabrication files be imported into an application on the controlling computer that can read the HPGL files and interface with the driver for the VersaLaser. Fortunately, a number of applications can do this and the one we are currently using is CorelDraw. The VersaLaser was used exclusively during the user tests (Chapter 6).

5.3 Ancillary Materials

The MachineShop software and the VersaLaser were the primary system components used during the user tests. While the test users were working one-on-one with a researcher comfortable with making contemporary automata, not every user of MachineShop will have that help when first starting out. To help support users, the MachineShop system includes a number of supplementary materials that introduce new users to the domain, guide them as they create their own automata, and help them explore the domain in order to expand their understanding. None of the ideas presented here are necessarily new, but by constructing these materials around and with MachineShop they become part of a consistent whole and users are encouraged to move freely among all of the components of the system.

5.3.1 Example Automata and Mechanisms

Providing examples of automata and simple mechanisms is one way in which MachineShop allows users to learn about the mechanical principles found in contemporary automata. During the testing presented in Chapter 6, users had to a small number of automata that had been created by adult users of the software in its early forms. In addition, nearly a dozen simple mechanisms that had been created and video-taped for use as Quicktime movies in the movement explorer (Section 5.1.2) were on hand at every testing session. These examples were made from wood and

plastic to help users gain an understanding of how these materials affected the operation of the mechanisms and to provide some insight into how the choice of materials might affect a finished automaton. A few of these examples are shown in Figure 5.14.

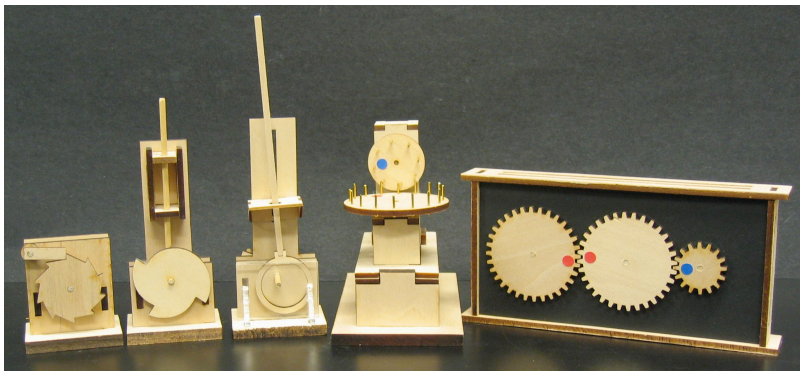


Figure 5.14: A selection from the simple movements used to explore motion during the user testing. From left to right: a ratchet and pawl, three-lobed snail cam, eccentric cam with ring follower used as a crank-slider, pinwheel gears with a 2:1 ratio, and a set of three spur gears with a 1:2 ratio.

These mechanisms proved invaluable when working through ideas with the test users. Many times a user would have an idea for an automaton and a sketchy notion of the desired behavior and motions but without a clear idea of how to make it happen. Very often, spending five or ten minutes examining and discussing the sample mechanisms either led to a possible approach for the desired automaton mechanism or led to a desirable change to the original idea.

5.3.2 Kits and Instructions

During the Spring 2004 semester, an undergraduate student became involved in this research with the goal of determining what would be needed to package an automaton into a kit that could be built by a novice system user before she set about designing her own automaton. To do this he took the fabrication files for the earliest of the automata built with an early MachineShop version and fabricated, assembled, and learned about the process with no input from any outside source. He created a set of instructions for assembling this automaton but because of time constraints was unable to present the kit and instructions to children for evaluation.

5.3.3 Videos

Seeing automata in motion reveals much more about them than seeing them at rest. Videos have been made not only of the simple mechanisms that are used in the movement explorer, but also of all of the automata that have been built with the system. While certainly inferior to having the chance to examine and manipulate automata personally, videos can supply many additional examples without the need to fabricate duplicates every time one is needed.

5.3.4 Posters

Posters of sample automata and mechanisms are simple to create but can be powerful learning tools. Because they can be annotated and important concepts or key points highlighted, they make an effective learning tool when displayed in the work area. They provide a resource to which a user can return as often as necessary to more fully understand concepts and ideas and they are valuable objects around which topics can be discussed. Because they are easy to create, users can refine their understanding by creating a poster for others to use.

5.4 Summary

The MachineShop system is composed of a computer-aided design and computer-aided manufacturing (CAD/CAM) application, a computer controlled device for fabricating components produced by the software, and a collection of educational materials to support children as they learn about making mechanisms for contemporary automata. The software supports four key tasks in the design process. First, it allows users to define the motions they wish an automaton to have and enables them to search for mechanical components that will supply those motions. Second, it allows users to create instances of those components specifically tailored for their needs and to create files from which those components can be fabricated. Third, it will allow users to assemble components into virtual mechanisms to insure that once fabricated a mechanism will perform as intended. Finally, it allows users to save components and mechanisms to libraries, to browse

the libraries and reuse components or mechanisms, and to share those saved components and mechanisms with other users. Many of these capabilities can be found in systems designed for adults, but MachineShop is unique in making them available to children.

The MachineShop system can make use of a number of computer controlled output devices to fabricate components created with the software. By automating the fabrication of mechanism pieces, MachineShop helps young users over the twin hurdles of tool use and properties of materials; neither of which most children are adept at or knowledgeable about. Having access to machines of this type allows children to design far in excess of what they are capable of fabricating. The landscape of these kinds of tools is continuing to grow and the software is capable of creating files for many different devices, not just the laser cutters that were used during this research.

The MachineShop system uses a variety of materials and examples to assist users as they learn about creating automata. These materials come in a number of forms; example automata and mechanisms, posters describing mechanisms and movement, kits that can be assembled into working automata, even videos that show and explain concepts and techniques. The combination of all of these elements into the MachineShop system is intended to help users succeed and have fun while becoming a more accomplished builders. Chapter 6 examines the how successful this process has been for the users who tested the system.

Chapter 6

Experiment and Assessment

The preceding chapters have served to situate and describe a program that endeavors to answer the research question posed in Chapter 1: *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?*

Chapter 2 reviewed the literature that focuses on mechanical reasoning and spatial cognition and found many examples where machines were used to study these abilities, but few instances where the study of machines was being used explicitly to affect changes in mechanical reasoning. This information was used to devise an approach for constructing reasoning through the design and creation of small machines. Chapter 3 examined a variety of tools that could be used to create machines in both virtual and physical environments and looked for attributes that could facilitate the design and construction of small machines for novices. All of the tools reviewed suffered from one or more flaws that limited their usefulness for children learning to create small machines. These flaws were addressed in the design requirements for the MachineShop system to help ensure that it would provide the support that users would need. Chapter 4 presented mechanical automata as an appropriate and interesting domain in which to create machines. In particular, the characteristics that define contemporary automata were examined and shown to be salient for novice machine designers and builders. Chapter 5 described the software and hardware components of the MachineShop system that resulted from the analysis of the material from the chapters that preceded it.

This chapter describes the experimental protocol devised to evaluate the use of the MachineShop system as it applies to the thesis question. It begins by examining the experimental method with a focus on the intended user population, the form of the user testing, and the plan for assessment. It continues with an exploration of the results obtained from the testing and concludes with a discussion of the methods and results and considers to what extent it is possible to answer the thesis question.

6.1 The Experimental Method

From its earliest incarnation, this research was intended to introduce children to the work practices and techniques of adult designers and engineers. It remains a firmly held belief that by presenting children with an authentic look at professional practice they will gain a clearer understanding of what it means to pursue that profession as a vocational objective. This objective constrained many choices for the design of the experimental method, from the domain to the users and from the tools to the process.

6.1.1 The Users

MachineShop was originally conceived as a tool for children as young as eight years old, but as the realities of creating a system like this became apparent, this was shifted upward somewhat, resulting in a target group aged eleven to thirteen years. It was further assumed that children using this tool (both during the testing and at other times) would not be familiar with contemporary automata or any other mechanical contrivances of this general type. Beginning MachineShop users were expected to have some experience building objects (with construction kits being the most likely method) but were not expected to be familiar with the tools or materials they would use in the construction of automata.

6.1.1.1 Recruiting Users

The users who participated in this research were recruited from two pools. The first consisted of the children of faculty and graduate students in the Department of Computer Science at the University of Colorado at Boulder. From an initial group of five interested children, three participated in the testing. A middle school science teacher in Boulder provided suggestions for students that formed the second pool. Five children expressed an interest and three of these participated in the testing. One user was a member of both groups. All users were self-selected and participated with the encouragement and cooperation of their parents.

6.1.1.2 User Demographics

The users for this study were two girls and four boys aged 10 years and 6 months to 12 years and 1 month at the beginning of their involvement with the testing. This placed them in the lower half of the anticipated age range and in some cases below the lower bound initially intended. All of the children attended public schools in Boulder; two were fifth-grade students at an elementary school and four were sixth-grade students at a middle school. In addition to their schoolwork and participation in this study, all were engaged in extra-curricular activities including sports, music, theatre, academic clubs and groups, and organized non-competitive games. Table 6.1 provides some information about the users and their participation for comparison.

User	Age	Grade	Participation	Automata Built
Dylan	10 years, 6 months	6	37 weeks	2
Calum	11 years, 8 months	6	21 weeks	1
Sam	11 years, 5 months	6	25 weeks	2
Frank	12 years, 1 month	6	20 weeks	1
Abbie	10 years, 10 months	5	16 weeks	1
Iris	10 years, 11 months	5	13 weeks	1

Table 6.1: A summary of information about the test users in the study. Users are listed in the order in which they started participating and their ages at that time are also shown. Pseudonyms are used here and in Chapter 7.

6.1.1.3 Prior Experience

All of the users did have prior experience with designing and building physical objects. This most often involved the use of construction kit toys of the type discussed in Section 3.3. While Kinex and Zometool [134] were prominent in this collection, all users had the largest part of their experience using products from the LEGO Group, including building moving constructions from Technic components and making robots using Mindstorms kits. In many cases the activities engaged in by the users with construction kits were social activities in which friends, siblings, and often parents participated. Two of the users had also built plastic model kits (airplanes and cars) while one had worked with her father in constructing a wooden whirligig for their garden. Another user had built a railroad locomotive model from found materials of wood, plastic, and metal. None of the users were initially familiar with mechanical automata of any form or with any related devices other than music boxes.

The tools most familiar to the users included screwdrivers, pliers, hammers and paintbrushes. Their use of drills, knives, and saws was more limited and almost universally undertaken while being supervised by an adult. The use of power tools other than electric drills was almost nonexistent. Users also had varying levels of experience using adhesives and paint. None of the users possessed the range of skills and knowledge necessary to undertake the construction of an automaton and that provided a useful baseline for evaluating the results of the tests.

6.1.2 The Experimental Procedure

Two potential approaches to the user testing were considered. Devising an educational curriculum around the design and construction of automata has a certain pedagogical charm and is the method by which thousands of children (see Section 2.3.3) are introduced to these types of machines. But it also poses significant difficulties for research designed to fit within the scope of a dissertation. First is the problem of creating an epistemologically sound program that can be used effectively with entire classrooms of children over extended sequences of short class peri-

ods. Second is finding one or more classroom teachers who are willing to expend the additional resources necessary over a full school year (the length of the longest cases reported here) to assist in making such a program work, particularly in light of recent trends toward assessment based public education [21, 124][1] . Third is the need to recruit additional researchers to interact with and assist students over the course of the testing. Fourth is the massive task of relaying the observations of a group of researchers to the primary investigator and making sense of it all. For these reasons this approach was set aside.

The use of case studies was the other approach considered. It promised a more tractable method with a higher probability that the primary (and in this case sole) investigator would not overlook important occurrences during, or results from, the user sessions. It would support an opportunity for the interaction between the test users and the investigator to be more like an apprenticeship than might be the case in other approaches. This was desirable because it allowed the test users a great deal of freedom in the manner in which they approached the work and encouraged them to learn from their choices and actions while still maintaining the presence of a collaborator who could provide appropriate levels of assistance when necessary. It additionally offered a more relaxed environment in which to work without the distractions created by two dozen children engaged simultaneously in a potentially chaotic activity. Case studies also have their shortcomings, most notably the small quantitative data sets they can provide which makes it difficult to extrapolate results to larger populations. Still, it offers an approach both practical and time honored [126] and, because it has proven successful in similar research efforts (see [32] for one example) it became the chosen method.

6.1.2.1 The Design Process

The work that I envisioned the children doing was derived from my experiences working in engineering organizations and was intended to distill the essence of engineering process into

[1] Many innovative teachers are finding it increasingly difficult to convince administrators to accept novel curricula with no proven track record. This is particularly true where schools and districts receive financial inducements to perform well on the standardized assessments.

a form that children could adopt. In an ideal (for both the business and their customers) world, the procedures used to create a new product would approximately be:

(1) Determine a need. Profit is the motivating factor in product design for a company and often a tremendous amount of effort is expended in doing the research necessary to evaluate the money making potential of a new product before any further steps are taken.

(2) Devise and evaluate solutions. Once a need has been identified as a potential source of revenue, ideas are floated for possible solutions. These are evaluated and modified until one is determined to be best from a number of standpoints; satisfying the need, profit potential, support of core business goals, and many others.

(3) Propose and evaluate designs based on chosen solution. Designs for products that best embody the solution are proposed. Competing designs are compared and evaluated and the best features from each are combined, if possible, into a final design.

(4) Iteratively prototype and refine the chosen design. A prototype based on the final design is created and evaluated. Flaws in performance and difficulties in manufacturing are identified and corrected over a series of successive prototypes.

(5) Document the final design. Documentation is created that describes how the product is to be manufactured, how it is to be used, what its operational aesthetic characteristics are, how much it will cost to produce and procure, and so forth.

(6) Produce the product. At this point raw materials are collected, tooling is produced, staff or subcontractors are employed, and warehousing and distribution arrangements are made.

(7) Market the new product. Advertisements are created and placed with media organizations that have the broadest contact with the intended user population. Orders arrive,

providing the business with capital to begin the process over again for a new product.

These steps are very coarse-grained and do not reflect most of the tasks necessary to make them happen. It is also clear that several of these steps have no direct connection to the engineering portions of the process. By culling those that do and adapting them to the creation of contemporary automata, the procedures derived for the children in these trials took on the following form:

(1) Envision an automaton that you would like to build. It should be inspired by something personal: an event, interest, question, statement, or idea that has meaning for you. Think about the story you would like to tell and how your automaton would tell that story. Determine what figures, props, and settings would be needed to tell your story.

(2) Decide what actions and behaviors your automaton may need to tell the story you have chosen. Don't worry about how these actions and behaviors will be implemented, but instead work at refining what you want your automaton to do.

(3) Determine ways in which the mechanism for your automaton can provide the actions and behaviors you've decided to use. Don't settle for the first idea you conceive but explore alternatives. Some of them may be even better at doing what you want.

(4) Make a prototype of your design from materials that are easy to work with. Don't worry if the prototype doesn't work like you want the finished automaton to. Its purpose is to help you learn about your design and how it can be made better. Once you understand where your design still needs work, come up with fixes and make them part of a new prototype.

(5) When you are sure that your design tells the story you want and works the way it should, make the pieces that you will need for the finished automaton and put it together. Decorate and embellish it as you see fit.

(6) Enjoy the results of your hard work. Think about what you would like to build next.

This process clearly owes its form to the commercial process, but is motivated by the child's desire to create an object that has personal significance rather than a profit. While there was some variation from user to user, these steps were followed consistently with support being provided to the users in the smallest amounts necessary and only when essential to allow users to successfully complete each step. Since users worked one-on-one with the researcher, it was possible to tailor this level of scaffolding to the requirements of each user. Some tasks, such as sketching and iterative prototyping, had been identified early on as important components of the scaffolding that would move from being initiated by the researcher during early phases in the testing to becoming integral and natural components of the task as work progressed.

Testing began by introducing each user to the domain of contemporary automata. This was accomplished by showing them photographs and videos of professionally created examples, giving them access to educational materials such as posters and books, and by providing them with the chance to play with a small number of example automata that I had previously created using early versions of the MachineShop system. The user and the researcher spent some time talking about the various features of all the examples, emphasizing the stories that they told and the behaviors they exhibited while limiting the discussion of how the actions and behaviors were obtained. At the end of this first session, the users were asked to return for the next session with, at a minimum, an idea for and a sketch of the automaton that each wanted to create.

The requested sketch served three important functions. First, it provided the researcher with some understanding of what the user hoped to accomplish with respect to style and scope and provided a first instance of what was hoped to be a series of drawings that would document the design process. Second, it provided insight into the user's comfort level with the task. This was gauged by the level of detail included and whether the user had provided any hints at a possible mechanism. This latter seemed plausible in light of each user's exposure to the example automata in the introductory session given the ways in which the combination of figures and mechanism

serve to define the behavior of an automaton. Third, asking the user to create a drawing at the very beginning of the testing helped integrate sketching into the entire process in a natural way. The role of drawings in these tests will be discussed further in Section 6.1.3.

The users were also sent home with a set of four pre-test problems[2] in order to get a sense of their initial mechanical reasoning ability. Each problem consisted of a drawing depicting the input and output elements of a mechanism with its workings not shown and were based on simple examples presented by Cox [23]. The input and output motions were described and the users were asked to add mechanical components to the drawing that they believed could account for the stated operation of the mechanism. Since the purpose of these exercises was to get a feel for the users' abilities to reason mechanically, no strict time limit was imposed, although parents were asked to see that no more than five minutes was spent on each one.

The next few sessions were spent moving from the initial automaton concept to a first candidate design. During these sessions the users were introduced to the MachineShop software and were given opportunities to revisit any of the introductory examples and materials that they wished. At this time they were also provided access to a number of simple mechanisms created with MachineShop but decoupled from automata (see Section 5.3.1) to assist with their assimilation of the behaviors provided by basic mechanical components. Decisions were made at this stage regarding the size of the automaton, the nature of the figures and setting, and defining a more precise specification for the behavior. It was also at this time that the design of the mechanism was explored, conceived, and refined. Sketches and crude approximations of the necessary pieces were made to give the users a better understanding of their designs and the ways in which the designs were changing.

When a design was considered to have met the design specifications, the MachineShop software was used to create the necessary mechanical components and produce fabrication files for the laser cutter (see Section 5.2.3). Designs for the figures were scanned and converted by the

[2] One user did not receive the pre-test as he had begun testing in the pilot phase, before the pre- and post-test materials had been completed. He did, however, complete the post-test problems.

researcher into fabrication files at this time. The laser cutter was used to produce initial pieces in cheap, readily available materials like corrugated cardboard that were then used to test for fit and function. These pieces were also used to determine the structure needed for the supporting framework for the mechanism and preliminary fabrication files for the structural supports were also created and mockups of these pieces cut. The assembling of these pieces provided insight into flaws in the design or behavioral concept and these were addressed by modifications to the design and the construction of another prototype. Users were constantly revisiting the example materials and using the software to make changes to their mechanism components.

When the design had progressed to the limit of the capabilities of the cardboard prototypes, components for a final assembly were fabricated. In some cases, this assembly helped identify problems which could not have been discovered with the previous prototypes (see Section 6.2) and further iterations were made. The creation of the final parts signaled entry into the final phase of the process. Assembling the components into an automaton was a task that was important not to rush. Users who had shown great patience during the prototyping were now anxious to see how closely their design lived up to their expectations. The researcher paid particular effort to ensuring that users developed good techniques for preparing components for assembly as well as for fitting and gluing, especially with regard to allowing glued components sufficient time for the bond to cure. In all cases, as components were cleaned[3] they were test fit. This provided assurance that the automaton would fit and function as desired as well as giving the users multiple chances to learn the proper orientation of components and to determine a satisfactory sequence for assembly before anything was permanently attached. After the automaton was assembled, it was tested for function. In some cases minor adjustments were required to provide smooth operation. At this point, some users chose to paint and decorate their automata, while others chose to leave the materials in their natural states.

[3] The laser cutter creates components by vaporizing material to create the kerf. When this is done to materials like cardboard or wood it leaves a charred surface on the component which, if not cleaned, can leave a residue in the mechanism as it is removed through the normal operation of the mechanism. Steel wool has been found to quickly remove this loose material without changing the profile of pieces which can easily happen when an abrasive such as sandpaper is used.

6.1.2.2 The User Testing

Users were asked to come to the laboratory once a week for sessions which lasted from 60 to 90 minutes. The longest participation by a user was for a period of 37 weeks during which two automata were constructed. The shortest participation was for 13 weeks during which a single automaton was constructed. With respect to the construction of a single automaton, the maximum time spent was 21 weeks, the minimum was 12 weeks, and the median time to create an automaton was 16.5 weeks (see Table 6.1). There were two primary factors that account for this rather wide range. The first was the complexity of the automaton, with two of the three most complex taking the longest times and the two simplest taking the shortest times. Interestingly, one of the most complicated automata was also among those taking the shortest times (see Section 7.2 for more detail). The second was the speed with which a user gained knowledge of the domain and the design process. This was reflected both in attention to detail and in the creation of designs that challenged their abilities. Rather than speeding up as skill increased, users tended to slow down. This is discussed further in Section 6.2.

6.1.3 Assessment

The assessment goals were twofold. First and foremost was the goal of answering the thesis question; to see if using the MachineShop system to create contemporary automata had an effect on the spatial cognition and mechanical reasoning abilities of the test users. Second, and no less important, was the goal of understanding how children approached the design process and to what extent their skills in this area improved. While these goals both evaluate highly correlated features of the user tests (one might even argue that they are merely different perspectives on the same feature), breaking them apart in this manner allows us to talk about aspects of the activity that are separate from its cognitive effects.

As previously mentioned, these tests were not conducted with large groups of subjects so no effort was made to provide statistical analysis of the results. Further, there was no attempt to

compare the efficacy of competing approaches for acquisition and enhancement of mechanical thinking. Assessment of the users' performance was based instead on a number of qualitative measures suggested by the mechanical reasoning literature and described in Section 2.5. Because each user was interacting one-on-one with the researcher, it was possible to augment these metrics with observations made during test sessions. For example, there were occasions when a sudden insight was reflected in a facial expression or hand gesture or in sudden changes of mood or attitude. While not scientific criteria, these were nevertheless important pieces of the assessment puzzle and were significant harbingers of change.

6.2 Results

The results seen during the user testing follow closely from both the complexity of the automata created and from the length of participation in the tests. This is not surprising, as one would expect users to become more skilled and proficient with prolonged involvement. But this is a great oversimplification as the results showed far more in the way of differences than can be attributed solely to these measures. Although the number of users was small, the changes that were seen varied from negligible to striking. This section examines the changes that were observed in the users over the course of the testing with particular emphasis on noteworthy results. The interested reader will find more details in Appendix A.

6.2.1 Talking About Automata

None of the users had any exposure to mechanisms before starting these tests and knew little of the terminology of the domain beyond lever (from their introduction to simple machines in science class) and gear (from the incorrect name given the sprockets of a bicycle). Throughout the tests the researcher was careful to use the terminology that users were hoped to acquire and encouraged users to do the same. Initially, all of the users tried to apply the few terms they knew in as many situations as possible. This resulted in followers being called levers and cams being called gears (among others) for several weeks. Two users showed little progress in this ability

over the course of the experiments and at the conclusion of testing were still using more generic terms (“cam” rather than ”eccentric cam”) even though the automata they were building used only eccentric cams and this was the term used exclusively by the researcher. The majority of users were able to pick up the descriptive terminology after several weeks and were using secondary terms (lobe, follower, tooth) correctly by the end of the testing. One user assimilated quite a large domain vocabulary in a very short period time about 12 weeks into his first automaton (this is discussed more in Section 7.1).

The ability to describe the workings of components and mechanisms using domain appropriate terms was a more challenging task for all users. Users who had shown improvement in their abilities to use appropriate descriptive terms with components were unable to consistently apply that skill when discussing components in assemblies and they often reverted to terms like “bump” and “stick” instead of “lobe” and “follower” which were terms they readily used when talking about the components in isolation. Even when describing the transmission of motion from component to component within a mechanism, users chose more general terms rather than domain terms that they knew. This was a surprising result. I had originally suspected that the use of descriptive terminology for components and more technical language to explain the function of mechanisms would change more or less concurrently, but in these tests the use of functional terminology trailed the use of descriptive terminology by a significant amount.

6.2.2 Using External Representations

The use of external representations during the design process took three forms. First were the example automata and simple movements (Section 5.3.1). These featured most prominently during the early sessions when users were first exploring their designs. In the beginning all users just played with these, but the majority quickly moved beyond simple play to an exploration of the features of the mechanisms and the motions that they provide. Most users returned to the simple movements over the course of the testing even after work was well under way on what would become the final designs. These objects supported the generation of new ideas for the design,

were useful in acquiring domain knowledge, and were used as shared objects for the exchange of ideas between users and the researcher.

Next were the prototype objects. Somewhat interestingly, these objects were not initially given as much interest as the sample materials, possibly because their appearance was somewhat rough and they were not as robust. This tended to change over time however, and users began spending more time with, and effort on, their prototypes. Expectations had been that beyond being useful for evaluating fit and function in the evolving design, users would find that prototypes spurred new ideas and the acquisition of domain knowledge. This result was not seen to any substantial extent.

Finally were the drawings and sketches. Throughout the testing the researcher created, and encouraged users to create, drawings. These were used to codify ideas and stimulate new ones, record pertinent design details, and provide a visual journal of the evolution of the design. It had been expected that the users would create many sketches during the testing but none were spontaneously created. Only at the urging of or questioning by the researcher did users draw sketches. This was somewhat puzzling, and putting the question to the users revealed no good explanations for their reluctance. Perhaps the best explanation is that design process was an unfamiliar one and that, with more experience, they would understand the importance of drawing to design. As was shown in Section 2.5.2, drawings are very powerful forms of external representations and are capable of conveying large amounts of relevant information in simple forms. Goel [44] has shown how ill-structured representations in preliminary designs support the transformations necessary for design evolution. Suwa [75] suggests ways that hidden features in sketches can be discovered and used to advance the design. Clearly, this is a disappointing outcome and one that deserves to be investigated further.

6.2.3 Components, Motion, and Complexity

While described individually in Section 2.5, the abilities of mapping structure to motion, discrimination and integration, and dealing with complexity are intertwined in practice. This was

obvious during the user testing when observed changes in one ability were reflected in similar changes in the others. By the end of the tests, all users could look at a drawing or photograph of a simple mechanism and describe the motion that would be produced. This was true even for users who showed little change on other metrics. When asked, users most often remarked that "playing" with the simple movements had helped them to better understand how the shapes of components and the ways in which they were connected to other components determined the behavior that would be seen.

But as mechanisms became more complex, the ability to discriminate became a limiting factor on the ability to map structure to motion. This was particularly true when the unknown mechanisms contained components that differed in significant ways from those with which the users were familiar. As an example, a poster from Cabaret Mechanical Theatre hangs on the wall of our laboratory near the laser cutter. It shows an automaton of two swimming fish with a mechanism composed of familiar components (levers), unfamiliar components (cams with unusual profiles), and familiar components used in unfamiliar ways (pinwheel gears that mesh with a rack). All of the users could identify the levers and gears, and most were able to identify the cams as cams. Two were able to fully describe the motion of the automaton by the end of the testing period. This is a wholly remarkable result given that the behavior of this automaton has puzzled many of the adults who have spent time with it.

Even less change was observed with respect to the users' abilities to integrate components into new mechanisms. The results of the post-tests showed uniformly that when given a mechanism design task with constraints the users preferred the components with which they were most comfortable, even if they were not good choices. It was often the case that if the chosen component was a poor pick, the user would attempt to modify it in some way in an effort to make it work better. This was observed with all users to some extent although there were variation across test problems for each user. It is noteworthy that there was little difference in the quality of the solutions between the pre- to post-tests although there were pronounced changes in the styles of the solutions.

Results were more promising for the users who created a second automaton. Although only two users are in this category, both of the later designs were more ambitious and complex than their first ones. In both cases they chose to work with components they had not previously used and to combine them into assemblies that they had not seen in any of the examples. In one of the cases, the user came to the researcher with a fully formed design for the mechanism and was able to produce a drawing of it for the researcher when asked.

6.2.4 Confidence Levels

With the exceptions of the users who showed the least change in all measures, there was a significant increase in the confidence of the users with respect to their abilities for creating automata. This was apparent in a number of ways: increasing enthusiasm, transfer of tasks from researcher to user[4] , content and intensity of conversations, and less fear of failure. This latter was particularly evident in users who were not only willing, but anxious to experiment with new ideas and concepts. Each of the two users who built a second automaton exhibited an increase in confidence (as well as in domain knowledge) with the more ambitious nature of the second design. While each was a more complicated design than the first, a similar amount of time was spent in developing both designs and in each case prototyping for the second design started earlier in design process than it had for the first design. As all users became more confident they began to ask questions that indicated they had developed understandings of the domain and the process that were more than superficial. In general, it seemed that the more confident users got more from the testing and had a better time as well.

6.2.5 MachineShop System Usage

As with most other tasks during the testing, the use of the MachineShop software varied over a considerable range. Two users spent only enough time with it to create the fabrication files

[4] As users gained confidence they spontaneously took over tasks from the researcher. These included using calipers and tape measures to determine size and distance, performing calculations about the physical and functional properties of their automata, and setup and operation of the laser cutter under the supervision of the researcher

they needed for their simple mechanisms. One user spent a considerable amount of time with the software, not only designing the components he needed, but also exploring most of the software components and by the end of the testing had become almost as familiar with its use as I am. The remaining users' time with the software was between these extremes. While none of the users found the software difficult to use, comfort with both the interface and operation of the software increased as more time was spent interacting with it.

Watching users interact with the MachineShop software provided valuable information about the design of each tool and their integration into the larger whole. The balance of this section presents a number of key observations made relating to the ways in which the users employed the software in the making of their automata and what these mean for the current form of the software. Remarks about each tool are presented in the order that the tools are described in Section 5.1.

The movement explorer (Section 5.1.2) received very little use, seldom more than one or two quick visits. In the context of the user testing this is not unexpected. All of the mechanisms available to users in the movement explorer were available to the test users in physical form since the simple movements present during testing were also used to create entries for the movement explorer. The simple movements were, however, used extensively both to shape the designs the users created and as aids in exploring and understanding the domain. Too little attention was paid to this tool to truly gauge either its usefulness or accessibility to users.

The component editors (Section 5.1.3) were far and away the most used tools during the testing. This was due mostly to the fact that, with the design computer and laser cutter being located in the same room, users could receive rapid feedback on their designs in the form of physical objects. With respect to the relationships between the software tools and the automata created by the system, that of the editors is unique. These are the tools that ultimately define, shape, and produce the finished products. For the users in these tests, who are just on the cusp of the period of formal operations [45], the opportunity to work with physical artifacts is still a very powerful knowledge building activity and the most intellectually productive sessions

observed were when users were creating, examining, and manipulating components they had just designed. Users seemed to particularly appreciate the ability to view changes to component profiles in the editors in realtime, and it was not unusual to find users spending up to ten minutes creating and modifying components in the editors.

The libraries (Section 5.1.4) were not used at all during the testing. Several factors seem to be at work here. First, most users knew that they would only be creating a single automaton and that provided no incentive to save components for reuse or later modification. Components were saved only as fabrication files, and if there was a need for modification, users found it easy enough to create new components from scratch. Second, users were not working on their own computers, but rather on a shared computer in the lab. To most users this meant that they would not have access to the files after the testing period so creating those files offered no benefits. Third, there was no sense of community. While all users were aware that there were other participants, and in some cases knew who those others were, the constraints of the testing were such that users were discouraged from talking to and working with others. Saving files was seen as a first step in sharing designs, an activity that was proscribed in the testing.

6.3 Discussion

Beyond illuminating the changes in the spatial cognition and mechanical reasoning abilities of the users, this set of tests was a rich source of information about children and construction.

The users came to the testing with little experience with the type of work they would be doing and with many naïve assumptions about the process. Commonly, users expected to design and construct an automaton in just a few weeks but most realized this error early on and came to understand that by requiring more effort, the process would be more rewarding. During this perceptual shift, users started to understand that there were a variety of materials available to support their efforts. While all users had been introduced to these materials at the beginning of the testing, users did not seek them out until they were needed. It had been assumed that introducing users to resources and examples in both the lab and on the World Wide Web would

stimulate an interest in the domain but in practice it was the need to progress beyond plateaus in the design process that stimulated that interest. When presented with the opportunity to use either a virtual resource (on the web or in the MachineShop software) or a physical resource, users overwhelmingly chose to pick up and manipulate the objects. A majority of sessions contained one or more uses of these resources, even after designs were completed and construction was underway, indicating that there was more to this activity than the simple acquisition of information necessary for the task at hand.

Most users showed similar behavior towards the creation of prototypes and spent more time evaluating and modifying them than might have been required. More than any other, this step in the design process was essential to the successful completion of the automaton and the user's satisfaction with it. Prototyping allowed users to work through difficult design problems, notably in the lion (Section B.3), the commuters (Section B.2), and the evil cat (Section B.5). While formal prototyping was a new task to users[5] most discovered its utility.

In these tests, prototypes were created in corrugated cardboard whenever possible. Cardboard is readily available and often can be acquired for free in the form of discarded packaging from businesses. These boxes are often large enough to duplicate the maximum material size that the laser cutter can accommodate (12 by 24 inches for the machine in our lab) and most desired material thicknesses can be obtained by laminating. Pairing highly available materials with the rapid fabrication capabilities of the laser cutter makes the prototyping step even more powerful. Without this ability it would be necessary to assess design changes through calculation or speculation before creating a modified prototype. With this ability, the quality of a modification can be assessed directly, further speeding the process. During the testing this allowed users to make incremental changes without regard to the number of component or support structure modifications that were required. The laser cutter[6] offered the further advantage of using the same

[5] All of the children had created prototypes in their previous activities but were unaware of it. In particular, all had used LEGOs to design and build and, when asked, admitted that this activity involved making an object and modifying it several (sometimes many) times before considering it finished. The design of LEGO components offers the affordance to build in this manner and none of the users saw the parallels across domains.

[6] The laser cutter is a fascinating device to almost everyone who sees it. The users were no different, and their

fabrication files for both prototype and final components, needing only changes in speed and power settings to work with different materials.

The creation of cardboard prototypes was not without its limitations. Problems most often arose because of the differences in structural properties between the materials used for the automata (most often wood and plastic in these examples) and cardboard. The wood and plastic employed were far more rigid for a given thickness than cardboard. This was especially evident in larger pieces, particularly structural supports. In the prototypes it was necessary to use gussets and stiffening ribs to eliminate unwanted movement of these parts and mechanical components such as pinwheel gears could not be made functional. Wood and plastic components are heavier than their cardboard counterparts. This makes mechanical components like cam followers and pawls that depend on the force of gravity for operation less likely to function consistently when made from cardboard. Wood and plastic components have different textures than cardboard which also affect the operating characteristics of the mechanism. This is particularly conspicuous when the cut edge of a cardboard component exposes its corrugations. These corrugations leave the edge surface uneven with respect to strength, stiffness, regularity of the surface. This in turn makes it difficult to ascertain how motion will be transferred between components that contact one another along their edges. When these conditions made it impossible to proceed further with refinement of the design it became necessary to start creating prototype components in the final materials, although in all automata if this was needed it was very close to the completion of prototyping.

Another interesting observation from the testing was the difficulty that the users had in thinking about size in the context of their automata. In nearly half of the cases, there were significant differences between the initial stated size and the size of the completed automata. In some cases, the initial size chosen by the user was half that of the finished automaton. This problem manifested itself in two ways. The first was a problem of scale. Ten and eleven year old children

captivation never ended. Some learned to configure the machine for cutting (always done with supervision from the researcher) although the constraints of the testing prevented them from learning everything necessary to fully utilize it.

(and many adults it should be added) have great difficulty in estimating size either accurately or consistently. This led to problems when the initial placement of components in a mechanism prevented them from aligning properly with other components or with their connection points on the moving parts of the figures. The second difficulty came when users were forced to identify the source of mechanism malfunctions. These were most often due to misalignments or improperly supported components. For example, shafts in gear trains must be properly spaced (or the gears will not mesh correctly) and they must be supported so that they run true without wobble or excessive endplay.

Finally, it should be noted that the choice to work with children aged 10 to 12 years was particularly fortunate. Besides being at an interesting point in their cognitive development, children of this age are also at an interesting point in their social development. The mentoring provided to these users required less instruction than might have been the case with younger children and in a significant number of instances the sessions felt very much like collaboration between peers.

6.4 Summary

The MachineShop system was tested in an experimental setting where the users interacted with the researcher in a manner similar to the apprentice model of skilled crafts and trades. Six users, 2 girls and 4 boys, aged 10 and 11 years participated in these tests and a total of 8 automata were produced (see Appendix B) over periods of from 13 to 37 weeks. Each user designed at least one automaton and refined that design by iterating over a series of prototypes made primarily from inexpensive materials. Mechanical components were created using the MachineShop software and a computer controlled, carbon dioxide laser cutter was used to fabricate most of the pieces required for construction. Users completed their automata by assembling the parts they had designed and fabricated and, in three instances, by painting and decorating.

Most users showed increases in their mechanical reasoning and spatial cognition abilities, as well as their domain knowledge and their skill in creating automata. There was a marked

improvement in the confidence of most users with respect to their abilities in design and construction as well. The results presented here will be illustrated in Chapter 7 where the work of one user is described in more detail.

Chapter 7

A Case Study in MachineShop

This chapter provides a brief account of one user's experiences building automata with MachineShop. Its purpose is to convey some sense of what the sessions were like, how the users interacted with the researcher, and give some insight into how user attitudes and abilities changed over the study. Sam[1] was 11 years and 5 months old and a sixth grader at a local middle school when he began working on his first automaton. Over the next 25 weeks, working one and sometimes two 60 minute sessions per week, Sam designed and built two automata. Sam's is an interesting case for two reasons. First, he showed the greatest change in all of the measures of any of the users. Initially, his understanding of mechanical principles and his apparent interest in participating in the testing were both poor but, about half way through, something clicked for him and in the remaining sessions he was knowledgeable and involved. Second, the two automata he built show a clear trajectory of increasing ability and provide a compelling argument for the capacity of children of his age to become skilled automatists given appropriate environments.

Sam's first session began with a tour of the lab and a discussion of what he would be asked to do during the testing as well as the overall goal of the testing. He was then introduced to the domain of contemporary automata by showing him pictures of automata from Cabaret Mechanical Theatre and allowing him to play with three automata created by researchers in our lab with earlier versions of MachineShop[2] . He was given a short demonstration of the MachineShop software and

[1] Pseudonyms are used here and in Chapter 6.

[2] The automata that children had a chance to interact with were a flying bison, a swimming sea serpent, and a circus sea lion. Both the bison and sea lion served as archetypes for at least one automaton created by the users.

shown how the laser cutter operated. He was given the four pre-test problems to take home and was asked to come back the following week with at least one idea for his automaton and a drawing to help convey his ideas to the researcher.

7.1 The Soccer Player

On his return the following week, Sam brought the drawing shown in Figure 7.1. He had come up with the idea of a soccer player scoring a goal while at soccer practice and after some discussion he and the researcher decided that this would be a good project. The first item that needed to be resolved was the size of the automaton. Sam thought that he wanted the player to be about twelve inches from the goal and about four inches tall. Some rough approximations of the figure were cut from cardboard and a first layout using Sam's dimension was created. Sam felt that this put the player too far from the goal and with the options of shortening that distance or making the player larger, Sam opted for the latter and the player gained two inches in height. Sam and the researcher spent some time creating a new player from cardboard. A cardboard playing surface was also made which was large enough to locate the player and goal the way Sam wanted.

7.1.1 Designing the Soccer Player

Over the next several weeks Sam worked to design a mechanism. Sam's goal was a mechanism that would carry the ball quickly to the goal and return it slowly to the player's foot for another shot. The simple movements were examined extensively and the ones that showed some promise were discussed. At the researcher's request, Sam created his first design for a mechanism (Figure 7.2) based on a set of three pinwheel gears with the ball attached to the driven gear.

A lengthy dialogue ensued about this particular mechanism. It took Sam quite a long time to see three major flaws in this design. First, there is no way for the mechanism to move the player's foot. Second, the smaller horizontal gear is not needed and cannot mesh with the larger horizontal gear in the configuration shown. Third, attaching the ball to the gear as it is drawn will cause the ball to travel in a circle between the player and the goal, not from the player to the

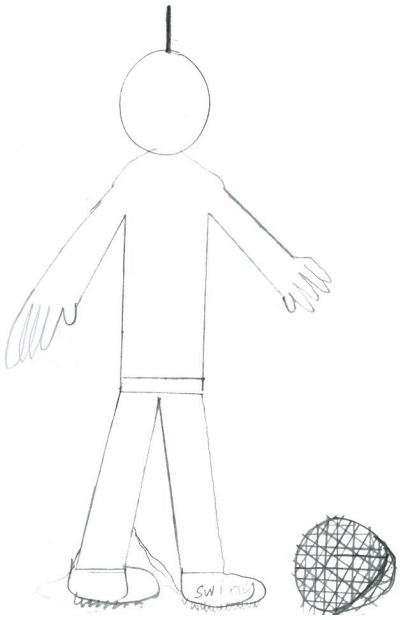


Figure 7.1: Sam's first conceptual drawing for the soccer player. Note the detail in the ball and cleats, but lack of any features in the face. Also note the only indications that this is not a static object: the word "swing" on the foot and what appears to be some means of connecting the heel to the mechanism. Although Sam couldn't remember, the line at the top of the head may have been an early attempt at a means for supporting the figure.

goal and back. Once these issues were identified, Sam and the researcher began to discuss the movement that Sam wanted and to look at the simple movements once again. This discussion would identify some desired behavior in the automata and then attempt to find a movement that would produce that or a similar behavior. Sometimes one of the simple movements would suggest a possible alternative behavior and those would be analyzed. For example, attaching the ball to a crank-slider mechanism (see Section B.3 for an explanation of this mechanism) would move it in a realistic arc to the goal, but would have moved it in an unrealistic arc below the "playing field" of the automaton on its return to the player's foot. Additionally, there was no way that the crank-slider would provide the change in speed (move quickly to the goal, slowly return to the player) that Sam wanted.

The difficulty lay in Sam's inability to think about alternative ways of getting the ball to

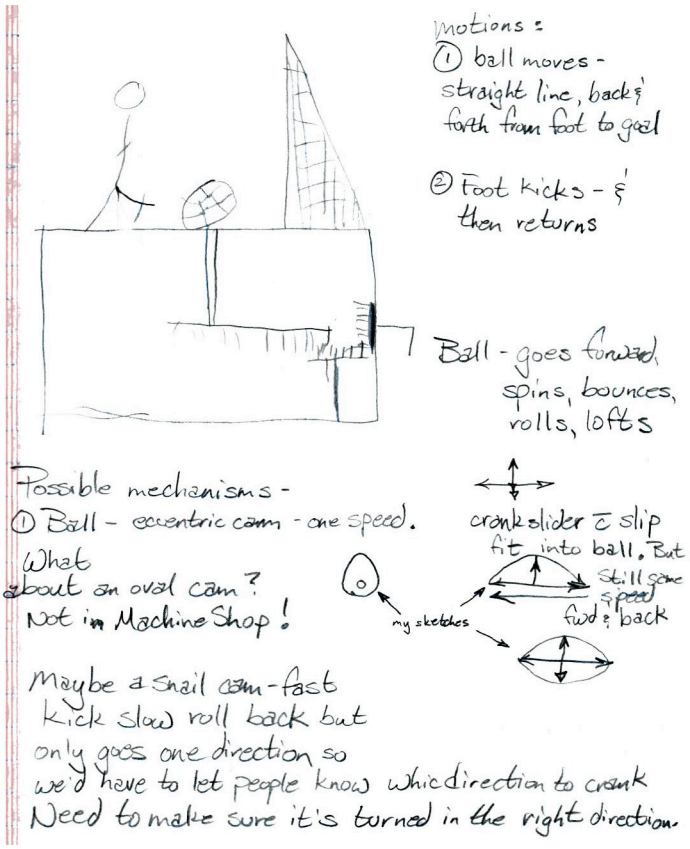


Figure 7.2: Sam's initial sketch for how the soccer player mechanism might be constructed (upper left). Based on his exposure to the simple example mechanisms, he has chosen a mechanism composed of pinwheel gears. This arrangement of gears contains unnecessary pieces and cannot provide the motion he desires. The annotations on the drawing were made by the researcher during the discussions he and Sam were having. These notes are a combination of comments on the desired motion and ideas for possible mechanisms that they were brainstorming.

move as he wanted without it being attached to the mechanism.[3] To break the impasse, the researcher asked Sam to consider what might happen if, rather than having the ball attached to the mechanism, the impact of the player's foot provided the motive power to get the ball to the net. Sam concluded that, if this were possible, that the ball would travel to the net quickly (he tested this by snapping the ball with his finger) but figuring out a way to get the ball to return to be kicked again posed a challenge. As this problem was being discussed, Sam hit upon the idea of elevating one end of the surface on which the ball would roll so that the goal was higher

[3] None of the users initially found considering alternatives easy. The ability to step back from a design and look at the behavior afresh only came with experience.

than the player's foot, allowing gravity to roll the ball back. He became quite excited about this prospect and a rectangular piece of cardboard the size he wanted for the automaton's top was cut to facilitate some testing of this new plan. It was readily apparent to Sam that this would allow the ball to return slowly to the player as he wanted but that some method of constraining the path of the ball would be necessary. His first thought was to install a pair of rails, one on each side of the foot that tapered out to the width of the goal at the other end.

It was now necessary to find a way that the player's foot could be moved so that it could kick the ball the full length of the automaton (12 inches) and into the goal. Sam was asked again about the motion of the ball and if there were any of the simple mechanisms that might provide that motion. Sam selected a pair of the snail cam mechanisms (the one-lobe and two-lobe variations) and thought that either might work. For simplicity he chose to work with the one-lobed cam and thought that by attaching a rubber band to the heel and hooking it over the lobe the rubber band would be stretched as the cam rotated (pulling the foot to the rear) and then quickly released when the rubber band slipped off of the lobe (Figure 7.3(a)). There were problems however:

> Sam: The rubber band is about right there *[indicating the heel of the kicking foot]*... and it goes down to the snail... cam and is attached right there *[indicating the lobe on the cam]*. But then, I just thought of something.
>
> Researcher: Okay.
>
> Sam: When it comes off, how will it attach back on? For it to snap back?
>
> Researcher: So you were thinking of putting the rubber band over the lobe on the cam kind of like a rubber band shooter.
>
> Sam: Yeah.
>
> Researcher: Okay.
>
> Sam: But then I didn't know how to get it back on unless it, like, umm.
>
> Researcher: So, why are we using the rubber band? Tell me again.
>
> Sam: Because it needs to snap to kick it in.
>
> Researcher: Okay. So we're going to use the force of the rubber band to bring the leg forward?
>
> Sam: Yeah.
>
> Researcher: Alright. So if that's the case, does the rubber band really have to attach to the cam?

Sam: Umm, *[very long pause while he rotates his hand back and forth rapidly]* maybe. It might. There might be ways to have it with and without.

Researcher: So let's talk about another way. How could we move the foot with the snail cam without attaching the rubber band to it?

Sam: Umm, maybe... have... I'm not really sure.

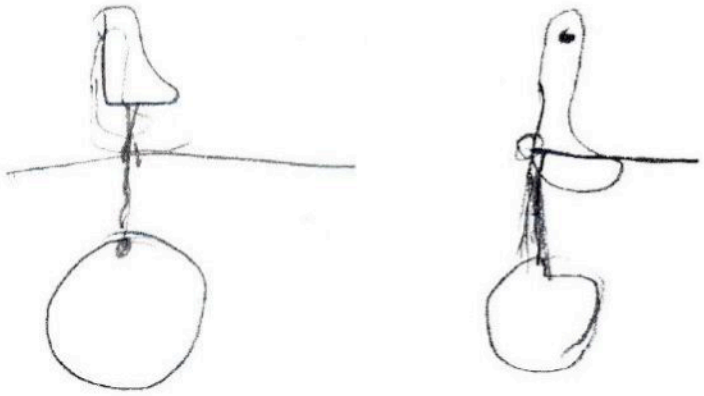


Figure 7.3: Sam's first drawings of the player's leg and the cam. (a): The foot is attached to the cam by a rubber band which is expected to snap the foot forward when it slips off the lobe. (b): The modified mechanism now shows the foot attached to the cam follower by one rubber band and being pulled forward by another. Attaching the follower to the foot will prevent the follower from remaining in contact with the cam. The other rubber band will keep the ball from contacting the foot. Note how the level of component detail is increasing as the design matures.

Researcher: *[The researcher takes the one-lobed snail cam from the box of mechanisms and gives it to Sam.]* So there's the snail cam. *[Sam cranks it several times]*

Sam: Um, maybe have a stick *[indicating the follower]* that attaches to the rubber band. So when it snapped down... it would *[cranking it again]*... when it... when... um... down maybe it would... then when it was going up it would make it go forward. Maybe?

Researcher: Okay. So the direction in the case where the follower is going up slowly... what direction is the leg going to be moving?

Sam: Umm, it would be... back. *[Which is the direction of slowest movement of the foot]*

Researcher: Okay. And then when we get to the point where the follower drops, that's where the leg's going to come forward?

Sam: Yeah.

While it was obvious that Sam understood the kind of motion the cam provided, and he could see that the motion mapped to what he wanted the foot and leg to do, he had no clear idea about how to combine the cam and follower, lever (the leg), and the rubber band that he needed to power the leg. He next talked about attaching the rubber band to the follower (Figure 7.3(b)), a move that would not provide forward motion to the foot. At that point, the researcher drew two arrows on the sketch pad, one indicating the vertical motion of the cam follower and the other indicating the horizontal motion of the foot and sketched a foot next to them (Figure 7.4(a)):

> Researcher: *[Pointing to the drawing]* In this case, this is the follower going up, and this is the follower going down. *[The researcher picks up the mechanism and Sam takes the paper they've been drawing on.]*
>
> Sam: So, like maybe um, when it was going up it would like hit, it would hit the foot make it go back. And then when it dropped it would unattach it, but then when it swung back, um, it would be going back up.
>
> Researcher: If we're going to use the follower, do we need to push on the rubber band or can we actually push on the leg or the foot?
>
> Sam: Umm, we can push on the leg.
>
> Researcher: So if we were going to do that, where would we push on the leg?
>
> Sam: Umm, in the heel. *[The researcher rotates the mechanism ninety degrees so that the follower is now horizontal.]*
>
> Researcher: We want to push it back and then when we come around here *[indicating the sharp drop of the lobe]* this would come forward.
>
> Sam: Yeah.
>
> Researcher: And we'd use the rubber band for that?
>
> Sam: Yeah.

Pushing back on the leg was not a practical solution since that would place the cam both above the top of the kicking surface and in front of the leg. Sam took the snail cam mechanism, oriented it vertically and tried to find a way to have the follower press vertically on the heel and move the heel back horizontally. He appeared to have little understanding of why what he was

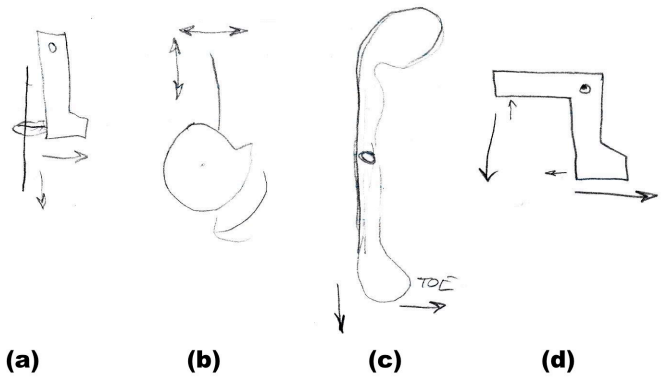


Figure 7.4: Refining the soccer player's leg. (a): Sam attaches the cam follower to the heel with a rubber band. (b): A sketch to show the cam and follower in relation to the motions that they need to produce. (c): Sam draws the leg as a lever of the first order. (d): The two lever solution (see text) is modified by rotating the upper part of the lever 90 degrees. This is the form that was used in the automaton.

trying to do would not work but he seemed to feel that he was on the right track (which he was) and that if he just thought about this (incorrect) combination of components that he would find a way to make them do what he wanted. The researcher asked how they could get the leg to move back by pushing straight up on it. Sam replied that the follower could be attached at the heel. The researcher pointed out that the follower will only move straight up and down, not backward and forward and Sam spent some time thinking about this.

The researcher asked Sam what type of component the leg was and after some thought Sam replied that it was a lever. The researcher removed the follower from the mechanism and replaced it with a lever. Sam turned the crank and saw that if one end of the lever moved along the profile of the cam, the other end of the lever moved like the foot needed to. This observation was tempered by the fact that any simple application of this method would again place the cam above the kicking surface. The researcher asked Sam to draw a cam and follower in the orientation Sam wanted them (Figure 7.4(b)) and then to draw the leg as a lever of the first order (Figure 7.4(c)). The researcher again added the directional arrows to the cam and follower drawing and asked Sam how the horizontal motion could be derived from the vertical motion. After making a number of unworkable suggestions, Sam decided that attaching a second lever at right angles to the leg would

work. The researcher asked if the assembly needed to be cross shaped and Sam soon worked out that by rotating the upper half of the leg 90 degrees an "L" shaped leg would function in the same way (Figure 7.4(d)).

The final requirement for the design was to allow the ball sufficient time to return to the foot after it was kicked. Sam had by now spent enough time with the simple mechanisms to know that he could do that by using gears. By letting the ball roll down the cardboard surface and pretending to crank at the same time he decided on a ratio of 3 to 1. Now that Sam and the researcher had the dimensions for the automaton and a workable first design for the mechanism they began creating the first prototype.

7.1.2 Prototyping the Soccer Player

The mechanism for the soccer player was relatively simple, consisting of a one-lobed snail cam with follower and a 2 spur gears with a 3 to 1 ratio. The structure to support the mechanism was a simple stretched cube with one end slightly higher than the other to facilitate the ball rolling back to the player's foot. Prototyping proceeded fairly quickly. First, Sam and the researcher cut a piece of corrugated cardboard to the the size needed for the kicking surface (this would also become the top of the support structure) and the preliminary locations for the goal and player were determined and marked.

Next, a simple structure to support the mechanism and kicking surface was built from more cardboard (Figure 7.5). One end was made taller than the other so that it could be gradually trimmed to the correct height that would make the ball return to the player's foot at the desired speed. A base was cut that was shorter than the kicking surface and two braces were placed on the sides, spanning the distance between the ends. These braces not only kept the end pieces upright, they also provided the bearing surfaces for the shafts used by the mechanical components. The support structure was assembled with tape to allow it to be easily modified. At this time two wedge shaped guide rails were also cut. These would insure that the ball returned to the proper location in front of the foot for kicking. The top was placed on the support structure and Sam

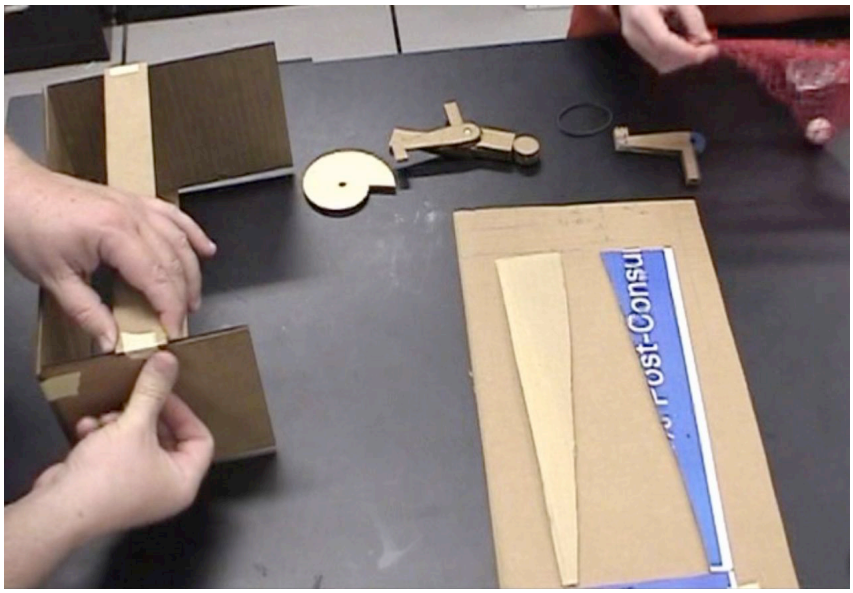


Figure 7.5: Rectangles and strips of corrugated cardboard were cut to approximate the look of the support structure of the finished automaton. These pieces were assembled using masking tape so that changes could be made easily. Notice the cardboard player figure and spare leg alongside the prototype snail cam. Sam is holding the net bag that had contained onions his mother had purchased and that would become the net for the goal.

proceeded to determine what height was needed for the taller end. Since there was no specified amount of time for the ball to return from the goal, Sam would let the ball roll from the goal area to the other end three or four times and decided if the ball seemed to roll too fast for him. If it did, the top was removed and one-quarter of an inch of cardboard was cut from the longer end. This process was repeated until Sam was happy with the speed of the ball (Figure 7.6).

At this time the spur gear train that Sam had designed with the MachineShop software was fabricated from basswood and test fit with the previously fabricated snail cam. These components were made from wood initially because of the difficulties inherent in assessing the functional qualities of cardboard mechanical components. Sam spent some time playing with the gears and cam to get a feel for how they would work together as well as their orientation and location within the support structure (Figure 7.7).

The mechanism was installed in the support structure and checked for proper location,

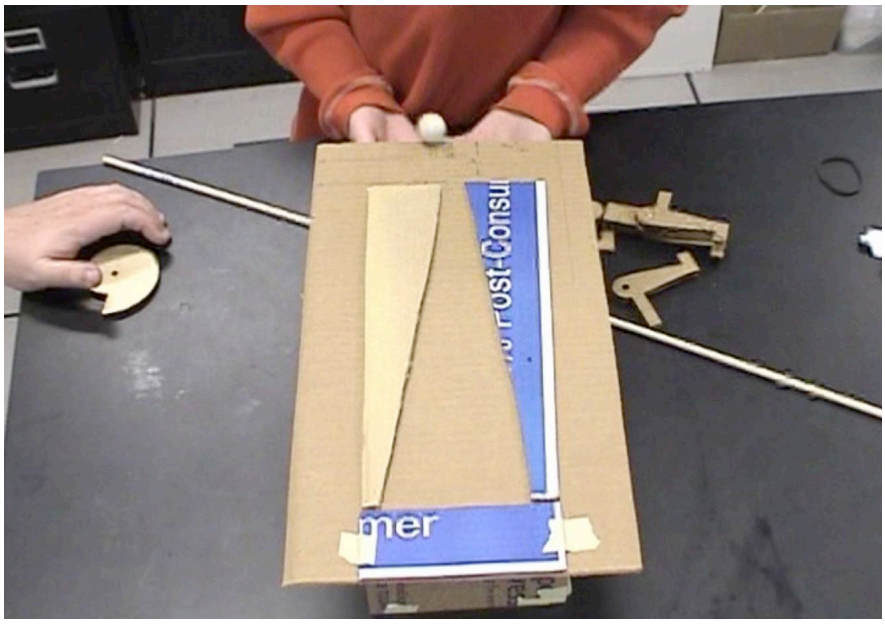


Figure 7.6: Sam tests the speed of the returning ball. If the speed was determined to be too great, a small amount of material was removed from the top of the tall end piece. This continued until he was satisfied with the performance.

alignment, and function. Once this had been done, the kicking surface was installed and secured to the supports with tape. The final location of the player was determined so that the cam follower would be properly located on the leg. Sam took a few minutes to see if the amount of motion that would be supplied by the follower would be adequate to get the ball from the foot to the goal and was somewhat confident that it would (Figure 7.8). At this point, prototyping was nearing an end and it was expected that the fabrication of the final components would commence with the next session.

7.1.3 The Soccer Player as Science Project

Sam returned the following week with an announcement; he would need to complete the automaton in three weeks for use at his school's science fair. This was a worrisome proposition for the researcher. First, a number of mechanical issues dealing with the action of the leg had not been resolved with the cardboard prototypes and he suspected that at least the first wooden

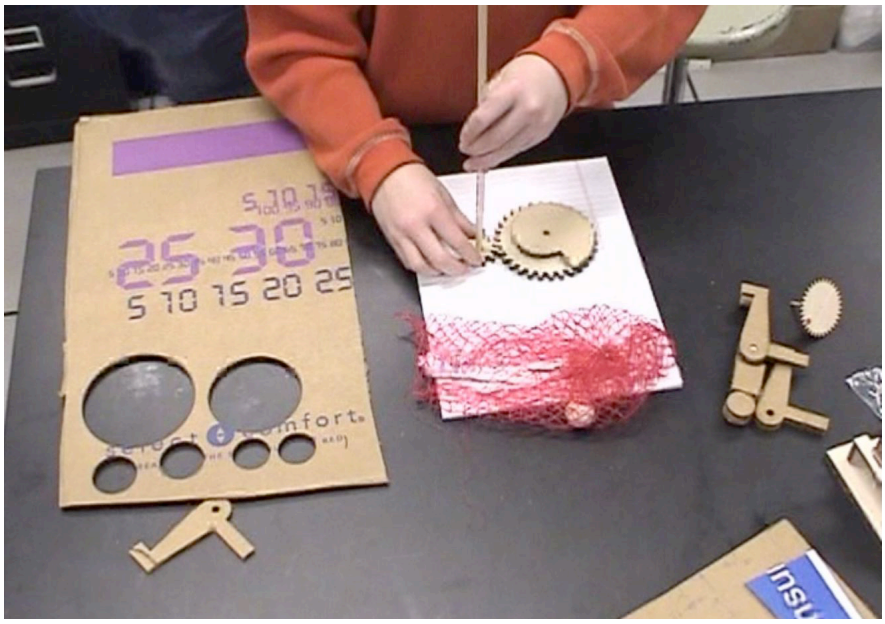


Figure 7.7: Sam tests the operation of the spur gear train and checks to see that there will be no interference when the cam is attached. The smaller gear in Sam's right hand supplies the input motion to the mechanism. Being smaller than the driven gear it will be necessary to turn it three full revolutions to get a single revolution from the larger gear. This was Sam's solution for allowing the ball sufficient time to return from the net before the player kicked again.

version of the automaton would need moderate to substantial changes in order to function correctly. Second, while Sam's domain knowledge and his mechanical reasoning had shown some improvement since the beginning of the project, his general attitude during sessions had been a passive one and to see his automaton completed in such a short period of time would require that he take a much more active role.

The researcher then received a second surprise as Sam proceeded to use the MachineShop software to give his mother an overview of the mechanical components that he intended to highlight on the poster that would accompany the soccer player. His explanations were technically correct and his use of vocabulary was better than had been seen or expected. It now appeared that Sam had acquired more knowledge and skill from working on his automaton than was obvious from his detached interactions with the researcher.

Even though time was short, this session was devoted to creating components and images

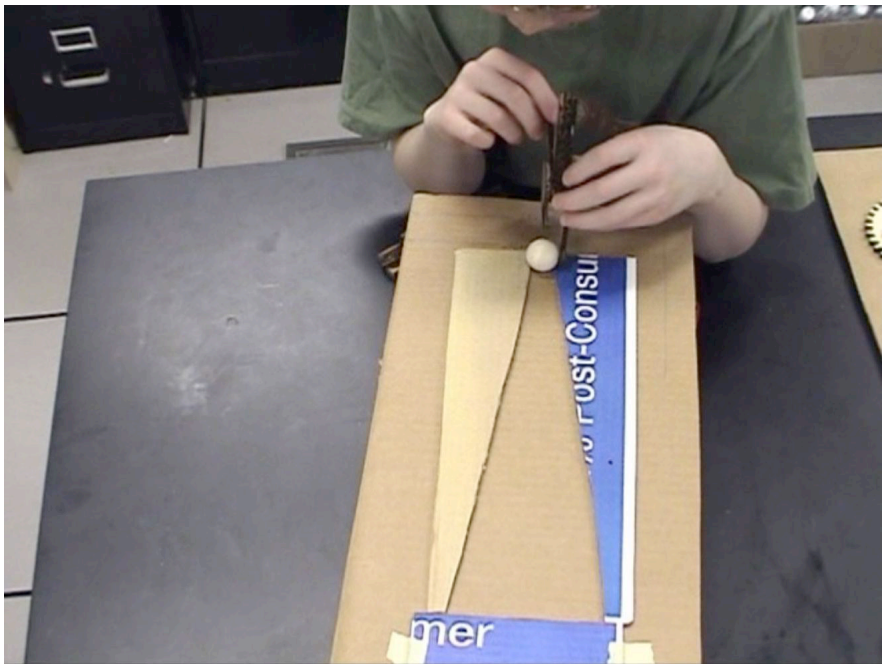


Figure 7.8: Sam works to determine if the amount of motion that the cam will supply to the leg is sufficient to propel the ball into the goal.

for Sam to use on his poster. While doing that, he and the researcher talked about the components he was designing and it was obvious that his thinking processes about the components had changed significantly over six weeks. He made one lever and saved its profile as an image file. He would use this same image on his poster to illustrate the three orders of levers:

> Researcher: So a first order lever is like what in the real world?
>
> Sam: A teeter totter. *[He selects the second order lever in MachineShop.]*
>
> Researcher: This is the second order lever and it's like? *[He thinks.]* Look at the interesting thing about this. In the first order lever which direction were you applying the force? Up or down?
>
> Sam: You're pushing down.
>
> Researcher: ... you're applying the force down in the first order, and the effort you're getting out is going in the opposite direction. But now in a second order...
>
> Sam: You're pulling oh, like a wheelbarrow.
>
> Researcher: Exactly. Because you're pulling up the effort is also coming up because the fulcrum is out at the other end.

Sam: And this one *[indicating the third order lever]* is kind of a hard one.

Researcher: The third order is a little harder. Which way are the force and the effort going?

Sam: With this one the force, they're both going up.

Researcher: Well they both go in the same direction, so they don't necessarily both have to go up. *[He thinks.]* You just reverse the positions of the effort and the force *[from those in the second order]*.

Sam: So that might be like... I can't really think of anything.

Researcher: Well, I can think of a couple. Have you ever seen pictures of a castle and the main gate where you go through across the moat? What is it they always pull up last to keep the bad guys out?

Sam: Um, the... Oh, the, the drawbridge!

Researcher: Think about the drawbridge. Let's go back to the third order lever there. So here's the big hinge... *[Pointing to the fulcrum]*

Sam: Oh yeah...

Researcher: back at the castle...

Sam: Oh yeah...

Researcher: and here's where they hook the chains *[pointing to where the force is applied]* and here's the end of the drawbridge. *[Pointing to where the effort is returned.]*

Sam: Oh yeah. Oh yeah!

Researcher: Another thing where you've seen this is probably in a fishing pole. Where your left hand *[Sam is right handed]* is the fulcrum, your right hand is where you're applying the effort, and the tip of the pole is moving back and forth.

Sam: But a lot more.

Researcher: You'll see that here *[pointing to the computer screen schematic of the lever]*. The distance that travels... It's the same thing with the drawbridge. By putting the chains in the middle the chains only have to come up half as much as the end of the drawbridge.

Sam: To save chains.

Researcher: And to also make it go what?

Sam: Faster!

It was obvious that Sam was still acquiring and assimilating knowledge about the domain, but this change was unexpected. During the creation of the materials for his poster, he was quite

animated and it appeared that all he needed was some purpose for what he had been doing. The next two sessions were very busy. As suspected, there were a number of issues that had not been apparent with the cardboard prototypes (alignment and support for the cam follower for instance) and wooden pieces were designed, fabricated, tried, and modified when needed. At the end of the last session before the science fair, Sam's automaton was little more than a pile of parts which he took home to assemble with the help of his mother and father.

The week after the science fair, Sam returned with the completed soccer player (Figure 7.9) and the poster he had created (Figure B.22). He and his parents had finished the soccer player the night before it was due and had done a good job. There were still a few small issues that affected its performance, most notably that the rails for the ball return did not constrain the position of the ball in front of the foot well enough, so Sam and the researcher set about correcting those problems. Sam was quite pleased with the project and progress on the repairs sometimes had to wait until either he or the researcher had stopped watching it in action. Sam left the automaton in the lab since the next session would be his opportunity to talk about the soccer player and his experiences in its construction.

7.2 The Carousel

At the end of the soccer player interview, Sam told the researcher that he would like to make another automaton. He said that it would help him to better understand what doesn't work (his mechanical thinking now included that knowing what won't work is sometimes more important than knowing what will), that it would help him be more proud of himself (his confidence in his abilities was increasing), and that he wanted to prove that his success with the soccer player was more than beginner's luck. He also wanted to make a smaller automaton so that it would be easier to transport. He told the researcher that he had an idea for the next one:

> Sam: A carousel.
> Researcher: A carousel. Okay. Why a carousel?

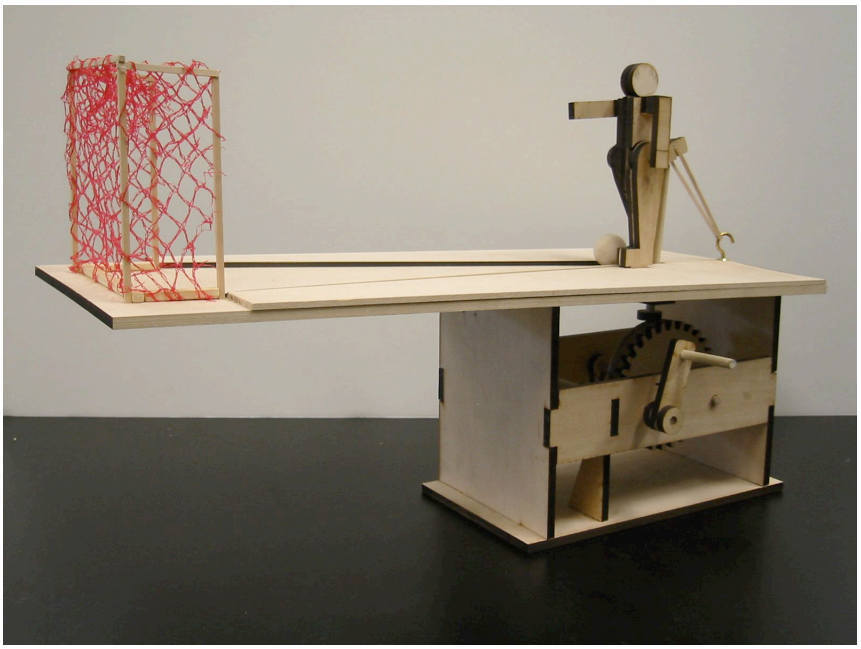


Figure 7.9: Sam's first automaton. This was the largest of all the automata built by users and was the only one to use either snail cams or spur gears. The netting, ball, and leg return mechanism were materials either found or purchased; something that all users were encouraged to do. Sam said that he was afraid that by the time the science fair was over the automaton might be broken since viewers couldn't resist playing with it.

Sam: Just because nothing would be loose like this one *[meaning the ball]* so it's a change. And the only thing that I would be using that's the same is the dowel and the crank. And I wanted something circular *[draws a circle in the air parallel to the table]*.

Researcher: So we're talking a carousel like at an amusement park or a circus. With animals on it?

Sam: Yeah. Four *[he marks out their locations with his finger]*.

Researcher: Are they going to be stationary or are they going to move up and down?

Sam: Two of them are going to move up and down and two of them will move side to side. And I've figured out how.

Researcher: You have? That's excellent!

. . .

Researcher: So, four animals, something about four by five or five by six. Now you're talking that the structure for the mechanism is that size?

Sam: No, the carousel itself is that size.

Researcher: So the carousel will be pretty small.

Sam: You know how at the top of the carousel it has that tent like thing? It's going to have to hold a tiny bit of the mechanism which will make them move up and down. Because it would interfere with the other dowel to make it turn.

Researcher: Do you know how carousel animals go up and down on real carousels?

Sam: Doesn't it twist? Or does it...I'm not sure because all I've seen is the outside.

Researcher: But you've ridden them. Have you ever looked up to see where the rods go?

Sam: No, not really.

Researcher: Well, I'm not going to tell you what it is right now. I'm going to let you think about it.

Sam: *[Grins]* Eccentric cams with followers?

Researcher: No, they're not eccentric cams with followers, but you're on the right track. It's interesting that you're thinking about putting the mechanism up above which is where the mechanism really is in a carousel.

Sam: Yeah, but some of it's going to have to be below. Wait. Would it be a lever? *[He holds up his hands to show what he's thinking.]* So it's like a lever and it goes...maybe a second order...actually, wait. That would be...a third. Yeah, a third order so that it pushes up from the middle and it pulls it up and down.

Researcher: That's not how it's done either, but that also would work. So even though that's not the way they do it in real life, both of those would do exactly what they do. And I think that when you get downstairs next week and you see what's in the box you'll figure it out. But it's going to be very much like your's because the mechanism that drives the carousel around in circles...

Sam: Is at the bottom.

Researcher: Is at the bottom and the mechanism that pulls the animals up and down is in the top. I think that a lot of the size is going to depend on how big your animals are. It's good to think it will be small now but once you get the animals we can figure out the scale from there. I'll tell you what. There's some paper, there's a pencil. I want you to show me how the mechanism to turn the carousel is going to work. I'm seeing two parts.

Sam: Yeah, there's only two parts I'm thinking of. *[He starts to draw]* It's gonna be a...I couldn't think of another way but to use a pinwheel gear. So that's pretty much it. 'Cause, like is there anything else I should be doing?

Researcher: No. We'll have to put some structure in there to hold everything. So are you going to use one to one gears?

Sam: One to one just because it doesn't need to go slower or faster.

Researcher: So were going to use a pair of pinwheel gears to take the motion from the crank and to rotate the base of the carousel. Now show me how, when the carousel goes around, the animals will go...so two of them are going to go up and down and two of them are going to go side to side?

Sam: Yeah, 'cause that's also kind of realistic, that's what they do for the parents to ride on, the one's that are stationary. My mom always rides on them.

Researcher: The stationary ones don't move though.

Sam: Don't they move around?

Researcher: They go around with the carousel...

Sam: But they don't go up and down.

Researcher: So when I say stationary they could just be glued on dowels to the carousel base because the don't have to move separately from the base.

Sam: But they usually have that thing up and down so you can hold onto them. I'm just going to draw it like this even though it would be the other way around. So, it would be like this...

Researcher: I see. This is a disk and you're showing it face on rather than side on. So these look like eccentric cams.

Sam: Yeah, with followers...I can't think of another way to make it go so you'd have to use more pinwheel gears...and then the dowel *[he connects the cams to the gears with shafts]* like that.

Sam's sketches can be seen in Figure 7.10.

7.2.1 Designing the Carousel

Sam had done a great deal of the preliminary design before work commenced on the carousel. His basic ideas were sound and the decision to split the mechanism into two parts was insightful. The next session was used to refine his design and to identify problems with it. The researcher had found one issue that had to be corrected; Sam's idea of putting the animal moving mechanism at the top of the carousel. He gave one of the pinwheel gear mechanisms to Sam and asked him to use it to demonstrate how the animals would move. Sam explained that a shaft

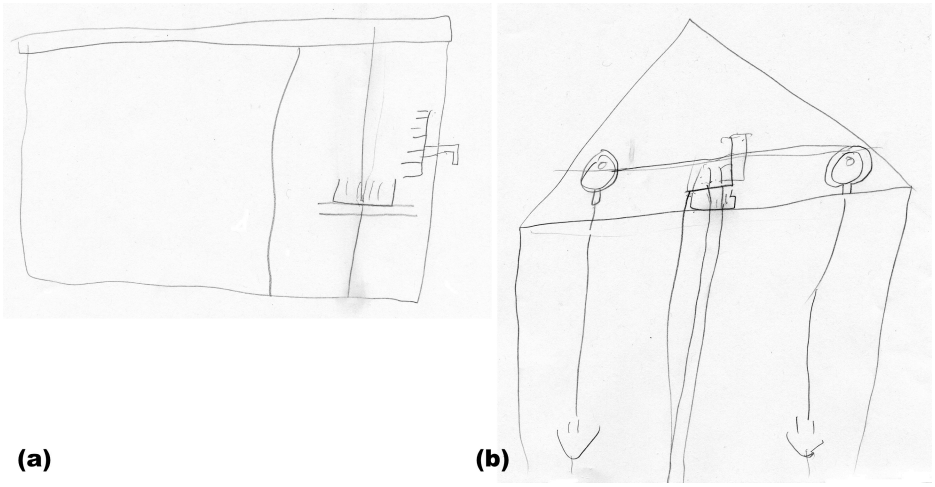


Figure 7.10: (a) Sam's sketch for the base of the carousel showing the two pinwheel gears that will convert the rotation of the crank into rotation of the carousel. (b) Sam's sketch for the mechanism to move the animals. His idea is to use eccentric cams with ring followers (which can work in any orientation) to move the animals up and down and to drive the cams with a set of pinwheel gears that receive their power from the base. Compare these first drawings to his first drawing of the soccer player in Figure 7.1 where the figure of the player is central and no hint of mechanism or structure is shown. In these drawings the structure and mechanism are key and the animals only represented by smiling faces.

would come up from the base, through the center of the carousel and connect to the central pinwheel gear which in turn would drive the secondary pinwheel gears. These would be attached to the eccentric cams that would move the animals. The researcher asked how the rotation of the carousel would affect what Sam had just described.

Sam had some difficulty in seeing the problem so the researcher asked him to take the mechanism he had, place it on the table and spin it around the axis of the horizontal gear since this would approximate the mechanism Sam was thinking about. Sam did this, but was still unclear about what he should be seeing. The researcher pointed out that rotating the entire mechanism did not cause the gears to turn. Sam replied that the shaft from the base would turn the horizontal gear when the crank was turned. The researcher asked if that shaft and the carousel would turn at the same speed and Sam said they would. The researcher asked Sam to look at the pinwheel mechanism as he again rotated it on the table. While Sam was doing this the researcher reminded

him that the framework represented the top of the carousel as it turned and he asked Sam to describe the relative motions of the framework and the shaft for the pinwheel gear. Sam was still puzzled, but slowly it became apparent to him that the shaft and the framework were turning at the same rate. The researcher then held the horizontal gear stationary while Sam continued to rotate the framework. This caused the vertical gear to start rotating and Sam seemed to understand what was wrong with his design; there could be no motion imparted to the cams if the driven gears were revolving around the drive gear at the same speed the drive gear was rotating.

Sam asked if there were some other way to make the cams move and the remainder of the session was used to consider alternatives, none of which would work. The researcher asked him to think about the problem during the week, and especially think about alternative placements for that part of the mechanism. Sam was also told to think about why holding one gear stationary and rotating the framework produced the same motion as turning the gear while holding the framework stationary.

When Sam returned the following week saying that in order for his idea to work he would need to find a way to keep the drive gear stationary while the carousel revolved. The researcher asked him if he thought that was possible if the gear was located above the carousel and Sam said that he had not thought of a way and reminded the researcher that the two of them had failed to find a method the week before. He said he thought it might be possible if there was some way to attach the drive gear to the base which would be stationary with respect to the carousel but that he had not figured out a way to transfer the motion up to the cams. At this point the researcher suggested something radical; could it be made to work if the base were placed above the carousel? Sam assumed that this was a joke, but the researcher asked him to consider it seriously. Sam concluded that such a solution might work but that it would not be practical to build the automaton that way. The researcher agreed, and asked Sam how this new mechanical arrangement could be made practical. Sam was left alone to think it over. After spending nearly ten minutes alone on the problem, Sam said that the carousel could be flipped over. This would put the base back on the bottom, but would leave the animals upside down. The researcher

suggested that there was an easy solution to that problem and Sam, seemingly a little embarrassed, said that the animals could be turned over as well.

This would place the mechanism for the animals between the base and the bottom of the carousel rather than on top as Sam had originally planned. But it did away with the problem of getting the proper behavior and was adopted as part of the next design which, it was agreed, should have a prototype constructed.

7.2.2 Prototyping and Constructing the Carousel

Sam and his mother had made a visit to a local thrift store and obtained four small plastic animals: a lion, a panda, an elephant, and a moose. While some were not typical of what would be found on most carousels,[4] they showed a great deal of promise. As Sam and the researcher had earlier discussed, the size of the animals determined the size of the carousel which ended up being almost twice the diameter that Sam had originally wanted. Armed with dimensions for the carousel, they began building a first prototype in corrugated cardboard (Figure 7.11).

Because of the complexity of the mechanisms for this automaton almost all of the prototyping for the base and mechanical components was done in wood. Since this was a more expensive material to use and not as plentiful as cardboard, Sam and the researcher spent a greater percentage of the prototyping time calculating and planning than they had for the soccer player. They first designed and constructed the gears that would rotate the carousel. During earlier discussions, Sam had decided that his original 1:1 pinwheel gears would allow the carousel to rotate faster than he wanted and he also knew that by slowing down the input he could gain some extra power for the rest of the mechanism. A pair of pinwheel gears with a ratio of 2:1 were constructed. The gears were used to determine the size of the structural framework for the base and some preliminary drawings were made. Sam's design had the weight of the carousel and animal mechanism supported by the shaft from the pinwheel gears. The researcher asked him if he could think of a way to support the carousel independent of the drive train while still allowing it to turn. Sam had

[4] Particularly the moose who at some point in his life had acquired a green head and antlers.



Figure 7.11: The first carousel prototype assembled and with the animals arranged to get feel for size and scale. The curved structures on the top are for future draping with cloth.

seen microwave ovens with rotating trays and had observed that these used rollers near their circumference to stabilize the tray and help support its weight and thought that this was something that could be used to stabilize and support the carousel. A set of four rollers were created and the top of the base was modified to hold them. The base was then assembled (see Figure 7.12).

Since the animal mechanism would be located between the base and the floor of the carousel, the next job they began was to design that mechanism. Work was deliberate although progress was slow and there were many design decisions that had to be carefully thought through. In the end a ring was made that would rest on the base rollers. Attached to this ring were the supports for the carousel floor and for the bearing surfaces of the cam shafts. A large pinwheel gear was created that would be attached to the top of the base coaxial with the shaft that would turn the carousel. Two smaller pinwheel gears were made that would be attached to the shafts for the eccentric cams and would mate with the large gear. The amount of motion that Sam wanted the moving animals (the lion and moose) to have was determined and eccentric cams were made that would produce this movement and two crescent shaped cam followers were made to reduce

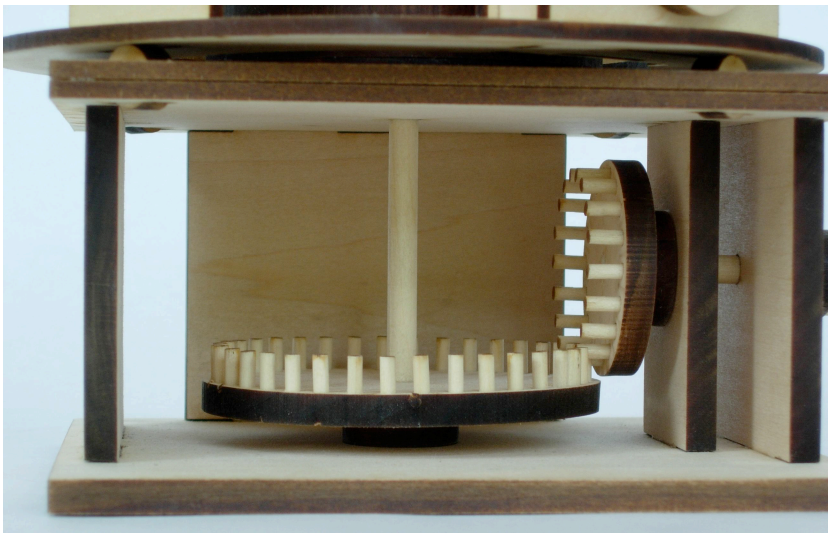


Figure 7.12: When the user turns the crank attached to the pinwheel gear at right, that motion is transmitted to the vertical shaft which is attached to the carousel. Note the rollers at the corners of the mechanism top that support the carousel as it turns.

the friction that a simple rod follower would have created. To complete this assembly for testing, a carousel floor was made from wood using the same file that had been used for the cardboard prototype. This mechanism in its final form is shown in Figure 7.13.

Once performance issues with the mechanisms had been corrected, the remainder of the carousel was completed quickly. The animals had small holes drilled in their backs (a process the researcher found somewhat gruesome) and wooden dowels were inserted. The researcher had told Sam that in his experience the center of carousels where the machinery was located were blocked from view, often by mirrors and that since they had some mirrored acrylic available to them it might be visually interesting to do the same. So a wooden framework was fabricated to both hold the mirrors and provide additional support for the roof. These pieces were assembled and along with the animals added to the carousel. Since Sam was planning on draping cloth over the top, it was necessary to create a false roof to keep the moving shafts of the animals from protruding into this space. With this done the roof pieces were put together and the carousel was complete (see Figure 7.14).



Figure 7.13: The mechanism that lifts the animals was one of the most complicated created during the user testing. The large horizontal pinwheel gear is attached to the mechanism base and does not turn. As the carousel rotates it carries with it the shafts connected to the smaller gears which causes them to turn. This motion is transmitted to the two eccentric cams which alternately lift and lower the lion and moose. The rollers which support the carousel can also be seen in this view.

7.3 Discussion

The results from Sam's test session, while impressive, are not unusual. Several others in the test user group have similar stories which show a trajectory of increased domain competence and improved mechanical thinking and while these comprise a small number of cases, there is little reason to doubt that similar results would be seen if these tests were run again with a different set of users from the same population. The results presented here support the claims made in Chapter 6. Specific examples for each of the evaluation measures include:

- **Talking about Automata**, Section 6.2.1: The changes in Sam's ability to use the terminology appropriate to the domain is seen when comparing his use of "stick" in an early transcript during the construction of the soccer player to the correct use of "follower" when describing his proposed design for the carousel.



Figure 7.14: The carousel in its final form. Turning the crank (lower right) causes the lower horizontal pinwheel gear to turn. This rotation is transmitted to the carousel proper via the central shaft that passes through the upper horizontal pinwheel gear which is fixed to the automaton's base. As the carousel rotates the small pinwheel gears are forced to turn as they move about the central gear. These in turn rotate the eccentric cams that move the lion and moose up and down through the motion of their followers. As can be seen, this automaton if both complex and visually stunning.

- **Using External Representations**, Section 6.2.2: The changes in Sam's use of drawings can be seen by comparing the items of prominence in the initial drawing for the soccer player where the figure of the player and the ball are seen in the absence of any mechanical details and the initial drawings for the carousel where the mechanisms are the key features and the animal figures are only hinted at.

- **Components, Motion, and Complexity**, Section 6.2.3: The changes in Sam's ability to deal with complexity is easily seen between the initial difficulty he has with the simple mechanism in the soccer player and his ability to deal with significantly more demanding issues with the carousel mechanisms.

- **Confidence Levels**, Section 6.2.4: Sam indicates how his confidence has increased both when he decides to put the soccer player on very public display as his science project and when he attributes his desire to construct a second automaton in part to his belief that doing so will make him feel better about himself.

- **MachineShop System Usage**, Section 6.2.5: Sam proves that his use of the software is becoming more sophisticated when he demonstrates its abilities to his mother.

Similar examples were seen with a majority of the test users. In some cases these examples were even more striking than those observed with Sam. In all cases, users took away some skill or ability that they had not previously demonstrated and for that reason alone the tests were a success.

Chapter 8

Conclusions, Contributions, and Future Work

The previous chapters have examined issues and presented data that are needed to answer the thesis question (Section 1.4). This chapter takes a step back in order to make sense of these sometimes diverse data. It begins by presenting the most important conclusions that have been reached in this research and follows this by identifying some of the core contributions made by this work. It concludes with a look to the future for this and related work.

8.1 Conclusions

The results obtained from the user testing described in Chapter 6 illustrate the breadth of the users' experiences. There is much to see in the intellectual changes of the users, the character of the experimental method, and the qualities of the automata created. In this section I present the three most important conclusions derived from these results.

8.1.1 Children and Automata

The question that guided this research has two parts. The first part asks about children as creative entities. Is it possible that they can successfully create mechanical automata? The answer to that question, as evidenced by the examples presented in Appendix B, is a very definite yes. Over a period of ten months, six 10-, 11-, and 12-year old children built a series of enchanting devices that can stand alongside the best of contemporary automata without apology. Their automata are clever, quirky, and fascinating and embody the eclectic gestalt of the form without

being formulaic. Children of middle school age can indeed build automata. But this claim comes with a caveat.

As with many activities for children, their success at creating automata depends in large part on how the activity is presented, structured, and supported. If you hand a child a box of tools, a stack of wood, and a book of automata pictures it is unlikely that she will even make the attempt. Neither would most adults. Success comes from working in an environment where one can succeed. The users in this study did well because the activity was presented as a chance for these children to be creators of technology in a setting where there was no wrong way. No idea was rejected out of hand although some were found unworkable for legitimate reasons. Applying the apprentice model to the activity and mentoring rather than teaching meant that users could explore at their own pace and in their own directions and never discover that they had become lost. Usually a little nudge was all that was needed to prevent a detour from becoming a dead end. And for support they were provided with materials and tools to help them over the rough spots in their knowledge and around the holes in their abilities. The MachineShop system was responsible for much of this, serving as domain expert and manufacturing assistant during the creation of components and mechanisms.

8.1.2 Automata and Mechanical Thinking

The second part of the question asks how this activity affects the cognitive development of children. Does building automata help children become better mechanical thinkers? The answer to this question is again yes. Using the measures presented in Chapter 6 every one of the users showed some level of heightened ability. This was sometimes evidenced by only a small change in one of the measures, other times striking changes were seen in all of the measures. All users left the testing with an increase in their ability to use appropriate language when talking about automata (Section 6.2.1). Only two showed significant changes in their ability to interpret complex mechanisms (Section 6.2.3). By their own accounts, users were not engaging in any other design or construction activities concurrently with the testing. This suggests that the changes seen

in users' mechanical thinking came from their work with automata in the tests.

With the acknowledged importance of visuospatial reasoning (Section 2.2), it seems strange that so much effort goes into measuring these abilities and so little goes into finding ways to enhance them. One of the early assumptions made in this research was that mechanical understanding was likely to be gained from working with machines. The results of the testing have validated this assumption.

8.1.3 Undiscovered Richness in the Domain

When contemporary automata were chosen as the domain for this research it was obvious that there was richness and depth waiting to be discovered. The stories that automata are capable of telling are nearly limitless in their number and type and in the emotions they can evoke in viewers. The range of complexity of their mechanisms spans a continuum from utterly simple to fiendishly complex and this not only supports the builders as they gain confidence and skill, but also provides them with space to grow as craftspersons. The creation of automata can be educational and social as well as simply being fun. All of these were observed in the user testing and many were mentioned by the users themselves. All of these factored into the success experienced by the users.

But beyond these obvious qualities exist a number of subtle intellectual dimensions in both the domain and the construction activity that, for the most part, were never recognized by the test users. While the tools in MachineShop can be used to explore and experiment with components, most users were satisfied with simply understanding *what* the mechanical components they created with did without wanting to understand *how* they did it. Those who did ask the *how* question left the testing with a deeper understanding of both mechanical principles (such as the relationships between the mechanism components they created and simple machines [98]) and the properties shared by seemingly different components. One example is in the way a gear functions. Force is transmitted not from gear to gear, but from the teeth of one gear to the teeth of another along a path tangential to the point of contact. This produces the rotary motion that

is observed. Now consider every tooth as a lever to which a force is applied at the fulcrum (shaft) and from which effort is returned where the teeth meet. This relationship between lever and gear is not immediately obvious but comes as what Gardner [42] calls an *aha!* experience. Sam had one when he realized why his spinning gears wouldn't rotate 7.2.1.

There are a number of possible reasons users failed to delve deep into the domain. Among them are:

- During the testing users had an assigned task and a limited time in which to perform it. This left little opportunity for activities that did not directly advance the state of the task.
- There was no organized set of activities to prepare and guide users in exploring the domain in depth.
- These hidden qualities of the domain may be too subtle for children of this age or may require abstract reasoning skills that they do not yet possess.

Whatever the reasons, even the most successful of the users acquired only a superficial understanding of the mechanical principles underlying the domain.

8.2 Core Contributions

Along the way to the conclusions reached by this work, several important contributions were made that are likely to prove useful for other research in this and similar domains.

8.2.1 MachineShop

The most visible contribution of this research is the MachineShop system. By combining a suite of software tools with recent progress in automated fabrication, there now exists an environment for assisting in the creation of mechanical automata and similar devices. MachineShop is capable of supporting a number of activities, but two are seen as most important.

First, MachineShop can be used to help children build contemporary automata. This activity is already part of educational curricula in a number of countries (Section 2.3.3) and shows every indication of becoming more widespread. MachineShop has great promise in helping children construct the knowledge that these curricula are concerned with by allowing them to design and build at levels far beyond those that their manual skills might otherwise allow. As seen in the user tests described herein, this has a tremendous impact on both ability and self-image.

Second, MachineShop can be used as a tool for conducting studies of mechanical reasoning. As was seen in Section 2.3, most of the studies in mechanical reasoning rely on diagrams or physical systems which possess little authenticity. On the rare occasions that reasoning is assessed using real machines, the pool of machines from which to choose is small. MachineShop can do double duty in addressing this shortcoming. By creating interesting machines with MachineShop, researchers can explore the ways in which people reason about a much larger variety of machines than current research has employed. Beyond the pulleys and gears so common in the literature, MachineShop in its current form would bring systems of cams and levers along with heterogeneous mechanisms to researchers. MachineShop is a tool that can support an entirely new area of research in which the activity of creating machines is used to determine how mechanical thinking is acquired and augmented.

8.2.2 A Design Process for Creating Automata

The success that users experienced in creating automata was due in large part to the environment in which they worked. One part of this environment was the MachineShop system. The larger part was the process created to scaffold their learning and cognitive development as they designed and constructed their automata. Nothing in this process was novel; apprenticeship is an idea centuries old and an active body of research attempts to revitalize it and place it in more contemporary contexts (see [47] for one example). What is novel in this research is the use of the apprenticeship model in an educational setting for children, something that was not found in the literature. For the creation of automata it was a particularly good choice. While labor intensive

from the researcher's point of view, it provides the opportunity to assess a child's needs at any point along the way and to tailor the support provided to that need. It allows a child to feel that she has the complete attention of the mentor and that the mentor is attending to what she is doing. It is particularly effective when the mentor introduces a new task or skill by demonstration and can then offer advice or answer questions as the child becomes familiar with the task.

By pairing the apprenticeship approach with a modified version of engineering practice the tasks undertaken by the users became authentic, and were seen as such by users. Children can easily resent being asked to do work which they see as contrived [92]. So although the objects they were building are toylike, the process of creating them was not a toy process and although not all of the elements of the process were embraced (standardization and reuse for example) others, such as iterative prototyping, were clearly important to the successful creation of automata.

8.2.3 A System for Using Novel Output Devices

The landscape of computerized fabrication and rapid prototyping machines is constantly changing. What was science fiction a decade ago can now be found in hundreds of factories. What might have cost a manufacturing company hundreds of thousands of dollars a decade ago can now be purchased by an individual for a small fraction of that price. What this means is that the rare is becoming commonplace and tools like laser cutters, 3-D printers, and CNC machine tools are becoming more accessible to all of us. But there is a certain *Catch-22* aspect to all of this. In order for software like MachineShop to use these tools they must be cheap and available. But for them to become cheap and available, there must be demand. That demand is created by software like MachineShop. In order to swing the balance in favor of the educator or craftsperson, there need to be more tools that can leverage the power of these new devices. MachineShop provides an example of how that can be done.

8.2.4 A Survey of Research into Mechanical Reasoning

This dissertation has brought together a small, but representative survey of the literature in mechanical reasoning (Chapter 2). With respect to the dissertation, this analysis served to situate the research and to highlight areas that the current literature has not addressed. Beyond this goal, the integration of work from the cognitive, vocational, and educational research camps provides an introduction to the literature that did not previously exist. In no example that I could find were the works of Hegarty mentioned with those of Stenquist or Dewey with Tversky. This seems a great oversight since a broad understanding of mechanical reasoning depends on a knowledge of the work of all of the disciplines that find it of interest. This work makes a modest beginning toward that goal.

8.3 Future Work

This research is hoped to be just a beginning. The domains are rich, the approach powerful, and the results exciting. Some small amount of work remains on the software to prepare it for release to the open source community. Much work remains to be done to augment what has been learned here and many opportunities exist to move in other directions based on what is now known. This section touches briefly on a few of those that seem most promising.

8.3.1 Technology for Children

MachineShop owes much of what it has become to other studies in the field of technology for children. These efforts have shown the power of blending computation, construction, and learning in a wide variety of children's activities. Mitch Resnick and his colleagues [102] were interested in helping children become amateur scientists, capable of building the instrumentation they needed to conduct experiments of their own choosing. Ann Eisenberg [32] gave children the power to explore the beautiful world of geometric solids. Sue Hendrix [58] has chosen an approach to topological exploration by making children creators of pop-up books rather than

consumers. Mike Eisenberg [33] has taken a broad look at how technological innovation has both changed and enhanced the ideas Papert first introduced us to in 1980. MachineShop was my first encounter with this community as a builder and designer. This experience has been particularly influential in helping me identify new domains in which this type of work shows promise.

The next steps with MachineShop will be in elementary engineering education. The potential for a tool like MachineShop to expose young children to engineering as a vocation was unknown to me when this all began, but has come to represent a natural evolutionary step in its maturation. The situation is simple; fewer students have been pursuing university degrees in the fields of science, technology, engineering, and math (what are called the STEM fields) and of those who do enter universities in these majors, fewer have been receiving those degrees [88]. While this trend has seen a slight reversal very recently [89], there is growing concern over what this means for the future of science and technology in the United States that has found its way even into the popular press [9]. Many students, in particular women [83, 129], unknowingly decide not to pursue STEM careers while still children when they begin to lose interest in science and mathematics. A growing body of research exists to address engineering education for younger children. Some projects endeavor to present engineering to elementary students in engaging ways that will instill lifelong interests [66, 131], while others define standards and methods of practice to help ensure that these interventions are effective [12, 27]. MachineShop, and the systems that it will influence, have great potential to offer children authentic engineering experiences, something they rarely see.

8.3.2 Meta-design

Meta-design is the process of designing tools and systems that will themselves be used for design tasks and the creation of MachineShop is one example. While the meta-design principles conceived and utilized for the building of MachineShop were never codified, the informal guidelines that resulted could form the basis for studies into and around meta-design for children's tools. Much of the work done in creating design systems, especially for children, is at best ad hoc

and at worst haphazard. Being able to understand the challenges and explicitly provide design criteria and procedures has promise to realize marked improvement in the quality and suitability of these design tools.

Bibliography

[1] Woo-kyoung Ahn and Charles W. Kalish. The Role of Mechanism Beliefs in Causal Reasoning. In Frank C. Keil and Robert A. Wilson, editors, *Explanation and Cognition*. The MIT Press, Cambridge, MA, 2000.

[2] Rudolph V. Alvarado. *The Life and Work of Thomas Edison*. Alpha Books, Indianapolis, IN, 2002.

[3] Geoffrey D. Austrian. *Herman Hollerith: Forgotten Giant of Information Processing*. Columbia University Press, New York, NY, 1982.

[4] Christian Bailly. *Automata: The Golden Age, 1848–1914*. Robert Hale, London, UK, 2003.

[5] Maria G. Bartolini Bussi, Mara Boni, Franca Ferri, and Rossela Garuti. Early Approach to Theoretical Thinking: Gears in Primary School. *Educational Studies in Mathematics*, 39:67–87, 1999.

[6] Theodore Baumeister, editor. *Standard Handbook for Mechanical Engineers*. McGraw-Hill Book Company, New York, NY, seventh edition, 1967.

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

[8] Erwin H. Brinkmann. Programed Instruction as a Technique for Improving Spatial Visualization. *Journal of Applied Psychology*, 50(2):179–184, 1966.

[9] William J. Broad. Top Advisory Panel Warns of an Erosion of the U.S. Competitive Edge in Science. *The New York Times*, Section A, Page 22, Column 1, October 13, 2005.

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

[11] Earle Buckingham. *Manual of Gear Design: Section Two*. Machinery, New York, NY, 1935.

[12] M. David Burghardt. Developing the Field of Children's Engineering. In *Proceedings of the ASEE 2000 Annual Conference*, 2000.

[13] Kirsten Butcher. *Effects of Diagram Complexity on Comprehension Processes and Learning Outcomes*. PhD thesis, Department of Psychology and Institute of Cognitive Science, University of Colorado at Boulder, 2003.

[14] Cabaret Mechanical Theatre [online, cited 09 October 2005]. Available from: `http://www.cabaret.co.uk/`.

[15] Cabaret Mechanical Theatre Stock Catalog, Winter 1998 [online, cited 09 October 2005]. Available from: `http://www.cabaret.co.uk/pdfs/stock.pdf`.

[16] John B. Carrol. *Human Cognitive Abilities: A Survey of Factor-Analytic Studies*. Cambridge University Press, Cambridge, UK, 1993.

[17] B. Chandrasekaran. Multimodal Perceptual Representations and Design Problem Solving. In John S. Gero and Barbara Tversky, editors, *Visual and Spatial Reasoning in Design '99*, 1999.

[18] Alfred Chapuis and Edmond Droz. *Automata*. Éditions du Griffon, Neuchatel, Switzerland, 1958.

[19] Highlights from John Drury Auction at Leslie Hindman's [online, cited 15 October 2005]. Available from: `http://chicagoantiquesguide.com/archives/20051014082916.php`.

[20] Paul Cobb. Where is the Mind? A Coordination of Sociocultural and Cognitive Constructivist Perspectives. In Catherine Twomey Fosnot, editor, *Constructivism: Theory, Perspectives, and Practice*. Teachers College Press, New York, NY, 1996.

[21] Colorado K-12 Student Assessment Index Page [online, cited 31 December 2005]. Available from: `http://www.cde.state.co.us/index_assess.htm`.

[22] Colorado Model Content Standards for Science [online, cited 05 December 2005]. Available from: `http://www.cde.state.co.us/cdeassess/standards/pdf/science.pdf`.

[23] John W. Cox. *Mechanical Aptitude: Its Existence, Nature, and Measurement*. Methuen & Company Ltd., London, UK, 1928.

[24] LEGO CAD [online, cited 09 October 2005]. Available from: `http://www.workshop3d.com/cybertoys/legocad.htm`.

[25] Unit 5C: Moving Toys [online, cited 10 October 2005]. Available from: `http://www.standards.dfes.gov.uk/schemes2/designtech/det5c/?view=get`.

[26] Unit 6C: Fairground [online, cited 10 October 2005]. Available from: `http://www.standards.dfes.gov.uk/schemes2/designtech/det6c/?view=get`.

[27] Josh Douglas, Eric Iversen, and Chitra Kalyandurg. Engineering in the K-12 Classroom: An Analysis of Current Practices & Guidelines for the Future. Technical report, The American Society for Engineering Education, November, 2004.

[28] A.G. Drachmann. *The Mechanical Technology of Greek and Roman Antiquity*. The University of Wisconsin Press, Madison, WI, 1963.

[29] Darle W. Dudley. *Practical Gear Design*. McGraw-Hill Book Company, New York, NY, 1954.

[30] Richard T. Duesbury and Harold F. O'Neil, Jr. Effect of Type of Practice in a Computer-Aided Design Environment in Visualizing Three-Dimensional Objects From Two-Dimensional Orthographic Projections. *Journal of Applied Psychology*, 81(3):249–260, 1996.

[31] Jacquelynne S. Eccles. The Development of Children Ages 6 to 14. *The Future of Children*, 9(2):30–44, 1999.

[32] 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.

[33] Michael Eisenberg. Mindstuff: Educational Technology Beyond the Computer. *Convergence*, 9(2):29–53, Summer 2003.

[34] James Essinger. *Jacquard's Web: How a Hand-Loom Led to the Birth of the Information Age*. Oxford University Press, Oxford, UK, 2004.

[35] Erika L. Ferguson and Mary Hegarty. Learning With Real Machines or Diagrams: Application of Knowledge to Real-World Problems. *Cognition and Instruction*, 13(1):129–160, 1995.

[36] William Fitzgerald, Franklin Gracer, and Robert Wolfe. GRIN: Interactive Graphics for Modeling Solids. *IBM Journal of Research and Development*, 25(4):281–294, 1981.

[37] Flying Pig Paper Animation Kits [online, cited 16 October 2005]. Available from: `http://www.flying-pig.co.uk/`.

[38] Kenneth D. Forbus. Qualitative Reasoning About Space and Motion. In Dedre Gentner and Albert L. Stevens, editors, *Mental Models*. Lawrence Erlbaum Associates, Hillsdale, NJ, 1983.

[39] Patrick N. Foster. The Heritage of Elementary School Technology Education in the U.S. *Journal of Vocational and Technical Education*, 15(2):28–43, 1999.

[40] Patrick N. Foster and Michael D. Wright. How Children Think and Feel About Design and Technology: Two Case Studies. *Journal of Industrial Teacher Education*, 38(2), 2001.

[41] Jeanette M. Gallagher and D. Kim Reid. *The Learning Theory of Piaget and Inhelder*. Brooks/Cole, Monterey, CA, 1981.

[42] Martin Gardner. *aha! Insight*. Scientific American, Inc./W.H. Freeman and Company, New York, NY, 1978.

[43] Girders and Gears [online, cited 13 October 2005]. Available from: `http://www.girdersandgears.com/`.

[44] Vinod Goel. Cognitive Role of Ill-Structured Representations in Preliminary Design. In John S. Gero and Barbara Tversky, editors, *Visual and Spatial Reasoning in Design '99*, 1999.

[45] Howard E. Gruber and J. Jacques Vonèche, editors. *The Essential Piaget*. Jason Aronson, Inc., Northvale, NJ, 1995.

[46] Roland B. Guay. The Relationship Between Mathematics Achievement and Spatial Abilities Among Elementary School Children. *Journal for Research in Mathematics Education*, 8(3):211–215, 1977.

[47] David Guile and Michael Young. Apprenticeship as a Conceptual Basis for a Social Theory of Learning. *Journal of Vocational Education and Training*, 50(2):173–192, 1998.

[48] Mary Hegarty. Mental Animation: Inferring Motion From Static Displays of Mechanical Systems. *Journal of Experimental Psychology*, 18(5):1084–1102, 1992.

[49] Mary Hegarty. Capacity Limits in Diagrammatic Reasoning. In Michael Anderson, Peter Cheng, and Volker Haarslev, editors, *Theory and Application of Diagrams: Proceedings of the First International Conference, Diagrams 2000*, pages 194–206, 2000.

[50] Mary Hegarty and Marcel Adam Just. Constructing Mental Models of Machines from Text and Diagrams. *Journal of Memory and Language*, 32(6):717–742, 1993.

[51] Mary Hegarty, Marcel Adam Just, and Ian R. Morrison. Mental Models of Mechanical Systems: Individual Differences in Qualitative and Quantitative Reasoning. *Cognitive Psychology*, 20(2):191–236, 1988.

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

[53] Mary Hegarty, Sarah Kriz, and Christina Cate. The Roles of Mental Animations and External Animations in Understanding Mechanical Systems. *Cognition and Instruction*, 21(4):325–360, 2003.

[54] Mary Hegarty and Valerie K. Sims. Individual Differences in Mental Animation During Mechanical Reasoning. *Memory & Cognition*, 22(4):411–430, 1994.

[55] Mary Hegarty and Kathryn Steinhoff. Individual Differences in Use of Diagrams as External Memory in Mechanical Reasoning. *Learning and Individual Differences*, 9(1):19–42, 1997.

[56] Mary Hegarty and David A. Waller. Individual Differences in Spatial Abilities. In Priti Shah and Akira Miyake, editors, *The Cambridge Handbook of Visuospatial Thinking*. Cambridge University Press, Cambridge, UK, 2005.

[57] Julie Heiser and Barbara Tversky. Diagrams and Depictions in Acquiring Complex Systems. In Wayne D. Gray and Christian Schunn, editors, *Proceedings of the 24th Annual Meeting of the Cognitive Science Society*, 2002.

[58] Susan L. Hendrix and Michael A. Eisenberg. Computer-Assisted Pop-up Design for Children: Computationally-Enriched Paper Engineering. In *Proceedings of the Eigth IASTED International Conference on Computers and Advanced Technology in Education*, 2005.

[59] Ann Marie Hill. Problem Solving in Real-Life Contexts: An Alternative for Design in Technology Education. *International Journal of Technology and Design Education*, 8(3):203–220, 1998.

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

[61] Lloyd G. Humphries, David Lubinski, and Grace Yao. Utility of Predicting Group Membership and the Role of Spatial Visualization in Becoming an Engineer, Physical Scientist, or Artist. *Journal of Applied Psychology*, 78(2):250–261, 1993.

[62] Ivan Illich. *Deschooling Society*. Harper & Row, New York, NY, 1971.

[63] S. D. Johnson. The Heritage of Elementary School Technology Education in the U.S. *Journal of Vocational and Technical Education*, 52(8):29–30, 1993.

[64] Allister Jones. The Development of a National Curriculum in Technology for New Zealand. *International Journal of Technology and Design Education*, 13(1):83–99, 2003.

[65] Yasmin Kafai and Idit Harel. Children Learning Through Consulting: When Mathematical Ideas, Knowledge of Programming and Design, and Playful Discourse are Intertwined. In Idit Harel and Seymour Papert, editors, *Constructionism: Research Reports and Essays, 1985-1990*. Ablex Publishing, Norwood, NJ, 1991.

[66] Sue Ann Kearns, Catherine Rogers, Judy Barosky, Merredith Portsmore, and Chris Rogers. Successful Methods for Introducing Engineering into the First Grade Classroom. In *Proceeding of the 2001 American Society of Engineering Education Annual Conference and Exhibition*, 2001.

[67] The Central Site for the LDraw Family of LEGO CAD Software [online, cited 09 October 2005]. Available from: `http://www.ldraw.org/`.

[68] Factory Homepage [online, cited 09 October 2005]. Available from: `http://www.lego.com/eng/factory/`.

[69] Richard Lehrer and Leona Schauble. Reasoning about Structure and Function: Children's Conceptions of Gears. *Journal of Research in Science Teaching*, 35(1):3–25, 1998.

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

[71] Marcia C. Linn and Anne C. Petersen. A Meta-Analysis of Gender Differences in Spatial Ability: Implications for Mathematics and Science Achievement. In Janet Shibley Hyde and Marcia C. Linn, editors, *The Psychology of Gender: Advances Through Meta-Analysis*. Johns Hopkins University Press, Baltimore, MD, 1986.

[72] The International LEGO Users Group Network [online, cited 09 October 2005]. Available from: `http://www.lugnet.com/`.

[73] James G. Madison. *CNC Machining Handbook: Basic Theory, Production Data, and Machining Procedures*. Industrial Press, New York, NY, 1996.

[74] Manolya Kavakli, Masaki Suwa, John Gero, and Terry Purcell. Sketching Interpretation in Novice and Expert Designers. In John S. Gero and Barbara Tversky, editors, *Visual and Spatial Reasoning in Design '99*, 1999.

[75] Masaki Suwa, John Gero, and Terry Purcell. Unexpected Discoveries: How Designers Discover Hidden Features in Sketches. In John S. Gero and Barbara Tversky, editors, *Visual and Spatial Reasoning in Design '99*, 1999.

[76] Juta McCord and Jim McCord. *Contemporary Automata: A Continuum*. MouseWorks Canada, Toronto, Ontario, Canada, 2004.

[77] Malcolm McCullough. *Abstracting Craft: The Practiced Digital Hand*. MIT Press, Cambridge, MA, 1996.

[78] Ann McKenna and Alice Agogino. Designing and Assessing a Learning Environment to Support Mechanical Reasoning. In *Proceedings of the 2002 American Society of Engineering Education Annual Conference & Exposition*, 2002.

[79] Merriam-Webster. *Merriam-Webster's Collegiate Dictionary*. Merriam-Webster, Inc., Springfield, MA, second edition, 2000.

[80] Heron of Alexandria [online, cited 09 October 2005]. Available from: `http://www.mlahanas.de/Greeks/HeronAlexandria.htm`.

[81] George A. Miller. The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity to Process Information. *Psychological Review*, 63(2):81–87, 1956.

[82] Joel Mokyr. *The Gifts of Athena: Historical Origins of the Knowledge Economy*. Princeton University Press, Princeton, NJ, 2002.

[83] Barbara M. Moskal. Looking to the Future: Women in Science and Engineering. In *Proceedings of the 30th ASEE/IEEE Frontiers in Education Conference*, pages F1B–19–F1B–24, 2000.

[84] The NASA SCI Files: The Case of the Powerful Pulleys [online, cited 11 December 2005]. Available from: http://whyfiles.larc.nasa.gov/docs/guides/guide1a_02.pdf.

[85] Illuminations Lessons: Balance Beam Discoveries [online, cited 11 December 2005]. Available from: http://illuminations.nctm.org/index_d.aspx?id=319.

[86] Design and Technology [online, cited 12 December 2005]. Available from: http://www.nc.uk.net/webdav/servlet/XRM?Page/@id=6004&Subject/@id=3624.

[87] National Curriculum Online [online, cited 09 October 2005]. Available from: http://www.nc.uk.net/webdav/servlet/XRM?Page/@id=6016.

[88] Division of Science Resources Statistics National Science Foundation. *Science and Engineering Indicators-2002*. National Science Foundation, Arlington, VA, 2002.

[89] Division of Science Resources Statistics National Science Foundation. *Science and Engineering Indicators-2004*. National Science Foundation, Arlington, VA, 2004.

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

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

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

[93] Seymour Papert. A Word for Learning. In Yasmin Kafai, editor, *Constructionism in Practice: Designing, Thinking, and Learning in a Digital World*. Lawrence Erlbaum Associates, Mahwah, NJ, 1996.

[94] Susan Pass. *Parallel Paths to Constructivism: Jean Piaget and Lev Vygotsky*. Information Age Publishing, Greenwich, CT, 2004.

[95] Donald G. Paterson, Richard M. Elliott, Leo D. Anderson, Herbert A. Toops, and Edna Heidbreder. *Minnesota Mechanical Ability Tests: The Report of a Research Investigation Subsidized by the Committee on Human Migrations of the National Research Council and Conducted in the Department of Psychology of the University of Minnesota*. University of Minnesota Press, Minneapolis, MN, 1930.

[96] Brief Outline of the History of I/O Psychology [online, cited 27 November 2005]. Available from: http://www.mtsu.edu/~pmccarth/io_hist.htm.

[97] Rodney Peppé. *Automata and Mechanical Toys*. The Crowood Press, Ramsbury, UK, 2002.

[98] Tillie Pine and Joseph Levine. *Simple Machines and How We Use Them*. McGraw-Hill Book Company, New York, NY, 1965.

[99] Steven Pinker. *How the Mind Works*. W.W. Norton & Company, New York, NY, 1997.

[100] Charles Poole and Gordon Stanley. A Factorial and Predictive Study of Spatial Abilities. *Australian Journal of Psychology*, 24(3):317–320, 1972.

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

[102] 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.

[103] Randy Sargent, Mitchel Resnick, Fred Martin, and Brian Silverman. Building and Learning With Programmable Bricks. In Yasmin Kafai, editor, *Constructionism in Practice: Designing, Thinking, and Learning in a Digital World*. Lawrence Erlbaum Associates, Mahwah, NJ, 1996.

[104] Michael S. Shapiro. *Child's Garden: The Kindergarten Movement from Froebel to Dewey*. Pennsylvania State University Press, University Park, PA, 1983.

[105] Francis T. Siemankowski and Franklin C. MacKnight. Spatial Cognition: Success Prognosticator in College Science Courses. *Journal of College Science Teaching*, 1(1):56–59, 1971.

[106] Ian M. Smith. *Spatial Ability: Its Educational and Social Significance*. Robert R. Knapp, San Diego, CA, 1964.

[107] Software 4 Teachers [online, cited 16 October 2005]. Available from: `http://www.software4teachers.org/`.

[108] Charles E. Spearman. *The Nature of 'Intelligence' and the Principles of Cognition*. MacMillan, London, UK, 1923.

[109] Guy L. Steele, Jr. *Common LISP: The Language*. Digital Press, Burlington, MA, 1984.

[110] John L. Stenquist. *Measurements of Mechanical Ability*. Columbia University Teachers College, New York, NY, 1923.

[111] Craig Strange. *Collectors Guide to Tinker Toys*. Collector Books, Paducah, KY, 1996.

[112] Carol Strohecker. Elucidating Styles of Thinking about Topology through Thinking about Knots. In Idit Harel and Seymour Papert, editors, *Constructionism: Research Reports and Essays, 1985-1990*. Ablex Publishing, Norwood, NJ, 1991.

[113] Donald E. Super and John O. Crites. *Appraising Vocational Fitness by Means of Psychological Tests*. Harper and Row, New York, NY, revised edition, 1962.

[114] Masaki Suwa and Barbara Tversky. What do Architects and Students Perceive in Their Design Sketches?: A Protocol Analysis. *Design Studies*, 18(4):385–403, 1997.

[115] Michael J. Tarr and Steven Pinker. Mental Rotation and Orientation-Dependence in Shape Recognition. *Cognitive Psychology*, 21(2):233–282, 1989.

[116] Frederick W. Taylor. *The Principles of Scientific Management*. Harper & Brothers, New York, NY, 1911.

[117] Ctesibius of Alexandria [online, cited 09 October 2005]. Available from: `http://www.tmth.edu.gr/en/aet/1/31.html`.

[118] Hero of Alexandria [online, cited 09 October 2005]. Available from: `http://www.tmth.edu.gr/en/aet/1/55.html`.

[119] Extensible Markup Language (XML) 1.0 (Second Edition) [online, cited 09 October 2005]. Available from: `http://www.w3.org/TR/REC-xml`.

[120] Cabaret Mechanical Theatre. Cabaret Mechanical Video. Videotape, 1991.

[121] Wendy Turnbull. The Place of Authenticity in Technology in the New Zealand Curriculum. *International Journal of Technology and Design Education*, 12(1):23–40, 2002.

[122] Barbara Tversky. What Does Drawing Reveal About Thinking? In John S. Gero and Barbara Tversky, editors, *Visual and Spatial Reasoning in Design '99*, 1999.

[123] Barbara Tversky. Visuospatial Reasoning. In Keith J. Holyoak and Robert G. Morrison, editors, *The Cambridge Handbook of Thinking and Reasoning*. Cambridge University Press, Cambridge, UK, 2005.

[124] No Child Left Behind [online, cited 31 December 2005]. Available from: `http://www.ed.gov/nclb/landing.jhtml?src=pb`.

[125] Philon of Byzantium [online, cited 09 October 2005]. Available from: `http://www-history.mcs.st-and.ac.uk/history/Mathematicians/Philon.html`.

[126] Arthur J. Vidich and Stanford M. Lyman. Qualitative Methods: Their History in Sociology and Anthropology. In Norman K. Denzin and Yvonna S. Lincoln, editors, *Handbook of Qualitative Research*. Sage Publications, Thousand Oaks, CA, 2000.

[127] Anthony F.C. Wallace. *Rockdale: The Growth of an American Village in the Early Industrial Revolution*. Alfred A. Knopf, New York, NY, 1978.

[128] Bruce Watson. *The Man Who Changed How Boys and Toys Were Made*. Viking, New York, NY, 2002.

[129] Judith Byrne Whyte. Starting Early: Girls and Engineering. *European Journal of Engineering Education*, 11(3):271–279, 1986.

[130] CNC [online, cited 09 October 2005]. Available from: `http://en.wikipedia.org/wiki/Cnc`.

[131] Denise Wilson, Tina Hudson, Susan Fletcher, Brannon Harris, Clinton Knight, Tonia Morris, Girish Patel, and Stephen DeWeerth. Establishing the Foundations for Engineering Education in K-5. In *Proceedings of the IEEE 1995 Frontiers in Education Conference*, pages 3b2.5–3b2.9, 1995.

[132] Bennet Woodcroft. *The Pneumatics of Hero of Alexandria*. Taylor, Walton, and Maberly, London, UK, 1851.

[133] Thomas E. Wrensch. *Programming Computationally Enhanced Craft Items*. PhD thesis, Department of Computer Science, University of Colorado, Boulder, 2002.

[134] Welcome to Zome!! [online, cited 30 December 2005]. Available from: `http://www.zometools.com/`.

Appendix A

Observations on the User Testing

This appendix is intended to provide the interested reader with more information on the process and results of the user testing presented in Chapter 6 and to add breadth and context to the case study of Chapter 7. A large amount of interesting and instructive data were gathered during the testing and what follows is a sampling from those data. This appendix begins with examples of the language users employed, with an emphasis on the kinds of information contained therein. Next, it examines a number of activities and knowledge areas that proved problematic for the users. It continues with a brief discussion of the role of the MachineShop software in the tests and the ways in which the users interacted with it. It concludes with a look at how the overarching apprentice model used in the testing was implemented to meet the varying needs of the users.

The reader is directed to Chapter 6 to gain a better understanding of the context in which these results were obtained, to Appendix B for a more detailed description of the automata created by the users, and Appendix D for information on the sample automata and mechanisms available to the users.

A.1 The Use of Language During Testing

The language employed by the users was only one of the metrics used for evaluating the results of the testing, but proved to be tightly coupled to the other metrics, particularly with regards to components, motion, and complexity (see Section 6.2.3). The dialogues between several of the users and the researcher that are presented here show the nature of the language used dur-

ing the course of the testing and much can be gleaned from them about the how effectively users have internalized domain information. These examples are representative of those seen across all users and have been selected to highlight growth in vocabulary with respect to mechanisms and movement, changes in abilities to effectively express ideas and concepts within the domain, and statements or exchanges that indicate the nature of the users' understanding of the domain. Session numbers are given to indicate relative chronological occurrences.

A.1.1 Abbie

Abbie built one automaton; the Drowsy Dragon (see Section B.1). Her goal was to have the dragon's wings flap and tail move while breathing fire. She described her previous construction experience as being fairly limited; she had worked with LEGO Mindstorms and she and her father were in the process of building a whirligig.

A.1.1.1 Vocabulary

Abbie had little experience in this or related domains, and after her initial introduction to automata and mechanisms her language was filled with general terms and vague descriptions. During session one, as she and the researcher were discussing her requirements, we see this reflected in her suggestion for a possible means to make the dragon's wings flap. Here she is referring to one of the crank-slider mechanisms (Figure D.9) she saw during the introductory session:

> Abbie: So, like, maybe, you know that thing where you turned it and then the pole would go up and down? Maybe that's what we could use for the wings.

Imprecise terms like "thing" and "pole" continued to be a major part of Abbie's vocabulary throughout the testing. Even terms that she was exposed to during almost every session, particularly those that described the mechanism she was building, failed to become familiar. This exchange is from session nine:

Researcher: Remind me where we were last week.

Abbie: Okay, so we were on making the gears *[pause]* I mean planning where *[pause]* how big the thing is gonna be. And where the *[pause]* how *[pause]* well, what gears we're gonna use on the…

Researcher: Are we going to use gears? *[long pause]*

Abbie: Maybe *[long pause]* yes. *[pause]* Well no, not exactly gears. There's like…

The researcher hands her the simple pinwheel gear mechanism
Researcher: These are gears. Are we going to use these?

Abbie: We're going to use this one without the *[pause]* things.

Researcher: Without the things.

Abbie: Uhhh…

The researcher points to the teeth of one gear.
Researcher: What are these things called? *[Abbie doesn't answer]* These things are called teeth. So if we're not going to use gears, what are we going to use? What are they called?

Abbie: I don't remember.

Researcher: *[gently]* Come on…

Abbie: I'm thinking, I'm thinking, I'm thinking. *[pause]* Well anyway, they're these things. *[picks up the sea lion and points to the eccentric cams]*

Researcher: Right.

Abbie: Spinners!

Researcher: But those things are called…

Abbie: *[pause]* Cams.

Researcher: Right. And these ones in particular are called…

Abbie: Wait. What ones are you talking about?

Researcher: The ones that move Celia's[1] tail back and forth.

Abbie: Contracting.

Researcher: Eccentric.

Abbie: Encentric [sic] cams.

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[1] See Section D.3

A.1.1.2 Expressing Ideas and Concepts

Abbie often found herself searching for a word or concept and this was reflected quite often in her use of incomplete sentences that either ended abruptly or simply trailed off. This example comes from her final interview at the end of the user testing:

> Researcher: What have you done in the past? Have you worked with LEGOs, have you built models, . . .
>
> Abbie:I have worked with LEGOs, um LEGO Mindstorm. Where you program the LEGO thing that you built to do things. So that's kind of like this only it has gears and things and you *[pause]* and so yeah.

Abbie also found it difficult to explain the operation of the mechanism she had built in words and relied heavily on pointing to her automaton in an effort to clarify her descriptions. The following is also from her final interview:

> Abbie: . . . And then how it works is when you, if you were to turn this *[pointing to the crank]*, turn it, these *[paired eccentric cams at the tail]*[2] would go around and make the tail go back and forth.
>
> Researcher: And those are called what?
>
> Abbie: These are called, called, um, *[pause]* uh, *[pause as she looks up]* cams I, yeah, cam. And they're. . .
>
> Researcher: Do you remember what kind of cam those are?
>
> Abbie: Um, I think they're, um, I for *[pause]* flat cams or something?
>
> Researcher: They have a strange name. They're called eccentric cams.
>
> Abbie: Yeah, eccent *[pause]* um huh, and so this thing's *[the entire mechanism]* mostly were made out of eccent, it's uh egcetric [sic] cams, and so this one *[the tail]* would just move back and forth. And then on the wings we had a couple of ideas where just keep the wings like sta *[pause]* down. Um. Like from right here *[points to wire connected to wing]* there's actually a little hole right here where, so it actually is this thing is the thing that makes it go up and down, instead of just having another thing pushing it up and down. It just has one thing now. So then we put on this thing *[the large follower to which the wires are attached]* which would help it come down

[2] This particular mechanism is one I refer to as a Markey oscillator after Peter Markey. While he may not have invented it, he was the contemporary automatist who made it popular in many of his works. A description of how it functions can be found in Section D.3.

> *[due to its weight]* because it wouldn't just do it with one so we put two more *[the follower is laminated from three pieces of wood]*.
>
> Researcher: So why wouldn't it come down with just the one?
>
> Abbie: It was, um. These *[the wings]* were, are made like out of, um, like really light stuff *[craft foam]* so it wasn't heavy enough with these *[wings]* and just that *[follower]* so we put three more to help it come down easily and not just get stuck up there. And then so another cam *[for the wings]* only this one, *[pause]* oh yeah. And then this one is for the fire as you can probably see in here *[points to mouth]*. And so, if we were not, if we didn't have this *[the cam has a retainer disc for the follower]* we could see that it has, um, a little cam inside. And then, um, it would turn and this thing *[the ring follower]* would, um, turn with it. So to help it just turn. And so, that, those ones can go, um, anyway it wants *[referring to the ring follower's ability to function in any orientation]*. It can be sideways, up and down, um, upside down, and so hmmm.

A.1.1.3 Domain Understanding

When Abbie began the testing she was almost a complete novice in her knowledge of mechanics. One unexpected example came during session seven, the following exchange occurred:

> Researcher: ...and it also has to be able to work on the friction of these joints.
>
> Abbie: What's friction?

Abbie's understanding of the domain did increase over the course of the testing, but she sometimes still found it difficult to express her new knowledge in words. For example, when using ring followers with eccentric cams it is necessary to provide some method for preventing the follower from sliding off the cam. In Abbie's dragon, the ring follower that provides the motion for the fire breathing is kept on the cam by the support framework on one side and a thin disc that is glued to the cam on the other. During her final interview, Abbie was asked the purpose of that disc:

> Researcher: Why does that have the ring follower on that cam?
>
> Abbie: You mean this one? *[points]*
>
> Researcher: Uh huh.

Abbie: Well *[pause]*

Researcher: So, the other cams don't have that piece *[retainer disc]* on the outside of them. Why does that one have it?

Abbie: Well, I think that it's to keep the little tiny cam *[this cam is the same diameter as the other three]* from going in and out. From getting out of it.

Researcher: Can you think of any other reason we might done that?

Abbie: Unh uh. *[shakes head no]*

This shows that while she knows that the disc exists to maintain the alignment of the cam and follower, she is misstating the potential problem. Since the cam is glued to the main shaft and the disc is glued to the cam, the disc cannot hold the cam in place but serves to hold the follower in place.

A.1.2 Dylan

Dylan built two automata; the Leaping Lion (see Section B.3) and the Busy Beehive (see Section B.4). His craft and construction experience before the testing was the most diverse of any of the users and included model rockets, several challenging science fair projects, creating and modifying objects using found materials, along with the more common use of construction kits and toys seen in all users. The examples presented here come from his work on the lion which was the first of his automata.

A.1.2.1 Vocabulary

Dylan seemed to sense early on that he would be more likely to convey his ideas to the researcher if he used the terminology of the domain. As early as his second session he had already acquired a number of component labels that were specific to what he needed to do although his dialogue still contained a large number of ambiguous references. The researcher asks him to describe the mechanism he is thinking of using during the second session:

Researcher: . . . remind me now what we talked about for a mechanism.

> Dylan: Um, the, uh, uh, wheel thing that we have on the buffalo. Or it was one of those three *[crank-slider mechanisms]*. It was one of the three that we showed . . .
>
> Researcher: Do you want me to get those again?
>
> Dylan: Yeah.
>
> Researcher: Okay.
>
> Dylan: I think it was the one which wasn't, which didn't need the little plastic piece *[the eccentric cam with ring follower]*.
>
> *[The researcher hands him the crank-slider mechanisms.]*
> Yeah, it was that one *[points to the disc with offset pin]*. This one. And then we were going to have a little, uh, a little thing which stuck up and the wall would, I mean the jaw, the lower jaw would be a lever. And it'd push up on this *[he pivots his right hand around the palm]* which would push down when it comes down.

The only specific term he used is when he identified the moving part of the jaw as a lever. The rest of his explanation was vague, but a few minutes later, when preparing to design components he needed with the MachineShop software, this occurred:

> Researcher: We need to design a couple of things. We need to design a cam first of all. This is the cam tool *[MachineShop's cam editor]*. Show me what you're . . .
>
> Dylan: I wanted the ratchet one so you could only make it jump forward.

Not only did he correctly name the component he wanted, but he also provided a correct rationale for his choice. This continued over the course of the testing and while he continued to use ambiguous references, he was quite capable of using specific terminology when he wanted.

A.1.2.2 Expressing Ideas and Concepts

Dylan's brief explanation above for his choice of a ratchet was one of the earliest indications he made that he was not only learning about the domain, but learning to talk about the domain. The lion took just over two months to complete and in that time Dylan's ability to express his understanding of the domain continued to improve. While still relying on pointing to features

of his automaton to aid in his explanations (a common action with all of the users), he was still able to describe dependencies in an understandable way. This exchange is from the interview conducted when the lion was complete:

> Researcher: Explain to me what you have in your hands.
>
> Dylan: Um, well, it's a simple machine and it's got a ratchet, and the, when the ratchet goes around it pushes this *[slider rod]* up causing the lion to go up. And when it goes up, this little piece here *[the bottom stop on the actuating rod for the jaw]* hits this top *[the top of the support framework]* closing the mouth. Then, when it goes around and back down *[he tries to turn the ratchet by hand]* it comes around . . .
>
> Researcher: So what were you just doing there? You were turning it and then you turned it the other direction.
>
> Dylan: I was turning it the wrong way because of the pawl *[he smiles]*.
>
> Researcher: So when it goes down, then what happens?
>
> Dylan: Uh, then that *[the upper stop on the actuating rod for the jaw]* hits there *[the framework top]* causing this *[the actuating rod]* to open this *[the jaw]*.
>
> Researcher: How does that rod that you're holding in your hand right now, how does that open and close the jaw of the lion?
>
> Dylan: Well, uh, there's, uh, a little piece in here *[showing where the lever is in the lion's body]* and when you push up on here *[the rod]* 'cause this gets stuck *[the rod]* and so it starts to push up because this, the lion is still trying to go down, it opens the jaw because the jaw is pivoting on this *[points]* rod.
>
> Researcher: What kind of component is the jaw?
>
> Dylan: A first lever, uh, a first order lever.
>
> Researcher: What does that mean? That it's a first order lever?
>
> Dylan: Uh, the pivot, the fulcrum is in between the force, where you put in the force and where you get out the effort.
>
> Researcher: What else is kind of unique about this mechanism? I see some things that I haven't seen anybody else do.
>
> Dylan: Um *[pause]*
>
> Researcher: So, why did you pick a ratchet?
>
> Dylan: Well, 'cause I like, I don't think it's very realistic when lions jump, like, backwards. So if you put that up *[he raises the pawl and turns the crank in the opposite direction that it normally goes]* then the lion looks

like he's jumping backwards. And so I didn't think that looked very realistic so I made it so he could only jump forward.

Researcher: So how does the ratchet do that?

Dylan: Well, the ratchet moves around and it's got these points and the pawl gets stuck on 'em. So, when you try and push 'em go backwards, the pawl is stuck on the points. So it can't go backwards.

Researcher: And when you go forward what happens?

Dylan: Then it *[the pawl]* just bounces up and down.

Researcher: Where did you get the idea of *[pause]* So the ratchet does do what you wanted it to. It makes sure that the lion only goes one direction. But this is the first time I've ever seen anybody put an offset on a ratchet to move the lever up and down to move the body. How did you come up with that idea?

Dylan: Well, uh, I was sort of playing around, and when I was looking at the software I saw that you had one which was just plain round with the little hole at the top *[this was actually in the sample mechanisms]*. And I said "hey, why don't we do that but use a ratchet? Wouldn't that work the same? Because then that'd just make it so it couldn't turn backwards, but it'd still be offset and make it go up in a oval."

. . .

Researcher: When you first came in and we started talking about the lion you had some things that you wanted it to do. Do you remember what those things were?

Dylan: Jump up and down, have its jaw go up and down, and have its tail move around.

Researcher: So I'm looking at it right now and I don't see a tail. What happened to the tail?

Dylan: Well, I, I don't really know how we could do it. But I could probably make a second try at this and do most of this about the same and then make, and then make the, this part *[the support framework]* a little wider out here and make a bar go up, and make the tail.

A.1.2.3 Domain Understanding

Because Dylan was the first user, he helped define the form that the testing assumed. He had more time to "play" with both the software and the sample mechanisms than did the other users (although all users did spend unstructured time interacting with both) and he was able to visit some of the more conceptual aspects of the domain. From session three:

Researcher: . . . look at the crank that you're thinking about using *[disc with offset pin]* and look at the one that we used in the buffalo *[eccentric cam with ring follower]* and think about, which one of these do you think might be stronger? Or do you think that there's any difference?

Dylan: Probably, this one's stronger *[pointing to the eccentric cam]*.

Researcher: Why do you think so?

Dylan: Um, 'cause it's not got this little thing *[pin]* which might pop out.

While experimenting with the design of snail cams later in the session, he asks this question:

Dylan: Can you put zero lobes on it?

Researcher: What would a zero lobe cam look like?

[Dylan moves the graph points so that they coincide and the profile becomes a disc.]
Dylan: Pretty much that.

Researcher: Okay, that's a disc. What does an eccentric cam look like?

[He switches to the eccentric cam tool.]
Dylan: That, only *[pause]*

Researcher: It's kind of a zero lobe cam when the hole is in the middle.

[Dylan moves the hole from the middle of the cam to an offset of about three-quarters of an inch.]
Researcher: How many lobes does it have when you do this?

Dylan: Zero.

Researcher: What's a lobe?

Dylan: One of the little stickie up things.

Researcher: That's how it's represented on the snail cam, but what's the function of a lobe? What does the lobe do?

Dylan: Push up the follower?

Researcher: Right. And let it go back down. What does an eccentric cam have? Can it push up a follower?

Dylan: Yes it can.

Researcher: So for every time it goes around, how many times does it push it up?

Dylan: Once.

Researcher: So it has how many lobes?

Dylan: One. But it's not exactly this kind of lobe *[indicating a snail cam]*.

Dylan was one of only two users (the other being Sam) to incorporate gears into an automaton when he built the beehive. But even before he started fabricating components for the lion, he was learning about gears. This occurred during session three:

> Researcher: So, we know what cams do. What do cams do?
>
> Dylan: Um, cams. They uh, make something go up and down or back and forth.
>
> Researcher: Right. So what they do is change rotary motion, which is the circular motion of the cam, into linear motion, which is the up and down or side to side motion. What do gears do?
>
> Dylan: They change the direction of stuff.
>
> Researcher: Of what kind of stuff? Do they change the direction of hurricanes?
>
> Dylan: *[laughs]* No. The direction the machine is going so if you turn the gear one way the other gear will turn the other way. And faster if it's smaller.
>
> Researcher: And what kind of motion is that? We just talked about it with the cams.
>
> Dylan: Rotary motion.
>
> Researcher: Is that always the case? Does a gear always change the direction of the rotary motion?
>
> Dylan: Uh, yeah. Oh, no. Um, yeah if it's right next to each other.
>
> Researcher: That's right. For gears that are touching, they always rotate in the opposite direction. But what about gears that aren't touching? Like in these three gear sets that you have right here?
>
> Dylan: If they aren't touching? Then they're going to go the same way if they're odds and the same way if they're evens.
>
> Researcher: Animate that and take a look. Which direction are those two going?
>
> *[Dylan moves his index finger in the direction the outer gears are turning.]*
> Researcher: Clockwise. Are they going the same speed?
>
> Dylan: No. This one *[the smaller gear]* is going a lot faster. It's going once for every ten ones this one *[the larger gear]* is going.
>
> Researcher: Not quite. What does it say here for gear ratio *[2:7]*?
>
> Dylan: For every two this *[the larger gear]* this *[the smaller gear]* spins seven. What's the biggest ratio you have?
>
> Researcher: In this tool right now, four to one or one to four. But is there any limit?

Dylan: Uh, no. Just how big you could make it.

He and the researcher then went on to discuss the relationships between speed and power and how the ratios of gears and the ratios of levers were related. These types of exchanges occurred on and off during the testing and the knowledge that Dylan built from them played out prominently when he designed the mechanism for the beehive by deconstructing the complex motion he wanted into simpler constituent parts.

A.1.3 Iris

Iris built one automaton; the Globe Trotter (see Section B.6). Her first concept was an automaton of an old woman pouring milk for a kitten, but she discarded that idea as being too complex, even before she had any familiarity with automata mechanisms. The person (eventually a man) with the globe seemed the ultimate in simplicity; a static figure with a spinning globe. Getting Iris to add motions, and consequently interest, to this automaton took several sessions and in some cases needed to be prompted by the researcher. It is particularly interesting that at the conclusion of her time in the project, Iris had a different recollection of the original form of the automaton and its evolution (see Section A.1.3.3). She had built some items from wood (a box at summer camp and a chicken coop built with friend and the friend's father), played with LEGOs on occasion, and liked to draw and paint, but she had never built an object that incorporated movement before making her automaton.

A.1.3.1 Vocabulary

Iris' automaton was among the simplest of those built by all users, and because the mechanism was very similar to that of Celia the sea lion (Section D.3) she spent little time exploring other mechanical options. Even with this focus on a mechanism with few component types, her vocabulary showed little change over the course of the testing. While discussing the mechanism for the sea lion in the second session the following exchange occurred:

> Researcher: When you turn the crank, what happens?
>
> Iris: It well, it takes the uh, it takes the um, big thing which rotate, which turns...
>
> Researcher: Okay. So this is the ball up here *[pointing to the disc that turns the ball]*...
>
> Iris: And that would be the tail *[pointing to the eccentric cams for the tail]*.
>
> Researcher: Right.
>
> Iris: So that turns that, right? *[the disc that turns the ball follower]* And that's connected to the ball.

Iris' use of generic and ambiguous terms ("big thing" or "that") far exceeded her use of domain specific terms during early sessions. This was mitigated only slightly by the end of the testing, and often more specific terms were used incorrectly. During the interview held at the completion of the project, Iris was asked to describe her automata:

> Researcher: So why don't you explain to me what your automaton is and how it works.
>
> Iris: My automaton was a person pushing a globe and then watching the globe go around and looking at the cranker. The gears worked because, well pushing this *[the crank]* it turns all the bottom ones. The bottom ones turn the globe 'cause it's, and we had to taper it because I wanted the globe to be more realistic and so we put it on a stand.

Iris uses "gear" for any of the circular cams and discs that comprise the mechanism for her automata. Indeed, her use of the word is puzzling, as gears were never discussed with respect to her mechanism and none of the sample automata she examined contained gears. Notice also that she is still using ambiguous terms such as "ones" and "this".

A.1.3.2 Expressing Ideas and Concepts

When Iris would explain how a mechanism worked it was common for her to skip around from feature to feature rather than progressing through the mechanism based on its dependencies ("cam A pushes on follower B which moves the short end of lever C ..." for example). When describing her automaton in the final interview, she says:

> Iris: My automaton was a person pushing a globe and then watching the globe go around and looking at the cranker. The gears worked because, well pushing this *[the crank]* it turns all the bottom ones. The bottom ones turn the globe 'cause it's, and we had to taper it because I wanted the globe to be more realistic and so we put it on a stand.
>
> Researcher: So it sits at an angle like the real Earth does.
>
> Iris: Yeah. And it pushes the globe to turn around. And there's a wire there *[indicating the globe]* so it pushes the arm *[pause]*
>
> Researcher: And the arm can move because *[pause]*
>
> Iris: Because we have a spring right there.
>
> Researcher: Okay.
>
> Iris: These two *[the eccentric cams]* are gears that control the head and they aren't centered perfectly so the head will go up and down and they have wires on 'em to stop the head from going all the way around and not catching.

In her automaton, the "gears that aren't centered perfectly" are the eccentric cams responsible for turning the head back and forth in the Markey oscillator (Section D.3). The wires she mentions are not attached to these cams but rather to the follower they rotate, and they constrain the motion of the follower so that it can turn only a limited distance in each direction.

Iris was obviously more comfortable discussing the layout and motions of the tableau components than she was with the mechanical components. From the final interview:

> Researcher: How did you choose this mechanism? So you had an idea about how you wanted it to work.
>
> Iris: I just, I just thought about this *[the figure and the globe]*. I didn't, I had no idea how we were going to make it work.
>
> Researcher: So once you had thought about that though, some decision was made to come up with the mechanism that's inside of that.
>
> Iris: Yeah, we were drawing it out and I'm just like "that doesn't look real 'cause the globe is standing straight up, not at a slant so it doesn't look like a globe."
>
> Researcher: So did you get any of these ideas from other examples or from books or from . . . ?
>
> Iris: Well, I was looking at the globe and I'm just like "that doesn't look like a globe" because it's at a hundred and *[pause]*

Researcher: So we figured out how to slant it. What about getting the guy's head to turn from side to side?

Iris: *[pause]* That's a good question. *[long pause]* Give me that question again.

Researcher: Did you look at other automata or look at pictures or books or websites or anything to come up with this idea?

Iris: Mmm *[pause]* Well, I could just picture it going like that *[she turns her head and moves her hand]* and looking at the, watching the globe and then it would keep going.

Researcher: But for actually coming up with the mechanism to get the head to turn like that though, did you have any examples that you saw that did similar kinds of things?

Iris: I think we looked at um, Celia the seal and her hind tail, her tail flippers went like that *[moves her hands back and forth]* so we used the same thing for the head.

A.1.3.3 Domain Understanding

Iris' understanding of mechanisms and mechanical components increased only slightly during the testing. Much of the knowledge she used in making her automaton was only seen in the short term and little was reflected in many of her responses during the final interview. One example:

Researcher: So that was your original idea, and you decided that that was too tough so you came up with this second idea which was simpler. In the beginning, did the head turn and the arm move and the globe spin? Were all three of those things there?

Iris: No. Well, we first thought "oh my gosh, there's not going to be enough room, the head can't move." So we just thought it would be *[pause]*

Researcher: So the arm was always going to move?

Iris: Yeah. 'Cause then it wouldn't, 'cause if it didn't move the globe would just be hitting like that *[she presses on the fingertips of one hand with the fingers of the other]* and getting tripped. And then we didn't know how, we didn't know how we were going to get this, the wire, to get the hand to move. Then I thought we were going to have like a wire attached to the hand that went around so it wouldn't, wouldn't, but it didn't work. After I thought about it, and we, I didn't know there's going to be these wires down here.

> Researcher: We needed those when the head started turning around backwards and it started looking like the Exorcist.
>
> Iris: Yahhh! *[she claps]*

This is actually a quite different take on the way the automaton would function than she presented initially. Here she says that the arm was always going to move, but after abandoning her first idea as too hard, her original idea for this automaton was overly simple. During her first session, the researcher asked about her preliminary sketch:

> Researcher: Okay. So what am I looking at?
>
> Iris: You're looking *[pause]* the globe spins around.
>
> Researcher: Does the person do anything?
>
> Iris: Umm, no, not really.
>
> Researcher: The person doesn't push the globe *[pause]* or point or *[pause]*
>
> Iris: I don't know what it would do but it could do something.
>
> Researcher: Just getting the globe to spin is just like getting the ball to spin on the nose of the seal. That's pretty simple. We can do that easily enough. But you've got a person there. So maybe the person, I assume the person is interacting with the globe in some way.
>
> Iris: It could have eyelids, eyelids that blink.
>
> Researcher: Would you want to have one of the hands push the globe as it spins?
>
> Iris: That'd be cool.

Iris never seemed to become comfortable with either the essence of contemporary automata or with the mechanisms that they contain. While having the eyelids blink would not have been overly difficult, in the context of her automaton it was not as central a motion as having the man appear to rotate the globe.

A.2 What Users Found Difficult in This Domain

Building automata is a challenging task, as any automatist will admit. The users in this study encountered a number of difficulties while working to complete their projects. Individual

differences in style, background, and ability presented themselves many times in situations that perplexed and confounded the users. Quite often, these situations were unique to one or two users, but almost all of the users experienced enough similar problems that the general categories that follow were readily apparent.

A.2.1 Size and Scale

All of the test users experienced some difficulty when thinking about either the size or the scale of their automata. These difficulties fell into three general categories: in choosing a size for the tableau that would be practical, in determining the correct proportions of tableau members, and in selecting appropriate sizes for mechanical components. A majority of these problems presented themselves because all of the users worked from the design of the tableau to that of the mechanism in a purely linear process. The method used by more skilled builders (and by both Dylan and Sam with their second automata) is to work alternately on both designs, starting with the tableau and moving between them until both parts form the desired whole. Novice users possess no skills or knowledge that would encourage them to proceed in this manner.

The most common problem seen was that users wanted to make their automata too small. This presented itself in two ways. First, the user would choose a size for the primary tableau element without sketching or measuring, and that was, in all cases, too small. When Dylan began working on his lion (Section B.3), he made the first body four inches long. With a cardboard prototype in hand, it became clear to him that this was much smaller than he had thought it would be and subsequently the body size was increased to about six inches. If this decision had not been made at this early stage, it would have been necessitated by the constraint of making the lever actuated jaw function properly. Frank encountered this problem when the initial body size for his cat (Section B.5) was too small to house the mechanical components needed to make it work. To overcome this, he made the second version roughly double the size of the first. Interestingly, Sam's first automaton, the soccer player (Section B.7) was designed large from the beginning and was built to those dimensions. But he had wanted his second automaton, the

carousel (Section B.8), to be much smaller and, as it turned out, it too was unable to house the mechanism he eventually developed and it ended up being made larger.

The second problem occurred when working with relative size or scale in the tableau of an automaton. This presented itself in three automata in these tests; the Globe Trotter (Section B.6), the Soccer Player (Section B.7), and the Carousel (Section B.8). When a simple tableau had only one element (like the Dragon, Section B.1) or when all of the elements were created and constructed with the laser cutter (like the Cat, Section B.5), this was not a problem. But when users brought found materials into the tableau, it was often a challenge to make the proportions of all of the elements correct. The Carousel became larger than Sam had originally wanted in part because of the mechanism needed, but just as importantly because of the size of the animals he found. With both the Soccer Player and the Globe Trotter, the balls used had some effect on the size of the human figures. Since the height of the soccer kicker had been determined early in the design process, Sam had to determine an appropriate size for the wooden ball he would use. Iris found the globe she was going to use at a toy store and while real globes come in a variety of sizes, it was necessary to see if the scale sizes of the globe and the man were acceptable. To do this, Iris needed to convert fractional measurements to their decimal equivalents and to use a scaling factor on elements of her tableau. From her third session:

> Researcher - "So you're good at fractions?"
>
> Iris - "Yeah."
>
> Researcher - "Have you done fractions to decimal conversions?"
>
> Iris - "No. I don't think so. Not the conversion part. Like one half is point five?"
>
> Researcher - "That's exactly what we're going to do. One quarter is *[pause]*"
>
> Iris - "Okay, we didn't do that."
>
> Researcher - "Alright. Well, what's the relationship of a quarter to a half?"
>
> Iris - "Two quarters equals a half."
>
> Researcher - "So one quarter is *[pause]*"
>
> Iris - "Is *[pause]* three point five? point, point three five, point three five."

Researcher - "Let's worry about the relationship to a half. So one quarter is how much of a half?"

Iris - "Half?"

Researcher - "It's half of a half. So, what's half of zero point five?"

Iris - "Zero zero point five?"

Researcher - "No."

Iris - "Oh."

Researcher - "What's half of fifty?"

Iris - "Twenty five. So, two point five. So, point two five."

Researcher - "Right. What's an eighth?"

Iris - "Twenty five. Oh shoot! *[pause]* twenty five *[pause]* one twenty five."

Researcher - "Exactly . . . "

. . .

Researcher - "I'm almost six feet tall. If we assume that this six inch tall person is six feet tall, how many inches equals a foot?"

Iris - "Twelve."

Researcher - "Well, in real life. But we have a six inch tall person *[pause]*"

Iris - "One inch equals one *[pause]* twelve *[pause]* two meters would equal one foot?"

Researcher - "Let's just worry about inches right now. You said it right. In this case one inch equals one foot. If I'm six feet tall, we're going to shrink me down to six inches tall. Every foot of me becomes an inch here."

Iris - "Okay."

Researcher - "So we can use this same conversion, we know that the globe is roughly one and a half inches . . . "

Iris - "So it would be one and a half feet?"

The third problem occurred when users attempted to create mechanical components that were of appropriate sizes for their tableaus and behaviors. This is actually two issues. First, users had difficulty deciding on the size of any necessary support framework for their mechanisms, determining the location of the components with respect to the tableau elements, and properly sizing components so that they would work together correctly. One example was seen as Abbie worked on the dragon. Her initial belief was that the support framework for the mechanism would

be as long as the dragon's body (nose to tail). It wasn't until she and the researcher determined the location of the mechanical components on the cardboard prototype that she understood that while the framework's size was more dependent on mechanical considerations than on the size of the tableau. For her dragon, the framework's minimum length was determined by the locations of the cams that moved the fire and the tail while its minimum width was the result of the distance between the wires that actuated the wings. Choosing these minimum sizes allowed the dragon to extend past the framework on all sides, making the tableau the dominating visual component.

The behavioral issue arose when users had to design components that would provide a desired type and amount of movement. Dylan saw it when the jaw of the lion didn't move as far as he'd hoped because the small size of the lion's body prevented him from using a longer lever. Iris saw it when the man's head turned farther than she'd imagined due to the large amounts of lift provided by the eccentric cams. Sam saw it when trying to get a sufficiently large movement of the soccer kicker's leg in order to get the ball to the goal and he was forced to use a high lift for his cam to counteract the size of the leg lever that couldn't be changed. And nowhere was it more troublesome than in the intricate linkages of Frank's cat that had to move a number of tableau elements (the mouse as well as the cat's paws and eyes) in different ways from a single input.

A.2.2 Simplification and Generalization of Mechanisms

All of the users, at least initially, had considerable difficulties moving beyond the form and function of the example automata and mechanisms that they used as references. This seems to be a reasonable response when learning a new domain, but for some of the users this was a persistent issue. For example, the mechanism in Abbie's dragon is based on the one in Celia the sea lion. Both mechanisms use a collection of eccentric cams or discs and followers to obtain all of the motions. Celia also uses a lever hidden inside the body to convert the motion of one of the follower rods to the oscillating motion of the front flippers. The dragon needed to do the same in order to get the fire to alternately move in and out of the mouth but because the lever in Celia's body is hidden and there were no example mechanisms with levers available for Abbie to view,

a considerable amount of time was spent attempting to find ways in which other mechanisms, particularly crank-sliders and snail cams might be used.

A.2.3 Considering Alternative Mechanical Solutions

Because the users were all new to the domain, there was a tendency to stop looking for solutions once one was found. Again, this is not a surprising result, but in a number of cases a better solution existed and was only discovered after some problem or problems with the initial solution had been discovered. In these tests the process of discovering those faults often led to increased domain understanding, so the time lost in pursuing a flawed solution was seldom wasted. While the number of users and automata in the tests were not large, it is interesting to note that in the cases of the carousel and the beehive, both second automata for their builders, that the experience gained from the previous builds was brought to bear on the new designs and a number of plans were conceived and evaluated before selecting the final candidate.

A.2.4 Reorienting Extant Mechanisms

When the users turned to example automata and mechanisms for ideas and understanding an interesting trend was observed. Because all of the examples had obvious top and bottom orientations, users would put them in that orientation before working with them. This usually meant that the base was placed on the work surface before the crank was turned and even when they were held in the hand, the base was almost always kept as the lowest part. It required explicit instructions from the researcher to get any of the users to rotate or invert any of the example machines. This was not something that seemed to change over the course of the testing and even the users who exhibited the greatest increases in domain ability would rarely spontaneously change the orientation of an example.

A result of this bias occurred when some alternate orientation of a component or mechanism was required to produce a desired behavior. In these cases, the users were puzzled by the solutions proposed by the researcher, even when the basic function of the components in their

"standard" orientations were understood. An example of this is the lever behind the mouth of Abbie's dragon that moves the fire in and out. This linear output motion is roughly horizontal while the linear input motion is applied vertically by the cam follower. In order to make the translation from vertical to horizontal motion, the lever had to be placed at roughly a 45 degree angle. Even when experimenting with this arrangement as an oversized cardboard mockup, it took some time for Abbie to appreciate the ability of the angled lever to do what she wanted.

A.2.5 Mechanical Dependencies

All of the automata built by the users contained multiple motions. This created dependencies between the motions that were not always obvious or easy to identify. These dependencies show themselves most often in either the timing of movements or when motions become conflicting or confounding. A simple example occurred when Iris wanted the head and the hand of the man with the globe to be operated from the main shaft. Because of the close proximity of those tableau elements, it was not possible to create a mechanism to move them both, and it was not until she hit upon having the spinning globe move the hand that both motions were possible. Another example is Abbie's initial plan to have the body of the dragon move up and down to produce the flapping of the wings as is done with Ralphie (Section D.1). Moving the body would have created a number of problems with the cam followers for the fire and tail that weren't obvious to her at the time and, in the case of the fire, would almost assuredly have proved impossible to overcome.

A.2.6 Lack of Mechanical Education or Experience

This category presented itself in a number of ways, and varied considerably from user to user. Some of these problems were related to the physical properties and interactions of the mechanical components and tableau elements. Users had little understanding of mechanical effort being lost to friction or how the proper choice of a fabrication material depended on attributes such as density and strength. For many users, this was a first experience in the real world uses

of mathematics. Making accurate measurements, calculating size and position, and working with both fractional and decimal measurements were unfamiliar activities. While some users picked these skills up quickly, others did not. None of the users came to the projects with a knowledge of proper construction techniques. Users were not likely to test fit pieces before gluing to determine the fit and operation of the mechanisms and to identify a reasonable series of steps for final assembly. All users needed instruction in the proper preparation of components and in the correct use of glue to secure them. Finally, none of the users were initially able to see the tableau as an extension of the mechanism. It took some time before users could see that the motion of their automata didn't simply proceed from the mechanisms to the tableaus, but was a closed loop in which each module acted on and reacted to the other.

A.3 User's Experiences with the MachineShop System

For all users, the amount of time spent interacting with the MachineShop software was a small fraction of that total time spent creating their automata. Some users such as Iris and Calum spent only the time necessary to make their mechanical components, although in neither case did this prevent them from creating high quality automata. Abbie and Frank spent more time with the software designing the more non-standard components found in their automata. Sam and Dylan were the most active users of the software and both spent a considerable time beyond creating components to explore the capabilities of the software.

The most often-used tools were the component editors. All users spent time with these tools creating and modifying mechanical components for their automata. Users rarely took advantage of the software's ability to save and open component files. This may be due in part to all of them sharing a computer in the laboratory and not having MachineShop available to them at home where they might have been more inclined to create components and save files that they then would have brought to the project sessions. It may also be a result of the simple nature of the components that they designed and the lack of difficulties they experienced in creating them. When users first created a component, they would create a fabrication file and a prototype part

would be made. Quite often, this part would have acceptable properties with respect to size and function and a revision would not be necessary. If the part did need modification, most users would simply recreate the component and apply any necessary changes rather than retrieving a saved file from the library.

Other than Sam and Dylan, the users also spent little time in the Movement Explorer tool. Overall, this may have resulted from their having access to the physical mechanisms that were created for the video files used by the software. Users found it more convenient to simply pick up a mechanism of interest and interact with it than to go through the necessary steps to see it on screen. The physical mechanisms also encouraged the users to compare similar mechanisms and to manipulate them in ways not shown in the video. The researcher was available to answer questions about the mechanisms and to ask questions that the users could then explore. For other users of the software, the Movement Explorer will certainly be a more useful tool and it will be interesting to see both the ways in which users leverage it and the amount of time they spend using it when either the mechanisms or a mentor are not available.

A fair question at this point would be: What advantages did the MachineShop system give the test users as they designed and built their automata? The goal of the system, both software and hardware, was to provide support for children whose skills and understanding were not sufficient to allow them to build automata without assistance. In that respect, the system has proven quite successful. The children who participated in these projects were able to produce accurate and robust mechanical components with the same ease as any skilled artist. The system helped them do that by allowing them to focus on what they wanted without having to worry about how they would then accomplish it. The system was able to do this in three ways. First, the software encapsulated significant domain knowledge that was transparently available to users. Much of that knowledge relies on mathematics that most users will be unfamiliar with: trigonometric functions to calculate the profile of a snail cam, or the involute curves found in manuals of gear design for instance. Second, the system acknowledged that these users are most likely inexperienced tool users with little or no knowledge of the properties of the materials they will need to use. By

incorporating fabrication tools that can work with a wide range of materials, that are capable of producing objects more accurately than almost any skilled individual could, and that can do all of this in the fraction of the time it would take by conventional means, the system allows the users to create beyond their abilities. Third, by coupling the software and the hardware in such a way that no information is lost, the process of moving from idea to object becomes a path that users can easily navigate. The need to produce drawings and to transfer the information they contain to raw materials for fabrication is eliminated through the use of files that are created by the software and utilized by the hardware.

A side effect of all this is that users spend less time fabricating and more time creating. Early experience with skilled adult builders had shown that creation of even the simplest of components, such as an eccentric cam, took significantly longer to do with traditional methods than using MachineShop. To create an eccentric cam with compass, band-saw, power sander, and drill can easily take five or more minutes. With MachineShop the finished cam is ready in no more than two minutes and is of considerably higher quality and finish. When creating more complex components, such as spur gear trains, this difference is even more pronounced. What this meant for the users was that they could accomplish in twelve or fifteen hours what might otherwise take them hundreds of hours. For two of the users, Sam and Dylan, this allowed them to make two automata each during the testing. It also gave several users additional time to become more knowledgeable about the domain as the extra time available to them in project sessions was used to explore facets of automata and machines that they found interesting.

A.4 Apprenticeship in Practice

Apprenticeship means different things to different people. In the crafts and trades, an apprentice learned by first watching a master work and then copying that process to the best of his abilities. Depending on the temperament of the master, those efforts could be gently guided to help the apprentice gain skill, or they could be denigrated in a desire to have only the strong survive. As applied to this research, apprenticeship was an opportunity for novices to engage in

a challenging activity knowing that they had support in the form of the researcher. While not precisely what has historically happened in the guilds, it very much embraced the philosophy of learning by doing inherent in that model.

Because of the age of the users, there was great variability in the the knowledge and skill that users brought to the testing and in their goals and desires. Each user had different needs and in the one-on-one setting of the project sessions the researcher was able to tailor his involvement as much as possible to meet those needs. Based on the needs of the users, the support provided by the researcher fell broadly into three categories.

First were the users who were only marginally engaged in the process. This occurred for a number of reasons. Some users seemed timid when asked to challenge themselves, possibly because they were afraid that they would not do well unless they were told what to do. These users rarely asked the "what if?" questions and were passive participants in defining their project's trajectory. These children were intelligent and in some cases very outgoing. This was the most difficult group for the researcher to support. While the desire was to see that these users were very successful, it was often necessary to withhold ideas or information that might have been more freely shared with other users. The researcher hoped to have the finished automata represent the user's designs without being too much a product of the researcher's input. These users were indirectly (and on a few occasions directly) guided toward possible solutions in the hope that the they would make exciting discoveries. This didn't happen as often as hoped, but did happen often enough that the resulting automata were very satisfying.

The second group of users were what could be described as archetypal. They were engaged and inquisitive and weren't afraid of doing something over again until it was right. They were among the most frequent users of the MachineShop software, and explored many aspects of the domain when away from the project sessions. These users challenged the researcher as much, if not more, than the researcher challenged them. This group was also the most prolific in terms of the number of automata they created. These users could be expected to provide a thoughtful answer to abstract or esoteric questions about the domain, even if it wasn't always correct. The

interactions between these users and the researcher were the most lively of any of that seen in any of the groups.

The third group of users were the boundary pushers. These were the users whose early design ideas could only be minimally supported by the MachineShop software but who decided to continue on anyway. This was the most challenging group for the researcher. Not only were these users exploring novel mechanical devices, but there was variety to that novelty. These differences were accentuated by differences in working styles. One of the users proceeded in a very trial-and-error manner, making quick decisions and then trying them out. The other was very methodical and reasoned through to a decision before applying it. Interestingly, it was the latter user who made the greatest number of prototype mechanisms. This was partly due to its greater complexity, but it was also due to his method of constantly refining the components for his mechanism. At many times during these projects, the researcher's knowledge and understanding of the domain were stretched past their limits. On a number of occasions, the researcher and user could be found sitting side by side pondering and discussing some subtle aspect of a mechanism that needed clarification. These interactions were more that of peers than of student and mentor.

Appendix B

Automata Created with MachineShop

This appendix presents the automata that the test users created with MachineShop. These eight examples display a wide variety of aesthetic and design styles but all are instantly recognizable members of the contemporary automata school and are whimsical and extraordinary objects.

B.1 Abbie - Drowsy Dragon

Abbie was 10 years 10 months old and in the fifth grade when she began this project. Abbie wanted to make an automaton featuring her favorite animal, a dragon. She brought a plush dragon to the initial design session that was roughly the size she wanted her automaton to be. She also brought a sketch she had made of what she hoped to build (Figure B.1. The plush toy was about twice the size of her sketch and the finished automaton figure ended up being roughly the same size as the plush toy. Abbie's initial goal was to have the dragon flap its wings, move its tail from side to side, and breath fire.

Because these three actions all appeared along the center line of the dragon's body, Abbie chose to use a single shaft to which she would attach a crank in order to power all of the motions of the dragon. She first set about getting the dragon's wings to flap. She decided to keep the dragon's body stationary and make the wings third order levers. The fulcrums would be located where the wings attached to the body and the force would be delivered somewhere near the middle of the wings. Her choice of mechanical advantage (ratio) and lift would determine how much the wing tips would move. Since she wanted the wings to move smoothly and at a constant rate she elected

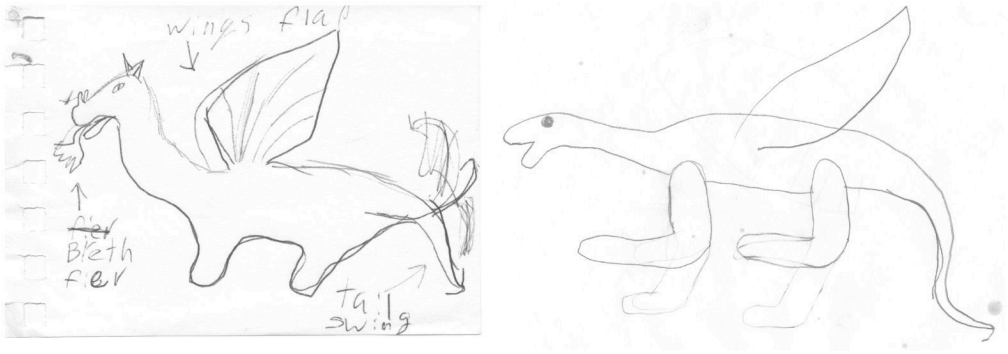


Figure B.1: On the left is Abbie's first sketch of her dragon. Notice that while she has behaviors annotated on the drawing, there is no indication of a mechanism or support framework included. This became the primary model for the finished dragon. On the right is Abbie's study for how the dragon might look lying rather than standing. Although this dragon has a substantially different appearance (it was drawn in the lab while the first sketch was done at home) you can see that Abbie is already starting to see that the legs and wings will be separate from the body. She hasn't yet discovered that necessity for the tail.

to use an eccentric cam to lift and drop a follower. This follower is a thick rectangular block that is wide enough to be attached to the wings by two pieces of small diameter music wire that pass through two small holes in the top of the support framework. The follower is thick so that its mass pulls the wings down as the cam rotates. To keep the follower properly aligned, it has two guide holes that ride on dowels protruding from the underside of the framework's top.

Abbie next turned her attention to the tail where she chose to use a Markey oscillator (see Section D.3 for a more detailed description). Not only did this provide the back and forth motion for the tail that she wanted, but it also introduced an up and down motion that she liked. To take strain off the oscillator, the shaft that rotates the tail uses two tabs at the rear of the body as bearings to hold it in alignment.

The fire breathing proved to be the most difficult motion to design. Abbie considered a number of possibilities from among the simple mechanisms that she had access to and was fairly certain that she could do it with one of the types of crank-slider (Figure D.9). This presented her with two major problems. First, how could a crank-slider be made small enough to fit inside the head and neck of the dragon while still moving the fire the distance she wanted? Second, how

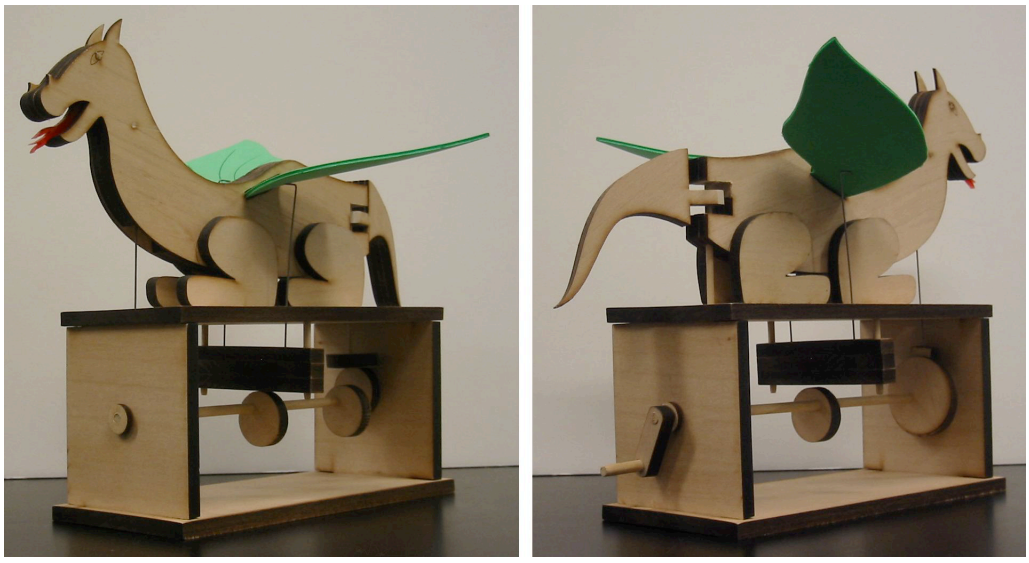


Figure B.2: Two views of the dragon. On the left, the follower for the wings and the Markey oscillator for the tail can be seen. On the right, the eccentric cam and ring follower for the fire are visible. The wires that move the wings can be seen in both views.

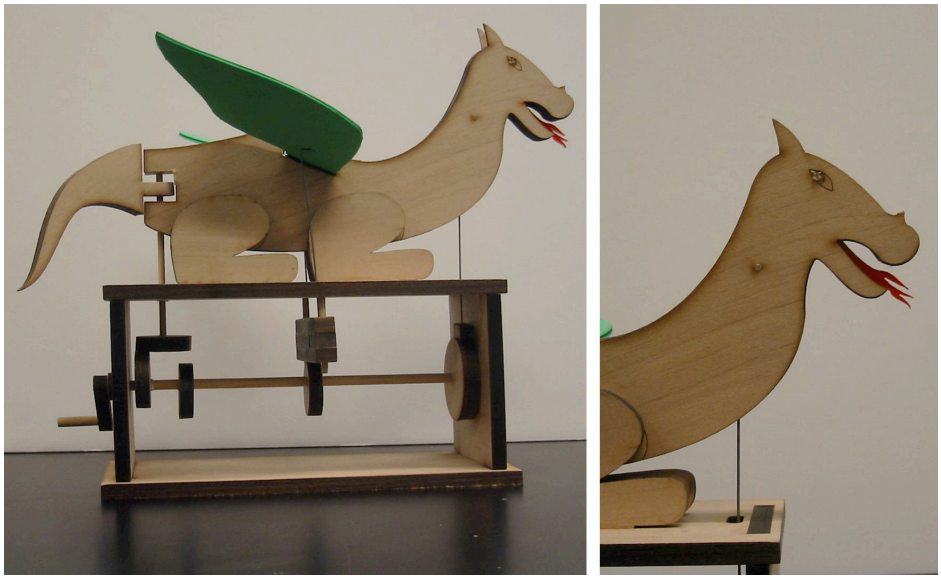


Figure B.3: Two views of the mechanism for the dragon. The left view shows the complete mechanism: the Markey oscillator for the tail, the eccentric cam and block follower for the wings, and the eccentric cam and ring follower for the fire. The close-up view provided detail of the fire breathing. The wire that actuates the lever inside the dragon's neck can be seen passing through the top of the framework and the fire can be seen coming out of the mouth. Not visible is the lever that translates the vertical motion of the wire into the horizontal motion of the fire, although the shaft on which it pivots is visible to the left of the mouth.

could she transmit the rotational motion needed by the crank-slider from the main shaft? This would require it to be rotated 90 degrees since the shaft of the crank-slider would need to be orthogonal to the main shaft to fit in the body.

These problems forced her to look for another solution and she ended up placing a lever of the first order in the neck of the dragon. She inclined the lever at about 30 degrees from the vertical to match the upper slope of the neck. To the lower end of the lever she attached another piece of music wire that terminated at a ring follower surrounding an eccentric cam on the main shaft. To the upper end of the lever she attached the fire so that it could move in and out of the dragon's mouth. By inclining the lever, she was able to change the vertical motion of the cam follower into a horizontal motion for the fire.

Abbie drew her inspiration for the mechanism she designed from two of the sample automata she had access to. Ralphie the flying bison (Section D.1) suggested her initial ideas on making the wings flap, even though the way in which this happens in the dragon is quite different. Celia the sea lion (Section D.3) provided the techniques used to move both the tail and the fire. Abbie used basswood of various thicknesses for all of the wooden parts except the dowels, music wire operates the wings and fire, the wings are cut from craft foam, and the fire is cut from red acrylic plastic.

B.2 Calum - The Commute

Calum was 11 years and 8 months old and in the sixth grade when he began this project. Calum was already an experienced Macromedia Flash programmer and had become interested in understanding the elements of human locomotion for a project he was working on. To expand on this, he decided to construct an automaton that would focus on people walking by representing three men on their way to work. To add variety to the figures, he chose to have one carrying a briefcase, one carrying an umbrella, and one carrying a coffee cup.

Since the walking motion was the key element of this automaton, Calum chose to design a single mechanism to create that motion and to replicate it. This decision simplified the prototyp-

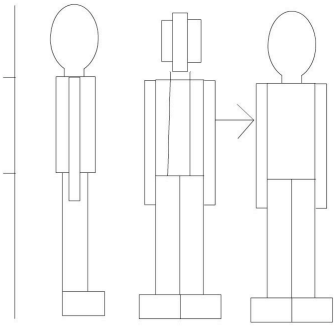


Figure B.4: Calum's first sketch of a commuter. Unlike the other users who drew their sketches with pencil on paper, Calum was already an experienced Flash programmer and drew these figures using his computer. Note the scale at the left of the drawing which is divided into thirds to provide the proportions for the head, torso, and legs.

ing since only one instance of the mechanism needed to be refined and that mechanism would then be copied for all of the figures. This automaton also presented some special challenges as the legs are also components of the mechanism.



Figure B.5: The commuters head to work. These views highlight the large number of mechanical components that all work together to provide the user experience. Each figure carries an item of importance: an umbrella, a coffee cup, a briefcase. The figures were colored using water base markers and the shirts and ties were cut from magazine advertisements.

Calum's sketch of the figures was used to create cardboard mockups to help in determining the size of the automaton and a cardboard framework was built to those dimensions. Since the mechanism contained so many components that needed to work together, no cardboard mechanical components were created. Instead, it was decided that one complete mechanism, up to and including the figure's torso, would be constructed from wood. Calum began by analyzing his own walking gait and looking for examples in the simple mechanisms that would provide a similar motion. He picked the offset crank version of the crank-slider mechanisms (Figure D.9) because he thought it would have an interesting look.

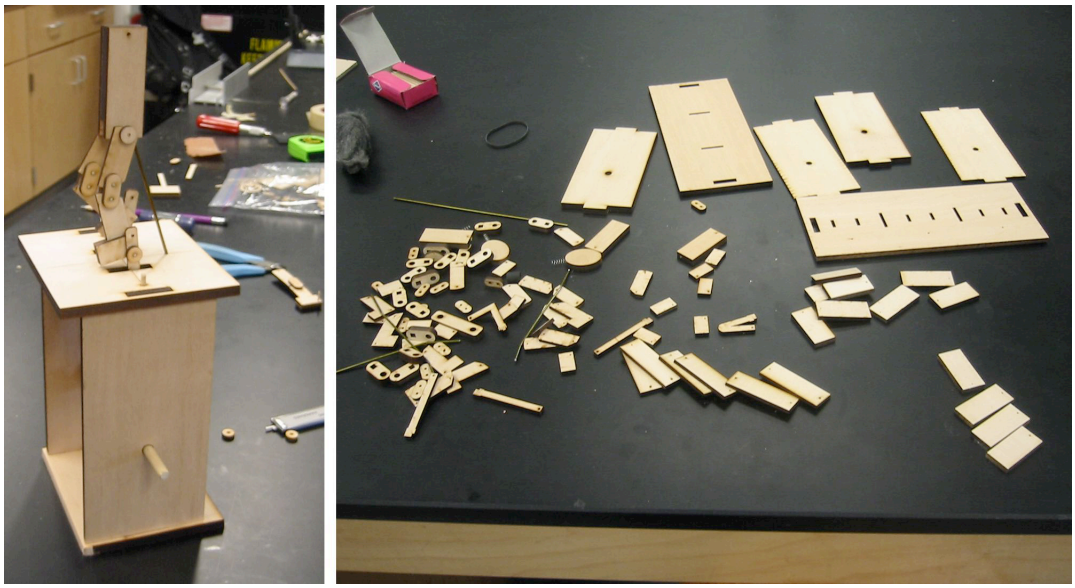


Figure B.6: On the left, the wooden prototype built to refine the mechanism. On the right, of the 130 pieces in the automaton, 107 pieces were fabricated with the laser cutter. Calum and his parents found the assembly process quite challenging.

The upper end of the slider rods attach to the figures' heels and move them in an oval path. As each heel moves up and forward, the upper leg also moves because of it's connection to the lower leg at the knee and to the body at the hip. The knee provides two pivot points, one for the lower leg and one for the upper. Calum found the design and assembly of the legs required that he insure that the knees would never lock or be allowed to move to the rear. He accomplished this by tapering both leg pieces so that at full extension the knees were very slightly

flexed. The cranks for each figure were rotated 180 degrees during assembly and these assemblies were rotated 120 degrees when attached to the crank shaft.

The body of each figure is supported by a piece of coat hanger wire that is inserted into a hole in the top of the framework. This provides a non-rigid attachment and causes the bodies to twist slightly as the legs move. By allowing the arms to move freely at the shoulders and by using small springs to attach the head to the body, a number of motions secondary to the leg movement are provided that give the figures a feeling of life.

The majority of the pieces for the automaton were cut from basswood on the laser cutter. Birch dowels were used for the main crank shaft and square basswood strip was cut to keep the halves of each crank aligned. Coat hangers were cut to provide the support and attachment for the bodies and the necks of the figures were made from ballpoint pen springs. Calum made the umbrella from construction paper and a toothpick, and the coffee cup was made from a section of the body of a pen. The figures were colored with markers and the shirts and ties were cut from magazine advertisements and glued on.

B.3 Dylan - The Leaping Lion

Dylan was 10 years and 6 months old and in the sixth grade when he began these projects. The lion was his first automata and was inspired by a chance encounter some of his classmates had with a mountain lion while on an overnight camping trip. The initial concept was to have been a mountain lion but the more obviously leonine profile of an African lion was substituted early in the design. Dylan wanted the lion to be ferocious, and to convey this menace he wanted the lion to leap forward towards its prey while opening its mouth. Dylan felt that the lion would be far less threatening if it were allowed to leap backwards and this became an additional constraint for the mechanism.

To provide the leaping motion for the lion Dylan chose to use a crank-slider mechanism. Of the three that he was able to work with, he decided that he wanted to use the disc with offset pin (Figure D.9). He had already determined that he could constrain the motion of the leap to

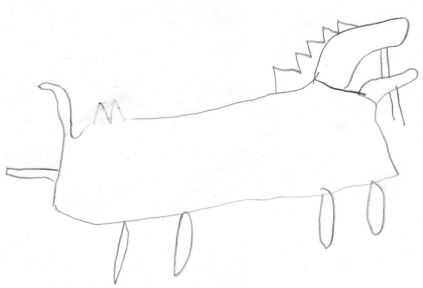


Figure B.7: Dylan's sketch for the lion shows a mane like that of an African lion. Also note that it appears that the operating mechanism for the jaw is intended at this early stage to move the upper jaw rather than the lower as in the final design.

forward only through the use of a ratchet and pawl (Figure D.8). While designing the crank-slider components in the software he concluded that he could reduce the number of components in his mechanism by eliminating the disc for the crank-slider and attaching the offset pin to the ratchet instead.

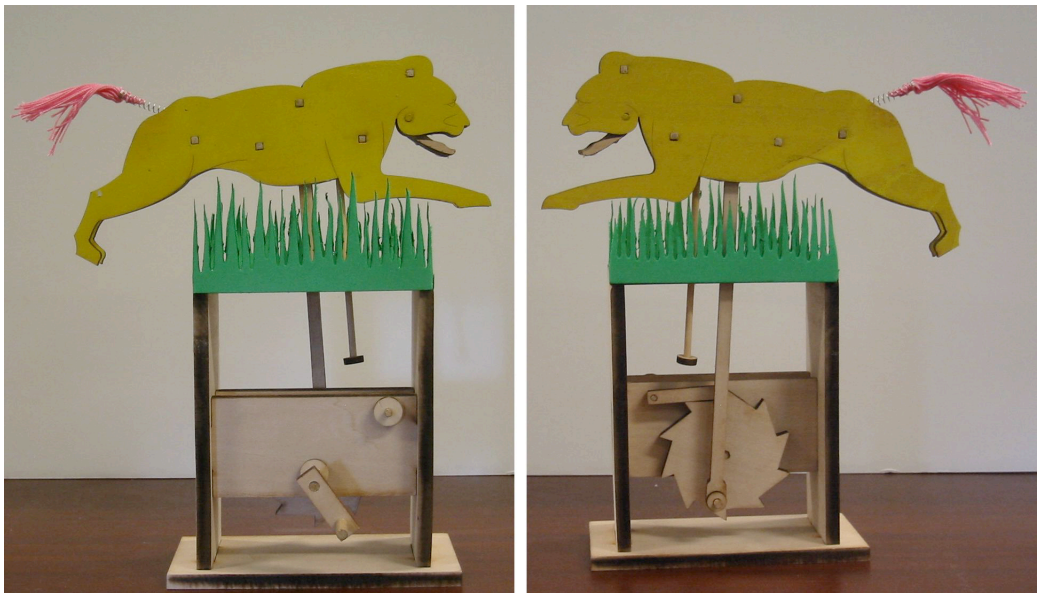


Figure B.8: The back (crank side) and front (ratchet side) of the Leaping Lion. In the front view, note the pawl which constrains the ratchet to turn only clockwise, and the pin affixed to the ratchet to which the slider arm is attached. The pushrod for the jaw and its lower stop can also be seen in both views.

While the leaping motion was accomplished quite easily, getting the jaw to open and close

posed a number of problems. Dylan considered a number of possible methods before deciding to integrate the lower jaw into a lever of the first order that would be placed inside the lion's body. By taking advantage of the up and down component of the leaping motion he was certain that he could make the jaw open and close.

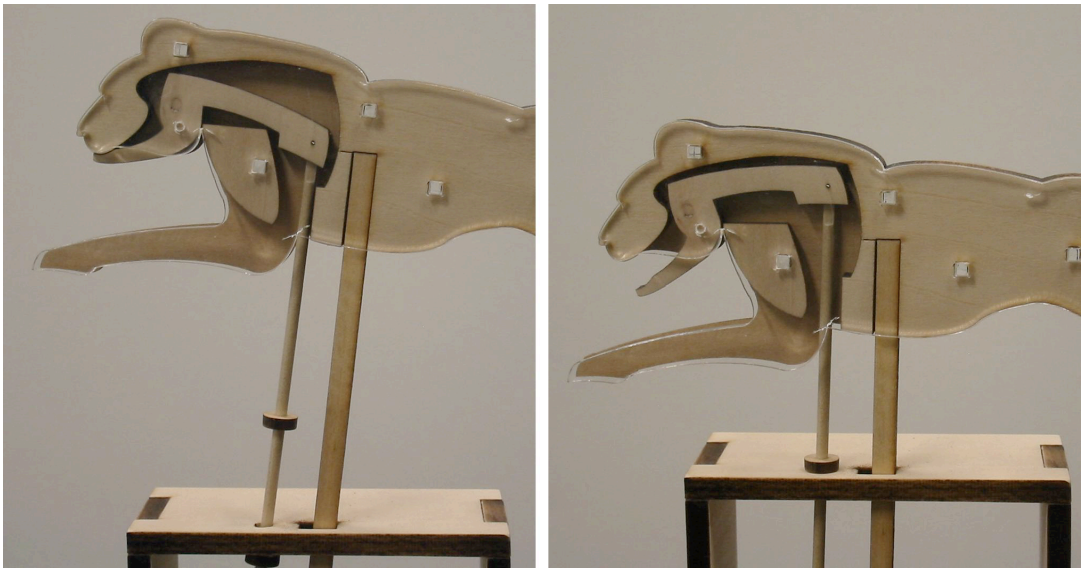


Figure B.9: The lion's jaw is a lever of the first order with its fulcrum near the lion's shoulder. As the lion is raised by the crank-slider, the lower stop on the pushrod contacts the underside of the top of the framework, pulling down on the rear of the lever which closes the jaw. As the lion is lowered by the crank-slider, the upper pushrod stop contacts the upper surface of the framework's top, pushing the rear of the lever upward which opens the jaw. This automaton was made from Dylan's original files and has the front side of the lion's body cut from clear acrylic to show the motion of the jaw.

The problem then became to utilize that aspect of the leaping motion without letting the front to back component interfere. He finally settled on a clever solution in which the jaw is moved by a rod attached to the end of the lever opposite the jaw. This rod passes through a hole in the top of the support framework that is long enough to allow it to rock back and forth as the lion moves front to back. The rod has two discs attached to it that act as stops to restrict its up and down motion; one below the framework top and one above it. As the lion moves up, the rod also moves up until the lower stop contacts the framework which occurs before the lion reaches the top of its motion. The additional upward motion of the lion causes the rod to pull down on

the lever and this closes the jaw. As the lion moves downward, the opposite happens, and the upper stop causes the rod to open the jaw.

The motion of the lion is similar to that of Ralphie the flying bison (Section D.1) but the action of the jaw is unlike anything Dylan had seen before starting. The body, crank-slider and ratchet components are laser cut from basswood. The grass attached to the framework is laser cut from craft foam. The tail is a bundle of kite twine twisted at one end and inserted into a spring from a ballpoint pen.

B.4 Dylan - Busy Beehive

Dylan's second automaton was a considerable departure from the lion. Begun in the spring of the year it was inspired by the bees that he was seeing flying around the flowers that were blooming in his yard. His idea was to have two bees engaged in the maintenance of the hive. One bee would fly from the hive to collect pollen and then return it. The second bee would shuttle back and forth, moving the collected pollen from one place to another. Dylan originally feared that this would be too hard to construct.

Dylan was able to design mechanisms that would provide the two motions he wanted and that could be driven from the same input. As it turned out, the input from the crank turned by the user is transferred to one mechanism which in turn transfers it to the second. The circular motion of the flying bee is driven directly from the input crank by a pair of pinwheel gears. This allows the shaft to which the crank is attached to be placed horizontally in the mechanism while turning an output shaft that is rotated 90 degrees to the input. This permitted Dylan to put the crank on the side of the support framework and to have the bee fly in circles that are parallel to the shaft. Because he wanted the two bees to move at different rates, the gears chosen for the flying bee have a two to one ratio; the bee flies one complete circle for each two turns of the input crank.

To get the back and forth motion of the other bee, Dylan added a third pinwheel gear that receives its input from the gear attached to the flying bee's shaft. Dylan wanted this bee to move faster than the flying bee so he chose a gear the same size as the one attached to the crank.

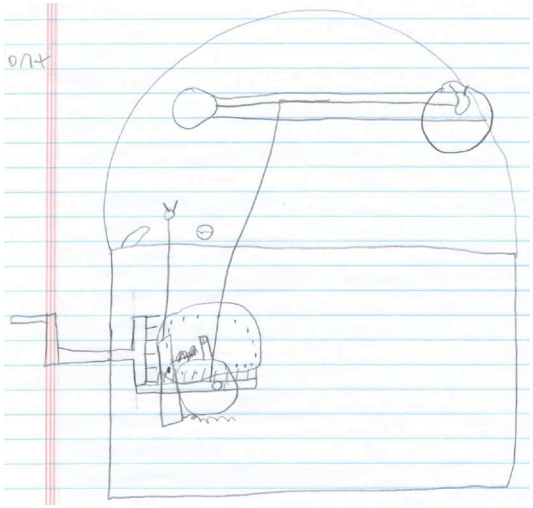


Figure B.10: Dylan's first sketch for the beehive. At the top, one of the bees flies in and out of holes cut in the hive while a second bee moves from side to side shuttling the pollen from one pile to another. This sketch was made after Dylan had decomposed the overall motion he wanted into several simpler motions. Note the difference between this sketch and the one he made for the lion with respect to the amount of detail in the mechanism.

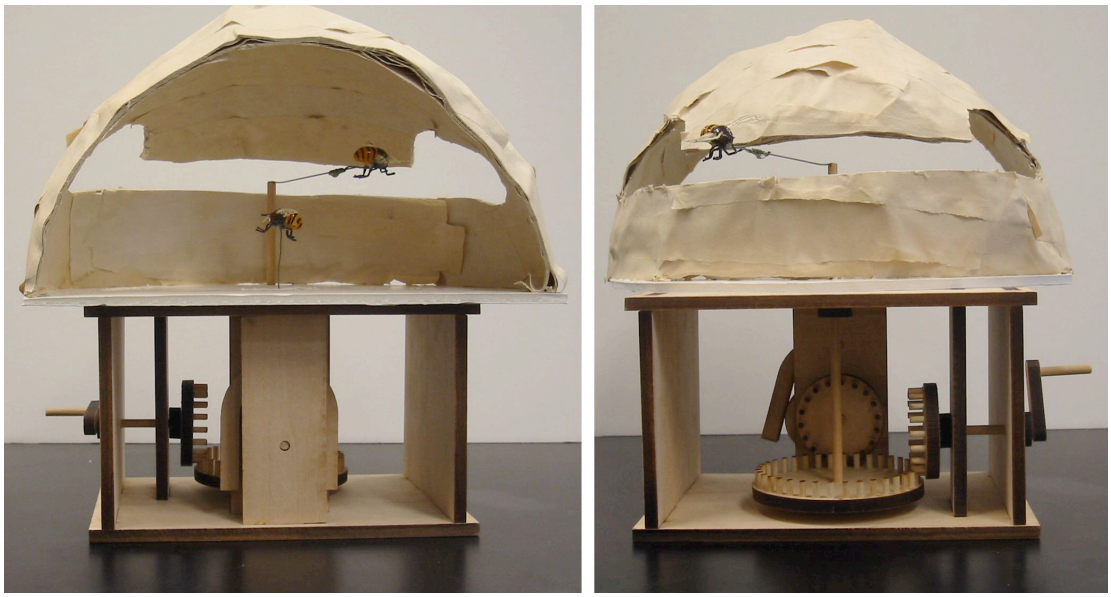


Figure B.11: Front (left) and back (right) of the completed beehive. The pinwheel gears can be clearly seen in the back view along with the Y-follower for the eccentric cam. The cam is hidden between the two vertical supports and just a small part of it can be seen touching the follower.

The ratio of these two gears is one to two and the effective ratio of this gear to the input gear is

one to one. This means that for each turn of the crank, the flying bee moves one half of its total path distance and the lower bee moves from one side to the other and back again. This gear is attached to an eccentric cam whose follower provides the even side to side motion of the lower bee. The follower is oriented vertically and cannot depend on gravity to hold it in contact with the cam. Dylan had originally planned on using a spring to hold the follower tight to the cam, but eventually decided to create a follower in the shape of an inverted capital "Y". The forked part of the follower straddles the cam to provide positive contact and the bee is attached to the end of the vertical leg.

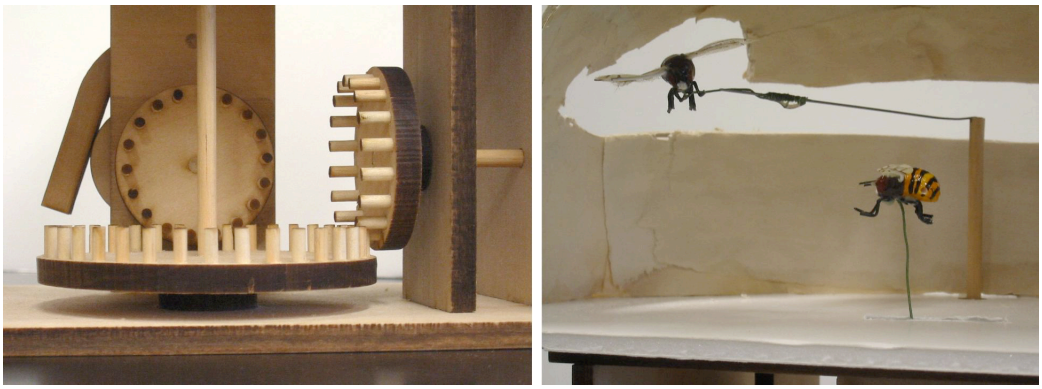


Figure B.12: On the left is a close-up view of the beehive mechanism. The pinwheel gear on the right is attached to the crank by the shaft seen here and supplies the input motion to turn the large horizontal pinwheel gear. This gear's shaft is attached to the flying bee and moves it along its circular flying path. The third pinwheel gear is driven by the horizontal gear and turns the eccentric cam just visible to the left of the vertical support. The motion of his cam rocks the Y-follower which in turn provides the back and forth motion of the lower bee. On the right is a close-up view of the two bees.

The framework and mechanical components were cut from basswood on the laser cutter. The shafts and teeth for the pinwheel gears were cut from birch dowels. The bottom of the beehive was cut from foamcore board and the beehive itself is papier mâchè, formed over an inflated balloon. The bees were purchased from a craft store and are used in making artificial flower arrangements. Each bee has an attached wire that is used to secure it to the automaton. The lower bee's wire was inserted into a hole drilled in the end of the follower and glued. The

flying bee had its wire wrapped around and glued to a piece of music wire that was bent 90 degrees at one end and glued into a hole drilled in the pinwheel gear shaft.

B.5 Frank - Evil Cat

Frank was 12 years and 1 month old and in the sixth grade when he began this project. The idea came from two sources. First, Frank's family were cat owners and he was familiar with the ways in which cats often play with their prey. This gave him the idea of building an automaton of a cat juggling a mouse. Second, his parents had been renting DVDs of Felix the Cat cartoons and the black and white coloring of Felix made its way into his design. Initially, Frank wanted the cat to simply toss the mouse from one paw to the other and then back again. During the prototyping he decided that the eyes should also move and track the mouse as it flies through the air.

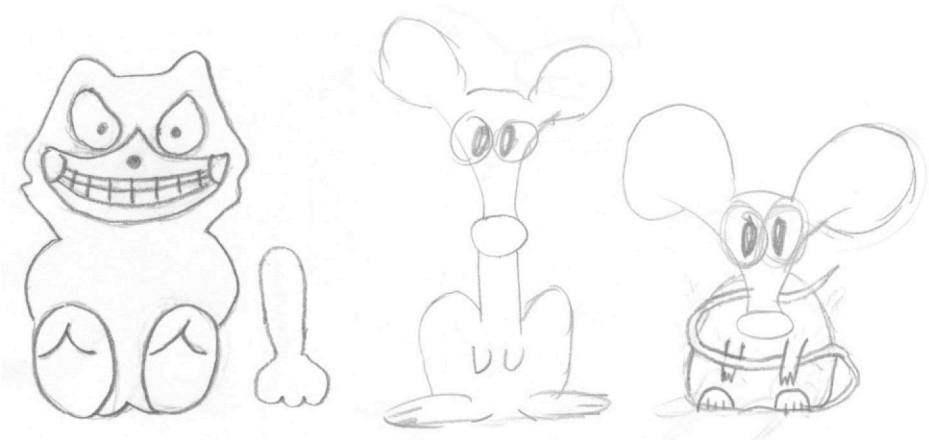


Figure B.13: Frank's first sketches for the evil juggling cat. On the left is his design for the cat and one of its paws. On the right are two possible mice that the cat could juggle. The rightmost mouse became the final design.

The initial requirements for the motion of the automaton seemed simple, but it soon became apparent that getting the timing to work out correctly for all three motions would be challenging. While the eyes have an obvious linear reciprocating motion, the movement of the mouse and the paws could also be seen a reciprocating along a curved, rather than a straight path. These three motions were all of different physical lengths but all had to occur in the same amount of

time; one rotation of the crank. Because this mechanism was the most complex of any built during the user testing, a significantly longer time was spent working with cardboard prototypes to insure that the mechanism was correct before fabricating components from more durable materials.



Figure B.14: Front views of the juggling cat showing the extreme positions of the mouse and how the paws and eyes move to match. Franks drawings of the cat and mouse were scanned and converted to files that were then used to fabricate the pieces with the laser cutter.

The first motion to be designed was the rocking motion of the paws. Attaching the paws to the ends of a first order lever was the obvious solution, but a method was needed to convert the rotation of the crank into the rocking of the lever. An eccentric cam, offset to one side of the levers fulcrum was considered but discarded early on when having the cam in that location made working with the other motions more difficult. Frank settled on a disc with an offset pin as used in the crank-slider but looked for a way to move the lever without resorting to a slider rod. He managed this by making the lever T-shaped. The paws were supported on the ends of the crossbar of the T and a slot was cut into the leg of the T that was longer than the total vertical travel of

the pin as it rotated. In this way, the horizontal position of the pin controlled the motion of the lever and the vertical position of the pin was ignored. The length of the crossbar was determined by the location of the paws with respect to the body and the length of the leg of the T and the distance from the disc to the lever's pivot were changed iteratively until an acceptable motion was obtained.



Figure B.15: The mechanism of the cat. The clear acrylic framework pieces can be seen on the left, as can the dowels that protrude through the body of the cat and attach to the paws. The rear view on the right shows the intricate nature of the mechanism. The disc near the bottom is attached to the crank and supplies input for all of the motions through its offset pin. The three-bar linkage at the left of the mechanism moves the third order lever that the mouse is attached to. The paws are attached via short dowels to the cross arms of the cross shaped first order lever. The top of the lever provides input to the second order lever that moves the eyes back and forth.

Frank then turned his attention to how the mouse would move. While the paws travelled only a short distance as they moved, the mouse would need to travel through an arc of nearly 180 degrees and would have to do it twice for each turn of the crank. Attaching the mouse to another

lever would sweep it through that arc, but directly attaching the lever to the disc (as was done with the paws) would not work. To convert the relatively short motion of the pin into the much longer motion of the mouse involved attaching the mouse to a lever of the third order and moving that lever with a linkage made from three other levers. Again, a significant amount of experimentation went into determining the the correct size and placement of the linkage pieces before the mouse moved as Frank wanted.

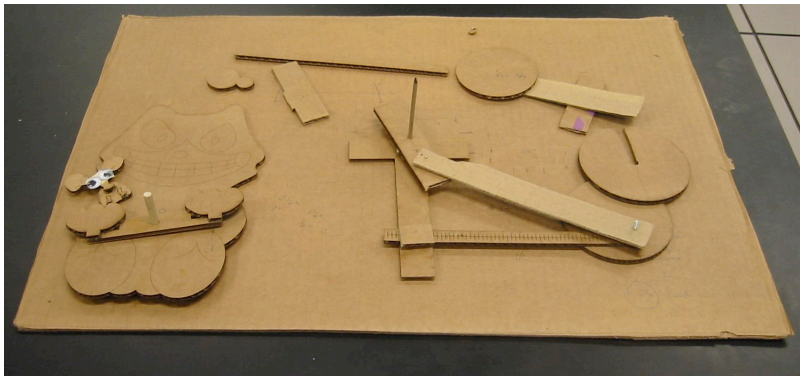


Figure B.16: Shown here are some of the cardboard pieces created during the prototyping phase of the cat's design. Because of the complex and intricate nature of the mechanism, considerable time was spent refining and perfecting the prototype.

It was at this time that Frank decided that the cat's eyes should follow the mouse as it moved. Once more, the problem of getting a useful motion from the crank became the immediate problem. The solution came while looking at example automata on the Web. By adding another leg to the T-shaped lever, and making it a cross, the movement of the disc could be transmitted to the eyes. In doing this, however, the direction of of movement was reversed as the lever ends moved in opposite directions. This would mean that the cat would look away from the paw where the mouse would be. The solution was to add yet another lever, this one of the second order, that would be driven by the cross-shaped lever and would move the eyes.

Because this was such a fascinating mechanism to watch in action, the support framework was made from clear acrylic plastic to allow all of the mechanical components to be visible. The components themselves as well as the body parts for the cat and mouse were cut from basswood

with the laser cutter. Frank painted the figures before final assembly, as well as a rectangular piece of wood that covers the lower part of the framework below the cat's body and represents a box on which the cat is sitting. Birch dowels attach the paws to the lever and the crank and main shaft to the disc are also made from clear acrylic. The mouse attaches to its lever with music wire and its eyes were purchased at a craft store.

B.6 Iris - Globe Trotter

Iris was 10 years and 11 months old and in the fifth grade when she began this project. The idea for this automaton came from watching a friend spin a globe in their classroom at school. Initially, the only motion Iris was thinking of was the spinning of the globe, but as she worked on it, she decided to have the figure move his arm as if causing the globe to spin and to move his head from side to side as if looking for a location on the globe.

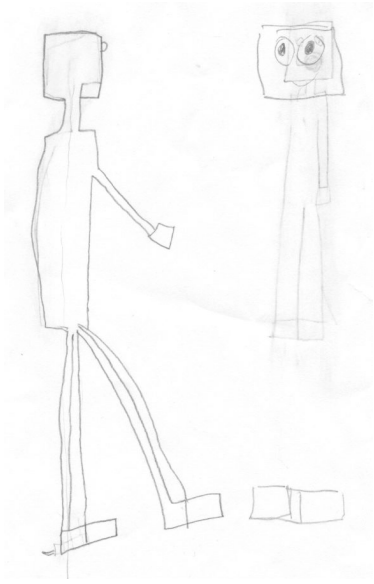


Figure B.17: Iris' initial sketch for the figure on her automaton. Note the curved legs and large eyes that made it to the final design.

During the design of her automaton, Iris was drawn to the mechanism in Celia the sea lion (Section D.3). The method used in Celia to spin the ball on her nose became the obvious choice

of how to spin the globe. Iris was insistent that the shaft that supported the globe should not be vertical as it was in the sea lion, but should be tilted as it would be with a real globe. By tipping the shaft, the contact area between the driving and driven discs became very small and because of the weight of the globe, it would not spin reliably. To overcome this, the driving disc (attached to the mechanism's main shaft) was tapered to allow more contact area between the discs.

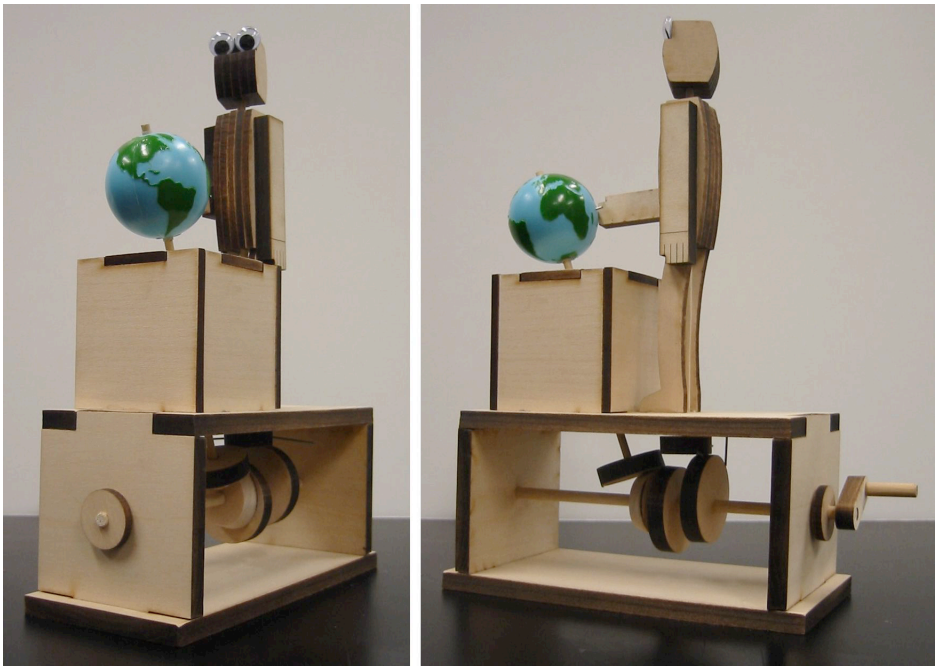


Figure B.18: Two views of the Globe Trotter showing the general arrangement of the tableau and mechanism. Note the detail of the figure's left hand that was etched into the wood by using a higher speed and lower power setting on the laser cutter.

The Markey oscillator used to move the tail in the sea lion was chosen to move the head of the figure. The sea lion's tail is limited to moving back and forth because it contacts the body at the limits of its motion. The figure in Iris' automaton had no such limiting features, and as first designed, the head would often end up rotating rather than looking left and then right. To prevent this, two small pieces of music wire were glued into the edge of the disc attached to the shaft that moved the head, and another two pieces of wire were glued into the underside of the framework's top.



Figure B.19: A side view of the Globe Trotter showing the mechanism. The main shaft is rotated by the crank at left and in turn rotates the two eccentric cams that move the head and the tapered disc that spins the globe. Wires in the disc attached to the head contact wires in the underside of the top of the framework and limit the amount of movement the head can make. A small wire inserted into the globe moves the right arm when the globe spins and the spring used at the elbow allows the arm to return to its original position.

Iris had wanted to have the figure's hand move as if that were the force behind the globe's motion, but as the head and arm were both attached to the body, there was insufficient room in the mechanism for additional components to move the arm. As the project neared its end, Iris happened to see another of the automata that used springs removed from ballpoint pens. By placing a spring at the elbow joint of the arm and having a small piece of wire protrude from the surface of the globe, the arm is moved as the wire strikes it and the spring allows that motion and moves it back into place to move again.

The framework and components for Iris' automaton were cut from basswood with the laser cutter. The main shaft and the those for the head and globe are cut from birch dowels. The base of the disc attached to the globe's shaft has sandpaper glued to it to increase the friction between the discs, thereby reducing the chances that the globe will slip when the crank is turned. The box

on which the globe rests and the pieces used in the figure are all laser cut basswood. The globe was purchased at a toy store, and the eyes for the figure came from a craft store.

B.7 Sam - Soccer Player

Sam was 11 years and 5 months old and in the sixth grade when he began these projects. The automata that he built and his experiences in the testing are related in greater detail in Chapter 7, but are reprised here for completeness.

The idea for the soccer player came one afternoon when he was attending soccer practice. Sam's initial idea for the automaton was simple; have the player kick the ball into the net. From his early encounters with the sample automata and mechanisms, Sam wanted the motion of the ball to be directly accomplished by the mechanism. After a number of discussions, he decided that the mechanism could be much simpler, and the entertainment value of the automaton much higher, if he built it so that the player actually kicked the ball.

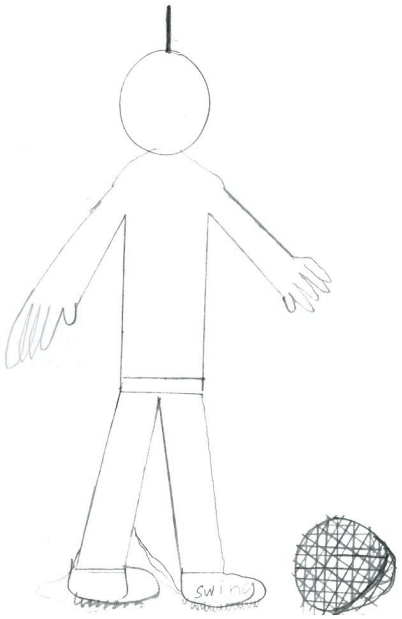


Figure B.20: Sam's first drawing for the soccer player included no indication of what mechanism might be needed nor what other parts of the tableau, such as the goal, would look like.

While simplifying the mechanism, this introduced two issues. First, the automaton would

need some way to insure that the ball returned to the proper location so that it could be kicked again. Second, the speed with which the leg moved needed to slow enough as it moved back to allow the ball sufficient time to return and quick enough on the forward stroke to propel the ball all the way to the goal. The first of these was addressed by two methods. A small slope was introduced into the kicking surface with the player's location lower than that of the goal. Then a second layer was added to the kicking surface that had a V-shaped section removed from it. With the wide end of the V at the goal, and the narrow end in front of the kicking foot, the ball not only returned to the proper kicking spot consistently, but the likelihood that any given kick would stay on the surface of the automaton was significantly increased.

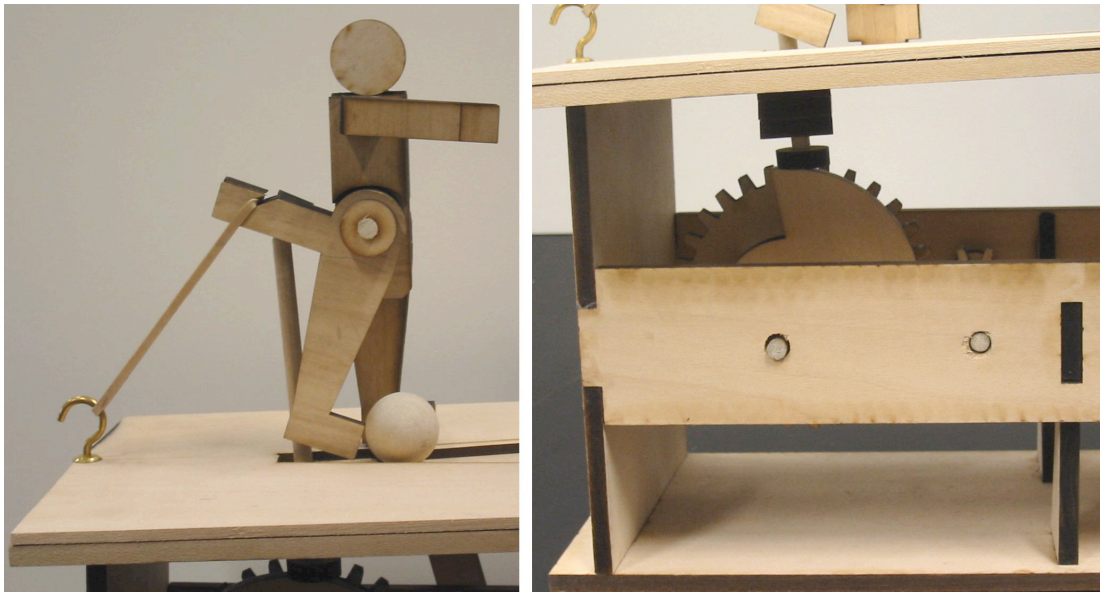


Figure B.21: Close-up views of the figure and mechanism. On the left, the player's leg is pushed back by the rising of the cam follower and this motion stretches the rubber band. When the follower drops, the leg is driven forward by the rubber band and this kicks the ball toward the goal. On the right can be seen the snail cam and follower that move the leg as well as the larger of the two spur gears that transmit the motion of the crank to the cam. The top of the smaller gear is just visible above the horizontal framework member. The shaft that carries this smaller gear is also attached to the crank.

The speed that the kicking foot traveled was controlled by the mechanism that Sam selected. To move the foot slowly to the rear, he used a pair of spur gears with a three to one ratio.

The smaller gear was attached to the crank's shaft and the larger gear was attached to the cam's shaft. Because of this, the cam rotates only once for every three turns of the crank. If the crank is not turned too vigorously, the ball will usually be in contact with the foot before the leg has finished moving. By using a snail cam to move the leg, the sharp drop off the lobe allows the rubber band to snap the foot forward with sufficient force to get the ball to the goal. Interestingly, because the ball is free to move in three dimensions, there are times when it doesn't get to the goal, times when it becomes entangled in the net, and times when it leaves the automaton altogether.



Figure B.22: On the left is another view of the mechanism that shows both gears and the cam. Note the tall cam lobe that was necessary to get the leg to move enough to propel the ball all the way to the net. On the right is the poster Sam made for the science fair explaining both the mechanical domain and his automaton.

During this project, Sam decided that he would use the automaton to illustrate some of the mechanical principles of the domain for his school's science fair. To supplement his automaton, he made a poster with both explanatory text and sample components that were laser cut from foamcore board and cardboard. His poster can be seen in Figure B.22.

For the soccer player, the mechanical components, support framework, player, and kicking

surface were all cut from basswood with the laser cutter. The shafts and followers are birch dowels. The ball is a decorative wooden item purchased at a craft store. A metal cup hook attaches the rubber band to the kicking surface and the net material came from an onion bag.

B.8 Sam - The Carousel

Sam's second automaton was a carousel. This project was much more ambitious than the soccer player, but Sam had acquired a good deal of skill, knowledge, and confidence while building the soccer player and his initial design was substantially complete and very similar in all important respects to the finished automaton. Sam wanted the carousel to have four animals, but only to have two of them move up and down.

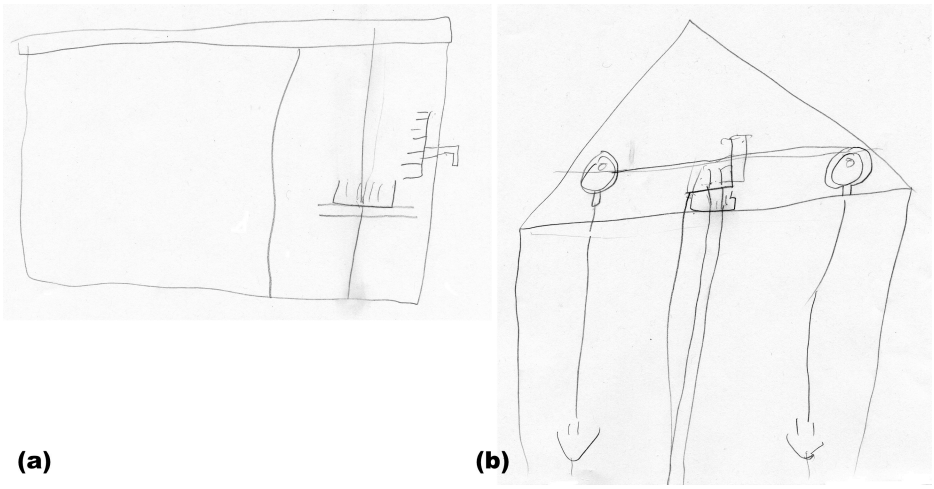


Figure B.23: (a) Sam's sketch for the base of the carousel showing the two pinwheel gears that will convert the rotation of the crank into rotation of the carousel. (b) Sam's sketch for the mechanism to move the animals. His idea is to use eccentric cams with ring followers (which can work in any orientation) to move the animals up and down and to drive the cams with a set of pinwheel gears that receive their power from the base. Compare these drawings to his drawing of the soccer player in Figure B.20 where the figure of the player is central and no hint of mechanism or structure is shown. In these drawings the structure and mechanism are key and the animals only represented by smiling faces.

Sam was able to decompose the mechanism into two fundamental parts: the part that would rotate the carousel and the part that would move the animals. To rotate the carousel, he

designed a spur gear train with a two to one ratio to allow the carousel to turn slower than the crank. He built this part of the mechanism into a box-like framework and put four rollers at the corners of the framework top to support the carousel in much the same way that rollers are used to support a rotating tray in a microwave oven. A large pinwheel gear was glued to the top and the shaft to connect the drive mechanism to the carousel passes through the center of the upper gear without touching it.



Figure B.24: The completed carousel. Sam had originally intended to drape cloth over the top to conceal the space between the two upper pieces but eventually decided against it.

The carousel itself sits between two structural sections that are necessary for the proper operation of the automaton. The two upper discs provide a space in which the lift rods for the animals can move without protruding from the top. The lower section contains the mechanical components that move the animals. To provide the up and down motion, each of the moving animals (the lion and the moose) is attached to a cam follower that is raised and lowered by an eccentric cam situated below the floor of the carousel. Each follower terminates in a crescent

shaped piece that provides constant contact with the cam and makes the mechanism more reliable.

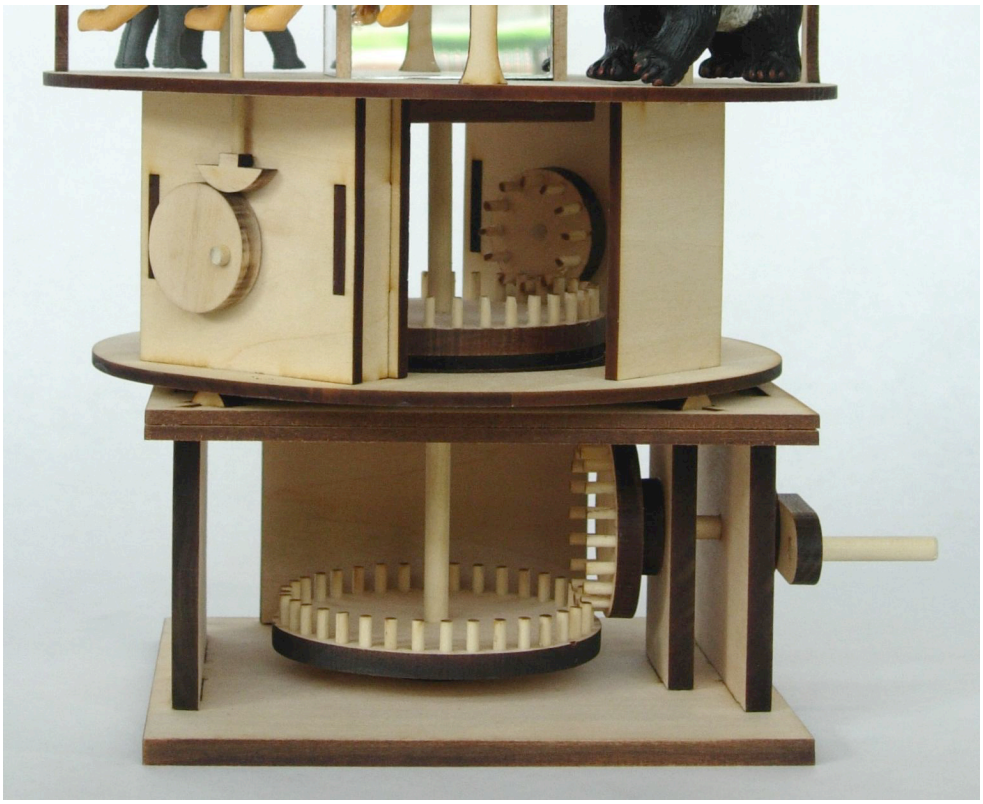


Figure B.25: The carousel contains two separate mechanisms working in unison. In the base, the spur gears turn the shaft that passes through the upper horizontal pinwheel gear (which is rigidly fixed to the top of the base assembly) and engages the bottom of the carousel proper. As the carousel rotates, the smaller pinwheel gears are forced to rotate as they mesh with the large gear. This causes the two eccentric cams to rotate which causes the moose and the lion to move up and down.

Each eccentric cam is driven by a shaft attached to a small pinwheel gear located on the inside of this part of the carousel. The teeth of these gears engage the teeth of the large stationary gear attached to the base. As the carousel rotates, these small gears rotate in the same way an automobile tire rotates as the car rolls along a road. The teeth provide a positive link between the gears which provides a guarantee that the animals will move properly. To finish the carousel off, four pieces of mirrored acrylic plastic were cut and glued to a framework in the middle of the carousel, much like the mirrors on a real carousel.

The majority of this automaton was cut from basswood with the laser cutter. Shafts are

made from birch dowels and the mirrors are acrylic. The animals were purchased at a discount store and in some cases bear the marks of previous ownership.

Appendix C

The MachineShop User's Manual

MachineShop User's Manual

(For MachineShop Version 0.9a, Macintosh)

C.1 Getting Started with MachineShop

Welcome to MachineShop! With MachineShop you can learn about the mechanisms that control contemporary automata by designing and building your own. Don't worry if you are new to automata; MachineShop can help you make not only your first simple automata, but more complex ones as well. This section will guide you through the process of getting and installing the MachineShop software, so let's get started!

C.1.1 System Requirements

To run MachineShop, you will need a Macintosh computer running OS X version 10.3 or later. You can find out your current version by selecting **About This Mac** from the Apple menu at the left side of your menu bar (Figure C.1).

You will also need Java 1.4.1 or later installed. To find out what version of Java is installed, launch the Terminal application (located in the Applications/Utilities folder on your hard drive), enter `java -version` at the prompt and press the **return** key. If you do not have any version of Java installed you will be told that in the Terminal window. Otherwise, Terminal will display the



Figure C.1: Selecting **About This Mac** from the Apple menu (left) will show you the current version of the operating system on your Macintosh (right).

version of Java that is installed. If this version is not at least 1.4.1 (Figure C.2), you will need an update. Updates can be obtained from `http://www.apple.com/support/downloads/`, but the easiest way to updated is to launch the System Preferences application on your Macintosh and choose **Software Update**.

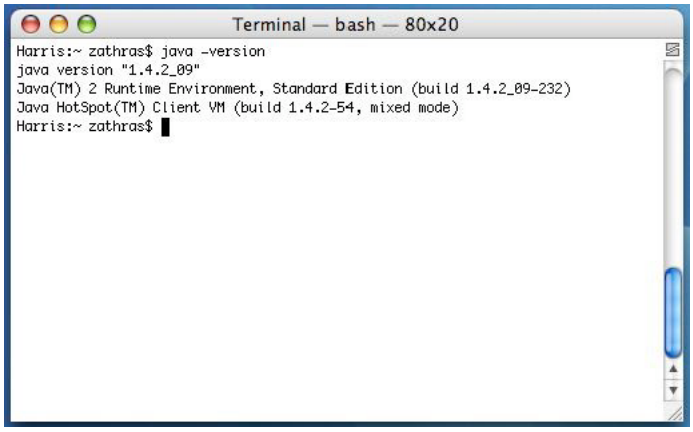


Figure C.2: Typing `java -version` in Terminal will let you know which version of Java is installed on your Macintosh. In this example it is version 1.4.2.

C.1.2 Getting the Software

When the software is completed you will be able to download it from the web. For now, contact the author via email at `zathras@cs.colorado.edu`.

C.1.3 Assumptions

This manual assumes that you are familiar with the Macintosh and that you are comfortable using the mouse, clicking and dragging, opening and closing files, and choosing menu items.

C.1.4 Installing MachineShop

The Macintosh version of MachineShop comes as a disk image. If the disk image is not automatically mounted, double click on the .dmg file to do so. In the image you will find 4 items. Move the **machine** and **machineMovies** folders to your home directory. Move the MachineShop.app file to the **Applications** folder on your computer. The ReadMe.txt file contains more detailed instructions and any important information that you should know about the installation and operation of the MachineShop software. Note that if you fail to put the **machine** and **machineMovies** folders in your home directory, new ones will be automatically created, but will contain no files and the library browsers and movement explorer will not function fully.

C.2 Starting the Program

Start MachineShop by double-clicking on the MachineShop icon. When MachineShop has loaded, you will see the screen shown in Figure C.3.

This screen is where you choose what you want to do. You can pick from the four main work areas, or you can choose specific tools from the **Tools** menu at the top of the screen (FigureC.4). The following sections will look at each of tools available to you and explain how to use them.

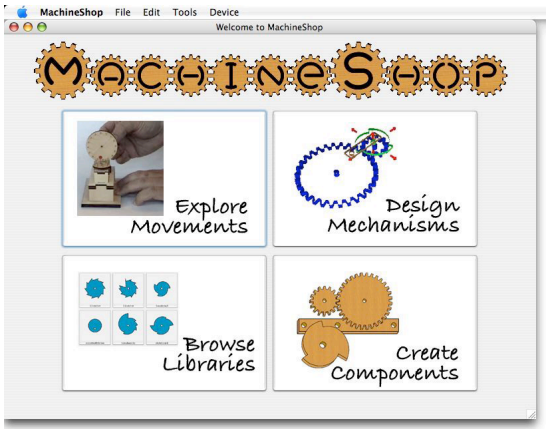


Figure C.3: The opening screen lets the user choose from among the tools provided by MachineShop. Here, the user can choose from the four general categories or may choose specific tools from the **Tools** menu.

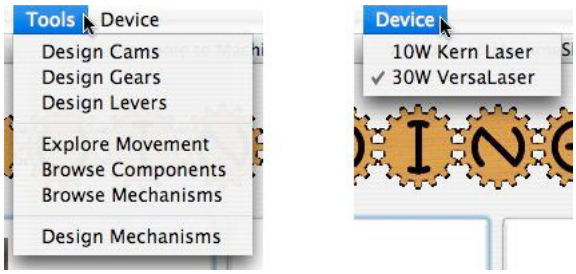


Figure C.4: MachineShop has two new menus. The **Tools** menu provides access to all of things you can do in MachineShop. The **Device** menu lets you choose which of the available fabrication machines you would like to use to create your mechanism.

C.3 Exploring Movement

If you're not very familiar with the kinds of mechanisms used in automata or just want to learn more about how they work, the Movement Explorer tool is designed to help you out (Figure C.5). To use the Movement Explorer follow these steps:

(1) Choose the kind of motion that will drive your mechanism. Select the **Circular** button if the input motion will come from the turning of a crank (as pictured) or if it will come from the circular output motion from another part of the mechanism. Select the **Back and Forth** button if the input motion will come from a sliding or lifting source.

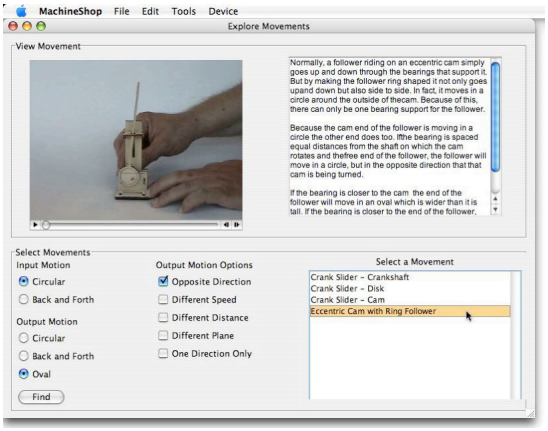


Figure C.5: Use the Movement Explorer to learn more about the kinds of mechanisms you can build with MachineShop and discover how they work.

(2) Choose the kind of motion that your mechanism will supply either to the figures in your automaton or to other parts of your mechanism. Select the **Circular** button if the output motion will be a rotating shaft of other component. Select the **Back and Forth** button if the output motion will be a side-to-side or up-and-down movement. Select the **Oval** button if the output motion will follow an oval shaped path.

(3) Choose any special features that the output motion will have. Select the **Opposite Direction** button if you want your circular or oval output to go in the opposite direction that the circular input motion is going, or if you want the back-and-forth motion to go up when the input goes down or to go left when the input goes right. Select the **Different Speed** button when you want the output motion to be faster or slower than the input motion. Select the **Different Distance** button when you want the output motion to travel a longer or shorter distance than the input motion (this is only used with back-and-forth input and output motions). Select the **Different Plane** button when you want the output motion to happen on a different side of the mechanism from the input motion (this is only used when both the input and output motions are either circular or back-and-forth). Select the **One Direction Only** button when you want the

circular output motion to turn in only one direction. You may select as many of these options as you would like or you may choose to select none of them if you wish.

(4) When you have selected the input motion, output motion, and any output motion options you want, click the **Find** button.

(5) If MachineShop has examples of movements that match your choices, a list of them will be displayed in the **Select a Movement** window. Selecting one of the examples will display both a more detailed description of the movement and how it works and a short movie of the movement in action that you can watch.

C.4 Designing and Editing Components

The Editors are where you do the work of actually designing and making the components for your mechanisms. While it might seem that you don't have many choices, the variety of mechanisms you can make from the parts available to you is limited only by your imagination. In the editors you can make snail cams, eccentric cams, ratchets and pawls, spur gears, pinwheel gears, levers, and cranks and you can make them just the way you want them. The following sections explain what each type of component does and shows you how to use the editors to make the parts you need.

C.4.1 Designing Cams

A cam is a device that turns rotary motion into up-and-down or back-and-forth motion as the shaft it is attached to turns. A cam can be a circular disk with the hole for the shaft located away from the center of the disk. This type of cam is called an *eccentric cam* (Figure C.7). A cam can have the shaft hole in the center but have bumps (called *lobes*) along the edges of the disk. There are a number of kinds of cams of this type, and the ones you can make in MachineShop are called *snail cams* (Figure C.6) because that is what the version with one lobe looks like.

Cams most often transfer their motion to the figures or other components in your automata through *cam followers* or more simply, *followers*. Followers can be rods or shafts that move along the edge of the cam or they can be levers that rock back and forth as one end is moved by the cam. In many cases, followers are held in contact with the cam simply by the force of gravity so they are located above the cam. But through the use of rubber bands or springs, followers can be located to the sides or even underneath the cam. Eccentric cams can have a *ring follower* that surrounds the cam so that it doesn't need to rely on gravity or springs to make it work.

There is another component that you can make with the Cam Editor that, while strictly speaking is not a cam, shares many of the characteristics of cams. This component is called a *ratchet* (Figure C.8). The primary purpose of a ratchet is to make sure that a shaft only rotates in one direction. To do this, the ratchet must have a *pawl* (Figure C.13).

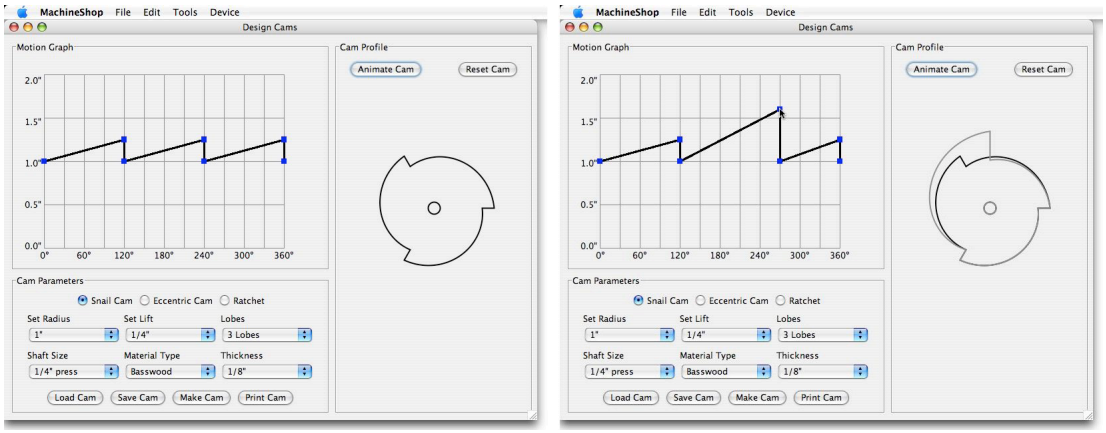


Figure C.6: Designing a 3-lobed snail cam. The screen on the left shows the default form of the cam while the screen on the right shows the user changing the lift and dwell of the second lobe. Note how the new profile (shown in gray) is shown along with the current profile (shown in black).

Making a cam or ratchet is easy:

(1) Choose the type of cam you want to make by clicking on the button next to its name in the **Cam Parameters** panel.

(2) Choose the base radius of the disk for the cam and the initial amount of lift you want

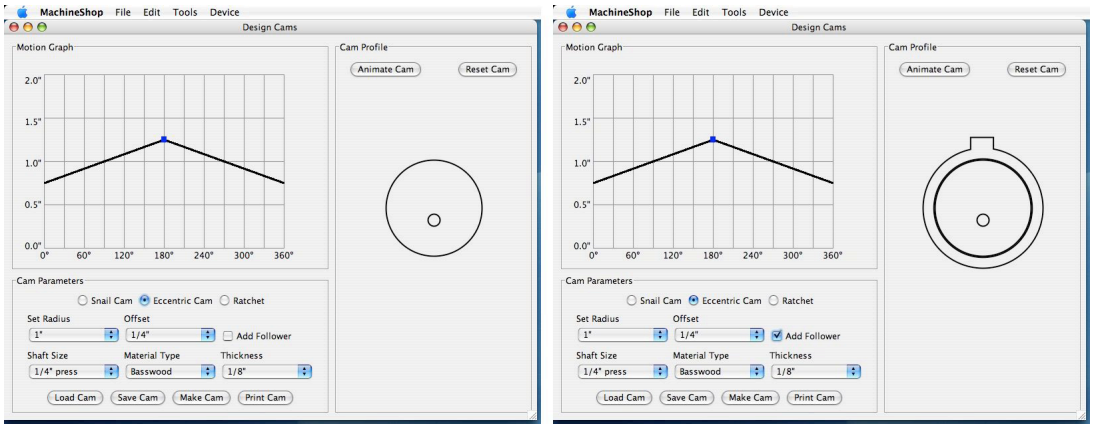


Figure C.7: Designing an eccentric cam. The screen on the left shows the cam without a follower while the screen on the right shows it with a ring follower.

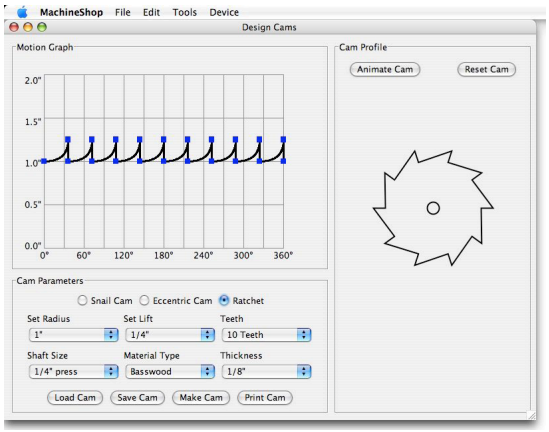


Figure C.8: Ratchets share many physical similarities with snail cams. Ratchets can be used to provide intermittent linear motion or, when used with a pawl, to constrain rotation to one direction only.

each of the lobes to have by clicking on the drop-down menus and selecting the proper values. Don't worry if the exact sizes you want are not listed; you will be able to change each of these values later.

(3) If you are building a snail cam, select the number of lobes you want from the drop-down menu. If you are building a ratchet, select the number of teeth you want.

(4) Using the next row of drop-down menus, specify the size you want the hole for the

shaft to be, and the type and thickness of material you want to make the component from. The values for type and thickness will depend on the fabrication tool that you will use to create the components. See Section C.7 for more information.

(5) If you are building an eccentric cam and you want it to have a ring follower be sure to click the box.

(6) The **Motion Graph** panel shows you what the motion of the cam follower for the current cam will be. If you want the follower to move differently than this graph, or if the values for lift and dwell that you set in the with the controls in the **Cam Parameters** panel are not exactly what you want, you can modify any of the lobe points by dragging the blue handles on the graph with the mouse. As you do, the graph will change and you will see the profile shape of the cam change in the **Cam Profile** panel. The black shape is the current profile and the gray shape is the profile you will get from the changes you are making.

(7) To get a feel for what the cam will act like when it moves, you can click on the **Animate Cam** button in the **Cam Profile** panel. Clicking this button again will stop its rotation. If you would like to restore the cam to its original position, click the **Reset Cam** button.

The four buttons at the bottom of the **Cam Parameters** panel let you work with files for your cams. The **Load Cam** button will let you browse the library of cams that you or other people have already made and then will load the one of your choice into the Cam Editor so that you can work with it. The **Save Cam** button works in the opposite direction. It allows you to give the cam you have just designed a name and then saves it to the component library with the other cams that are there. The **Make Cam** button lets you create a fabrication file for the currently selected fabrication tool (See Section C.7 for more information). The **Print Cam** button will send the profile of the cam you have just created to a printer attached to your computer. This is useful if you just want a picture or if you don't have access to a fabrication tool, but would like a pattern

that will help you make the cam with tools you do have.

C.4.2 Designing Gears

Gears transfer the rotary motion of one shaft to another shaft which causes it to rotate. *Spur gears* will keep the input and output shafts parallel while *pinwheel gears* will let you locate the shafts so that the output motion is 90 degrees away from the input motion. Sets of gears have some interesting properties. Because motion is transferred between gears as their *teeth* mesh, there is no way for properly working gears to slip. Second, by changing the relative sizes of the gears in a set you can alter their relative speeds and the power that can be gained or lost. For example, by making the output gear have twice as many teeth as the input gear you can make the output gear rotate at one half the speed of the input gear while applying twice as much force to its shaft as the input gear receives from its shaft. Third, no matter how many gears are in a set, gears that mesh with each other will always turn in the opposite direction. If you were to number the gears in a set starting at the input and moving to the output you will find that all of the odd numbered gears turn the same direction as the input gear (which is number 1) and that all of the even numbered gears turn in the opposite direction. By seeing if the output gear is even or odd numbered, you will know if it turns the same or opposite way as the input gear.

Gear sets are easy to make in MachineShop:

(1) Choose the type of gear set you want to make by clicking on the button next to its name in the **Gear Parameters** panel.

(2) If you are building a set of spur gears (Figure C.9) select the number of gears that your gear set will have from the drop-down menu. You can only build sets with two or three gears, but you can combine sets to get any number that you might need. Now choose the ratio between the input gear size and the output gear size. Choosing a bigger number for the input gear will make the output gear turn faster but with less power. Choosing a smaller number for the input gear will make the output gear turn slower

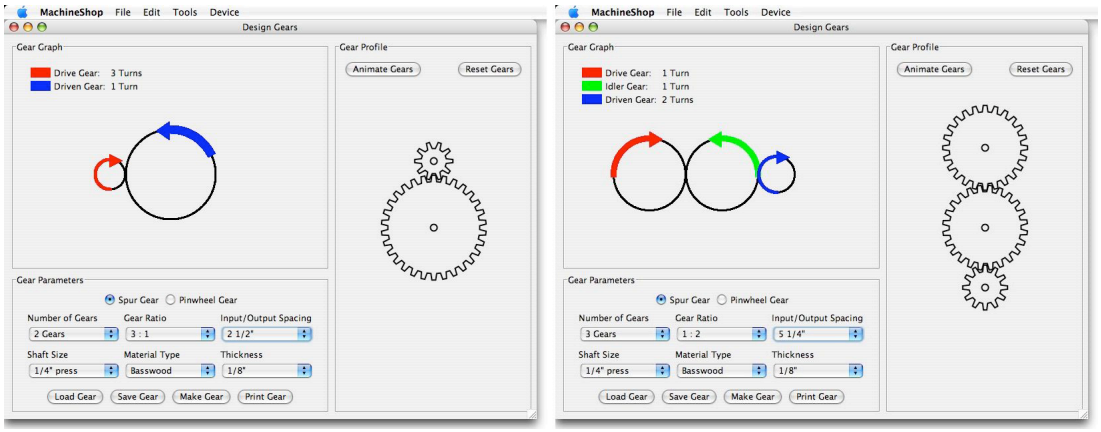


Figure C.9: Spur gears can be built in sets of either two or three gears. In two gear sets the input and output gears turn in opposite directions. In three gear sets the input and output gears turn in the same direction. Changing the relative sizes of the gears will affect their relative speeds and power.

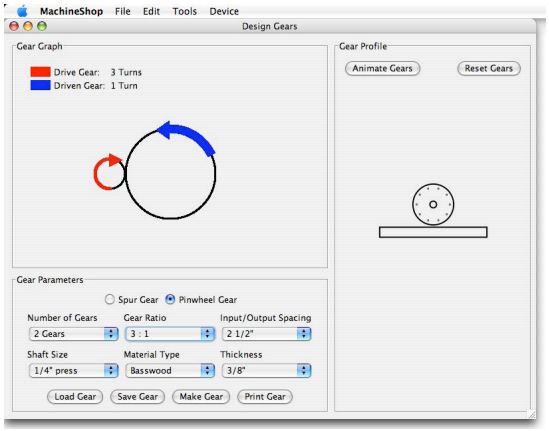


Figure C.10: Pinwheel gears are used to allow the input and output gears' shafts to rotate in planes that are 90 degrees apart. As with spur gears, changing the relative sizes of the gears will affect their relative speeds and power.

and with more power. Next, choose a spacing for your gear set. This is the distance between the input gear's shaft and the output gear's shaft. Choose a larger distance if you need the shafts far apart and a shorter distance if you need them closer together.

(3) If you are building a set of pinwheel gears (Figure C.10) you can currently only build sets of two gears. As with spur gears, if you need more gears you can build additional

sets and combine them. Now choose the ratio between the input gear size and the output gear size. Choosing a bigger number for the input gear will make the output gear turn faster but with less power. Choosing a smaller number for the input gear will make the output gear turn slower and with more power. Next, choose a spacing for your gear set. This is the distance between the pin surface of the input gear and the output gear's shaft. Pick the distance that best fits your mechanism's needs.

(4) Use the drop-down menus to select the size of the hole for each gear's shaft (all of the gears in a set must use the same size shaft) as well as the type of material and thickness that you will use to make the gears.

(5) The **Gear Graph** panel will show you how your gear set will function. Each circle represents the relative size of one of the gears starting with the input gear on the left and ending with the output gear on the right. The arrows on each circle indicate the the relative distance each will travel (the length of the arrow) and their relative powers (the thickness of the arrow). The arrows also indicate the relative directions that the gears will turn. The colored bars at the top of the panel also describe the relative distances each gear will turn and you will see that this corresponds to the gear ratio that you have chosen.

(6) The **Gear Profile** panel shows how your gear set will look in your mechanism and will change as you change gear ratios and spacings. If you would like to see what your gear set will look like when moving, click the **Animate Gears** button. To stop the animation, click this button again. You can return the gear profiles to their starting positions by clicking the **Reset Gears** button.

The four buttons at the bottom of the **Gear Parameters** panel let you work with files for your gears. The **Load Gear** button will let you browse the library of gear sets that you or other people have already made and then will load the one of your choice into the Gear Editor so that

you can work with it. The **Save Gear** button works in the opposite direction. It allows you to give the gear set you have just designed a name and then saves it to the component library with the other gear sets that are there. The **Make Gear** button lets you create a fabrication file for the currently selected fabrication tool (See Section C.7 for more information). The **Print Gear** button will send the profile of the gears you have just created to a printer attached to your computer. This is useful if you just want a picture or if you don't have access to a fabrication tool, but would like a pattern that will help you make the gears with tools you do have.

C.4.3 Designing Levers

Levers may seem simple, but they have many uses in mechanisms. Levers come in three different varieties, called *orders*. Levers of the first order (Figure C.11) are like a see-saw where the pivot (*fulcrum*) is located between the input force and the output effort. Levers of the second order (Figure C.12 on the left) are like a wheelbarrow and the output effort is located between the input force and the fulcrum. Levers of the third order (Figure C.12 on the right) are like a fishing pole and the input force is located between the output effort and the fulcrum. Levers can be used in mechanisms to supply an up-and-down or back-and-forth output motion from either an up-and-down or back-and-forth input motion supplied by another lever or crank-slider or from a rotary input motion like that supplied by a cam.

Cranks and pawls are kinds of levers that have specific purposes. In the kinds of mechanisms you will build with MachineShop, cranks will most often be the component you choose that will turn the motion of the user's hand into the rotary motion that will power your mechanism. Pawls will almost always be used with ratchets to make sure that they only turn in the direction that you want them to.

Making levers, cranks, and pawls is simple:

(1) Select what you want to build (lever, crank, or pawl) by clicking on the button next to its name in the **Lever Parameters** panel.

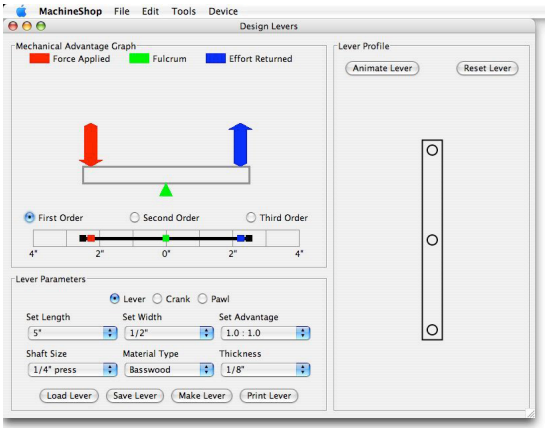


Figure C.11: Levers of the first order have their fulcrums located between the applied force and the effort returned. By moving the fulcrum the distance each end of the lever travels and the force required to do work can be altered.

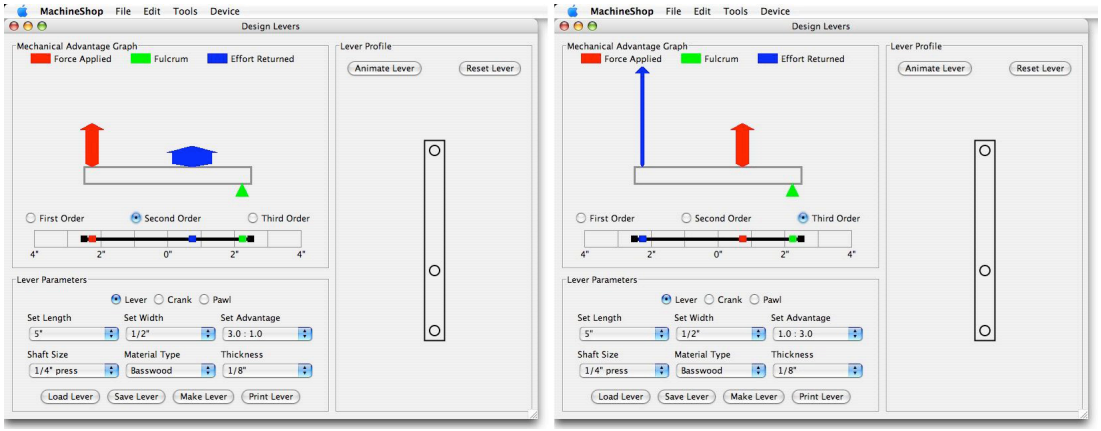


Figure C.12: Levers of the second and third orders look similar, but the positions of the applied force and the returned effort are switched.

(2) Set the length and width for the lever and choose an initial value for its mechanical advantage from the drop-down menus.

(3) Choose the size for the shaft holes as well as the type and thickness of material that you will use to make it from the drop-down menus.

(4) If you are building a lever, select what order it will be in the **Mechanical Advantage Graph** panel.

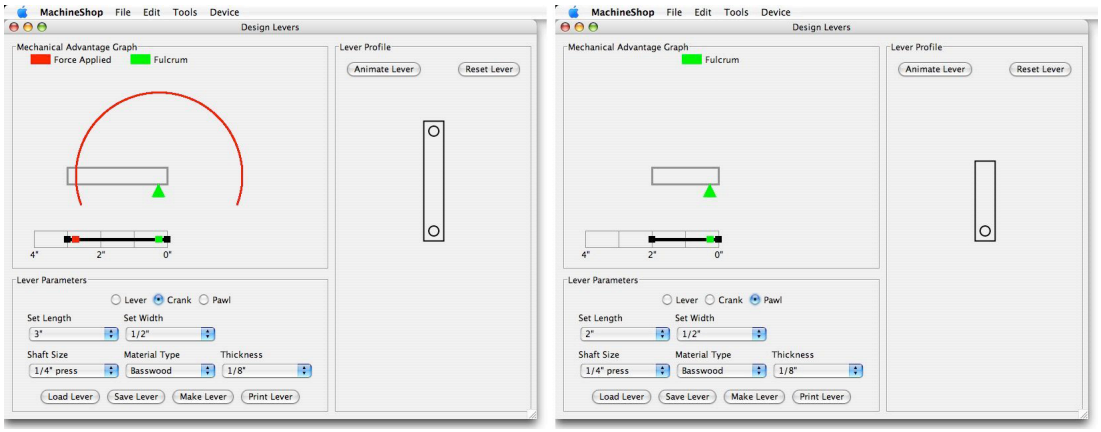


Figure C.13: Cranks and pawls are type of levers with specific purposes. Cranks are used in mechanisms to provide the input power to the mechanism. Pawls are used to keep ratchets from turning the wrong way.

(5) In the **Mechanical Advantage Graph** panel you can change the length of the lever by sliding the black squares with the mouse. You can also change the location (and mechanical advantage) by dragging the red square to move the location of the input force, the blue square to move the location of the output effort, or the green square to move the location of the fulcrum. When you do this the arrows will move to match and the output effort arrow (the blue arrow) will either get shorter and thicker (indicating that it will move a shorter distance but supply more effort) or longer and thinner (indicating that it will move a longer distance and supply less effort). You will also notice that the holes in the lever shown in the **Lever Profile** panel move to show the changes you have made.

(6) You can see how your lever, crank, or pawl will move by clicking on the **Animate Lever** button in the **Mechanical Advantage Graph** panel. To stop the animation, click on the button again. You can reset that lever's profile to its original location by clicking on the **Reset Lever** button.

The four buttons at the bottom of the **Lever Parameters** panel let you work with files for your levers. The **Load Lever** button will let you browse the library of levers, cranks, and pawls

that you or other people have already made and then will load the one of your choice into the Lever Editor so that you can work with it. The **Save Lever** button works in the opposite direction. It allows you to give the lever you have just designed a name and then saves it to the component library with the other levers that are there. The **Make Lever** button lets you create a fabrication file for the currently selected fabrication tool (See Section C.7 for more information). The **Print Lever** button will send the profile of the lever you have just created to a printer attached to your computer. This is useful if you just want a picture or if you don't have access to a fabrication tool, but would like a pattern that will help you make the lever with tools you do have.

C.5 Assembling Mechanisms

The Mechanism Assembly tool is not currently implemented.

C.6 Working with Files and Libraries

MachineShop lets you save components and mechanisms you have designed to libraries so that you can reuse them or share them with other people. All of the component editors have buttons that allow you to save or load files to the component library and you will be able to do the same things with complete mechanisms in a future version of the software.

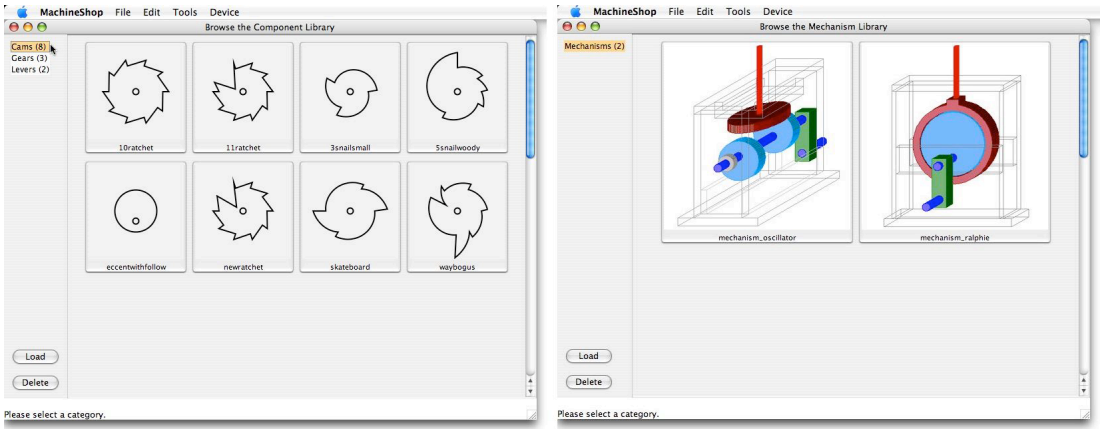


Figure C.14: MachineShop provides two libraries where you can store your designs. On the left is a view of the Component Library while on the right is a view of the Mechanism Library.

The Component Browser (Figure C.14 on the left) lets you see all of the components that are stored in your component library and allows you to edit any of them that you might want to. On the left side of the screen is a list of the component types that are stored in your library. There is one entry in this list for each of the component editors. Selecting any of these categories will show you the components of that type that are in the library. If there are too many to be seen in one screen, you can scroll through the entries using the scroll bar. Below the list of component types are two buttons. If you have selected a component in the browser view (by clicking on its picture) the **Load** button will open the appropriate component editor with your chosen component ready to be worked on. The **Delete** button allows you to remove a selected component from the library if you wish to do so. Be careful when using this button as the component will be removed permanently and if you need it again, you will have to create it once more.

C.7 Fabricating Components

One of the features of MachineShop is that it can use modern fabrication devices to create the components you design. In order to do this, the software must have a configuration file for the device you will be using. Currently only two different devices are supported and both are carbon dioxide laser cutters. As new devices become available, configuration files for them will be added.

In order to use an available device you need to select it from the **Device** menu. This will give the software the information it needs to create a fabrication file that the device can use when you click any of the **Make Component** buttons in the editors. Using these files may be different from device to device. For example, the Kern laser can use the fabrication files from MachineShop directly, while the VersaLaser will need to open the fabrication files in a graphics program like CorelDraw. As more devices are added to the software, this section of the manual will detail how to fabricate components you have created with MachineShop.

Appendix D

Sample Automata and Mechanisms

From the beginning of the testing, users had access to three completed automata and about a dozen simple mechanisms that had been created with various versions of MachineShop. These machines were used as reference and to stimulate ideas by all users, although the amount of interaction varied from user to user. This appendix provides a brief look at these objects.

D.1 Ralphie's Dream

Ralphie is the mascot of the University of Colorado at Boulder. His stylized profile is ubiquitous on and off campus and it was that profile that was used in creating this automaton. Building Ralphie served two purposes. First, it allowed those of us involved in this research the chance to actually construct an automaton in order to get an understanding of the difficulties that we could expect future users to encounter. Second, it served as a proof of concept of our early attempts at building software for this purpose and as a vehicle to learn about the process of carbon dioxide laser cutter fabrication. By all of those measures it was a tremendous success.

The idea for Ralphie comes from an automaton designed and built by Keith Newstead that featured a flying pig [15]. The path taken by Ralphie's body is elliptical and is provided by a crank-slider mechanism that utilizes an eccentric cam with a ring follower (see Figure D.9). The wings are first order levers that pivot at the wires anchored to the framework. As the body moves up, it brings the inner ends of the wings with it and, since the wires don't move, this forces the tips of the wings down. The reverse happens as the body moves down. The combined motion quite

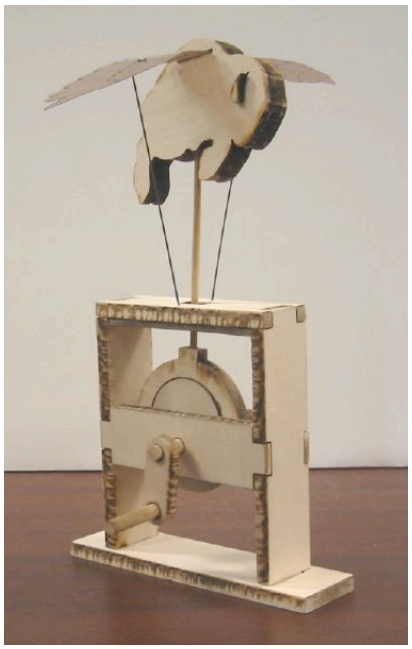


Figure D.1: Ralphie the flying buffalo. Ralphie is the mascot of the University of Colorado but he is generally found with a majority of his feet on the ground. This was the first automaton built using nascent software tools that would eventually become MachineShop and was fabricated with a crude second-hand laser cutter setup.

realistically mimics the motion of birds in flight.

The mechanism components and Ralphie's body pieces were cut from basswood on the original laser cutter in our lab. The slider rod and shaft for the crank are birch dowels. The wings were printed on overhead transparency material and cut out with scissors, while lengths of small diameter music wire were bent to serve the wings as fulcrums.

D.2 Nessie the Sea Serpent

While one crank-slider is generally found in automata that use them, Nessie was created to see what might be possible by using three. This is an original design that was not influenced by other automata. Nessie's body is divided into three segments, each attached to the ring follower rod of an eccentric cam. Each of the cams is rotated about 120 degrees from the one ahead of it. As is the case for all crank-slider mechanisms, each segment follows an elliptical path, but unlike

the front to back path in Ralphie, the paths in Nessie are side to side. When viewed from the front or back, she appears to swim with an undulating motion appropriate to her kind.

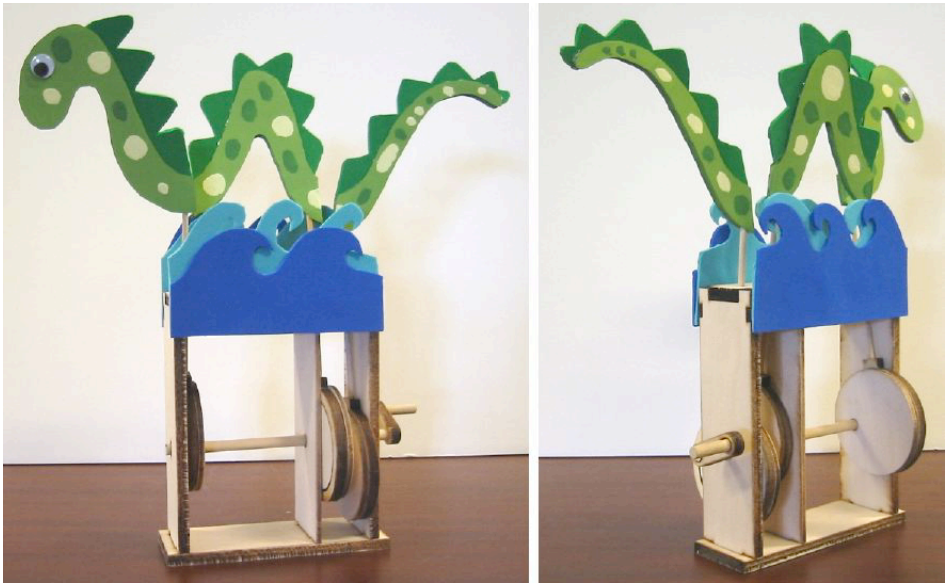


Figure D.2: Two views of Nessie the sea serpent. On the left, a side view showing the general layout including the three eccentric cam crank-slider mechanisms that move her body segments. On the right, a view showing the side to side motion that accompanies the up and down movement of the body.

The support framework and mechanical components are cut from basswood with the laser cutter. The shafts and slider rods are birch dowels. Her body is foamcore board, while her spines and the waves attached to the framework are craft foam, both cut with the laser cutter. She was painted with acrylic craft paint and her spines were attached with hot glue. Her eyes were purchased at a craft store.

D.3 Big Top Celia

Celia's design arose from the desire to take an existing automaton mechanism and, without altering it, create a new automaton in which the tableau appeared completely different. The mechanism shown here is the same one found in Peter Markey's *Angry Cat* [15]. To make Celia appear unlike the cat, the relation of her body to the mechanism was reversed from that of the cat

and a new set of motions to be provided by the mechanism were designed.



Figure D.3: Through the use of eccentric cams and discs, Celia moves her tail and flippers while balancing the spinning ball on her nose. The mechanism seen here was modified by two of the test users for inclusion in their automata.

The spinning ball on her nose is driven by a disc on the main shaft that turns a disc connected to the ball by the vertical shaft. By placing the driving disc at the outer edge of the driven disc, the ball spins at nearly the same rate as the crank is turned. In the cat, this mechanism rotates the cat's tail. Celia's front flippers rock back and forth around a shaft set into her shoulder. Inside her body, this shaft is attached to a lever such that the vertical motion of the lever results in the rocking motion of the flippers. The lever is actuated by the follower of an eccentric cam. In the cat this mechanism raises and lowers the cat's arched back. Her tail flippers move from side to side through the use of a Markey oscillator. In the cat, this mechanism opens and closes the mouth while moving the tongue from side to side.

A moment should be spent here to briefly discuss the Markey oscillator as it appears frequently in contemporary automata and provides a terribly useful motion without requiring a large investment in mechanism creation. The mechanism has, as far as can be determined, no official name and was given this label during the user testing. It is named for the artist Peter Markey

who has used it to great affect in a number of his automata. The oscillator consists of two eccentric cams attached to a common shaft, spaced some distance apart, and rotated so that their high points are some angular distance apart. A disc at the end of a second shaft is placed with its face parallel to the shaft that holds the cams with the shaft midway between the cams. As the cam's shaft is rotated, each cam will come into contact with the disc, one at a time, and will lift and rotate the disc. But, because the cams are located on opposite sides of the disc's shaft, the disc will rotate in one direction for one cam and in the opposite direction for the other, rotating whatever is attached to the shaft one way and then the other. By varying the size, lift, and angular separation of the cams, the motion can be controlled. To keep the disc from rotating too far, it is common to find stops added to the disc to constrain its motion. In Celia, her body keeps the tail from moving too far in either direction.

Celia's body, pedestal, support framework, and mechanical components are all cut from basswood with the laser cutter. The shafts and followers are birch dowels and her tail and flippers are craft foam also cut with the laser cutter. The ball is a decorative wooden item purchased at a craft store. Acrylic craft paint and aerosol paints were used to decorate the automaton.

D.4 Example Mechanisms

In additon to complete automata, the users had access to a number of simple mechanisms. These mechanisms were originally created for use in short videos that were incorporated in the Movement Explorer tool in the MachineShop software (see Section 5.1.2), but proved helpful when users were defining a mechanism or stumped by some aspect of their design. Not all components that can be made with MachineShop have had these kinds of examples built (levers are conspicous by their absence) and when there is the ability to create many variations on a component only one or a few were made. For all of these examples, the support structures and components were cut from basswood on the laser cutter. Shafts, followers, and rods are birch dowel. Other materials such as matte board or acrylic plastic were used rarely, but were also laser cut.

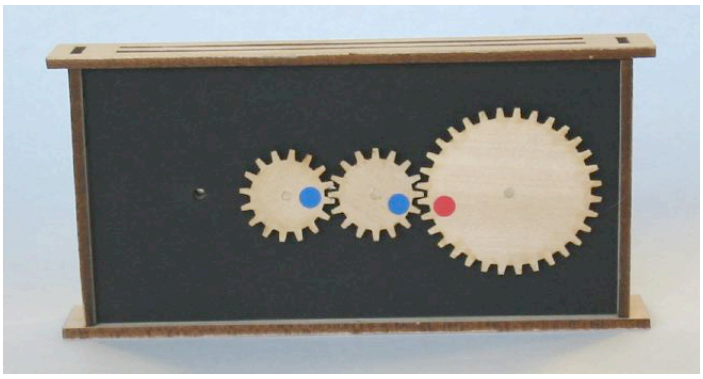


Figure D.4: Spur gears keep rotation in the same plane. Gears that mesh rotate in opposite directions, and power and speed can be changed as a property of ratio of the gears. The support structure for this example has several holes that allow the gear sizes to be changed and to create gear trains of either two or three gears. Colored dots aid in determining gear ratios.

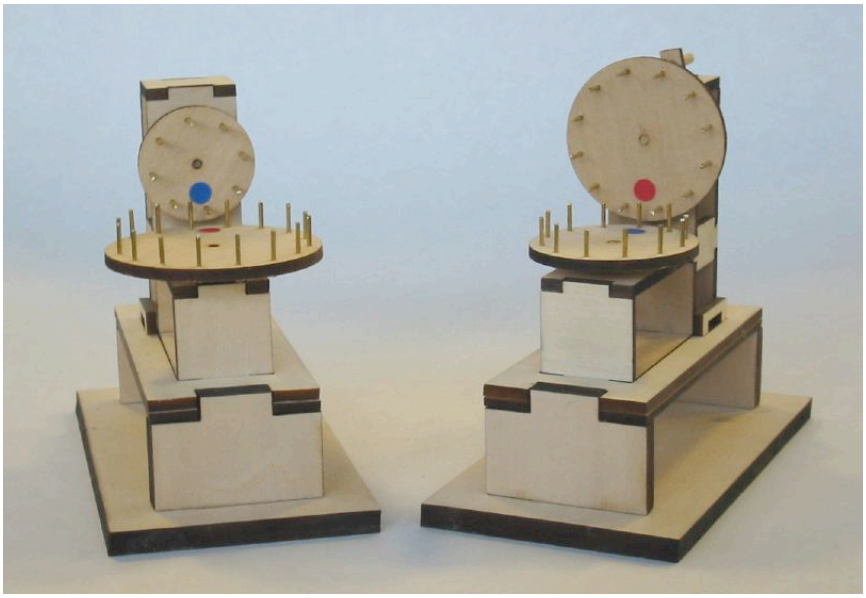


Figure D.5: Pinwheel gears move the plane of rotation through 90 degrees. As with spur gears, meshing gears rotate in opposite directions.

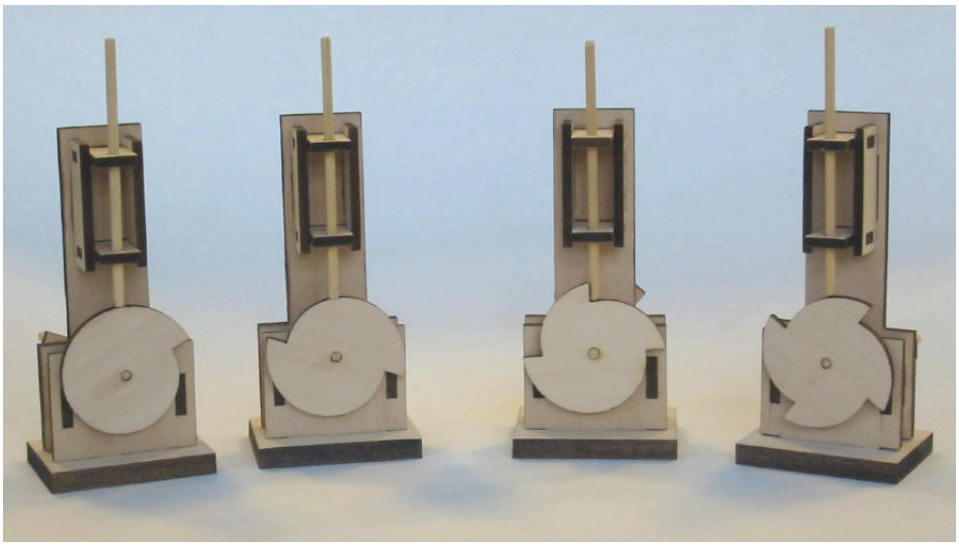


Figure D.6: The follower of a snail cam moves gradually away from the cam's shaft and then returns quickly. Shown here are snail cams with (from left) one, two, three, and four lobes. The height of each lobe (lift) can vary independently and all lobes do not have to have the same angular dimension (dwell) as can be seen in the three lobed example. This cam produces a galloping rhythm as the follower drops.

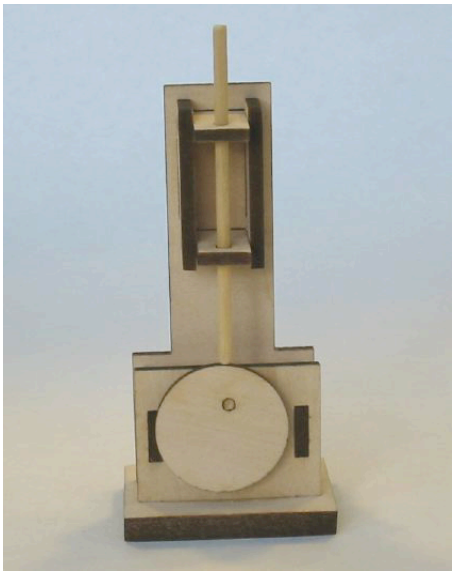


Figure D.7: The follower of an eccentric cam moves at a regular rate between the extremes of its travel. In effect an eccentric cam has just one lobe so the dwell cannot be changed, but the lift can be modified by changing the distance from the shaft hole to the edge of the cam.

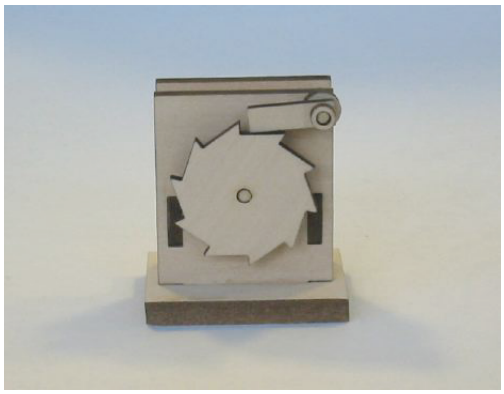


Figure D.8: The rotation of the ratchet is limited to one direction only (counterclockwise in this example) by the action of the pawl (upper right).

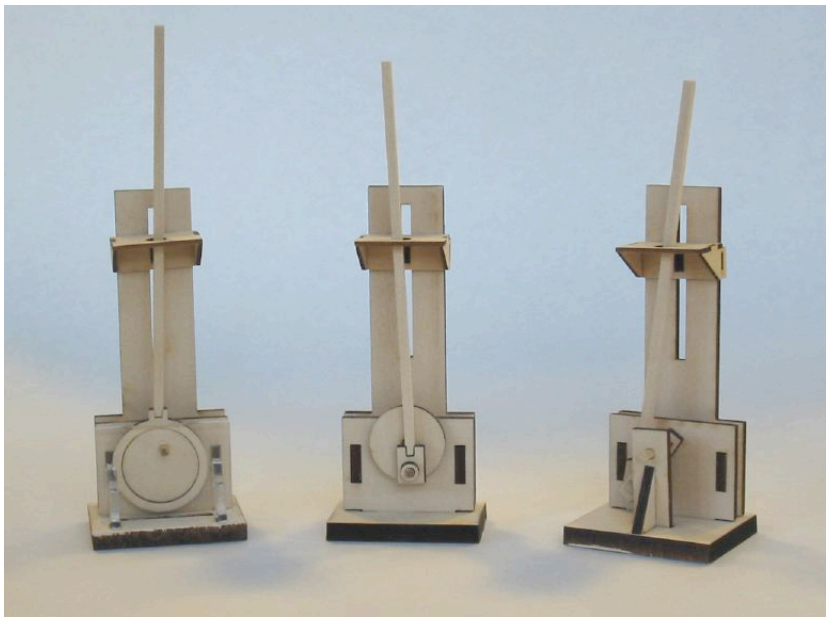


Figure D.9: Crank-sliders are not a simple component that can be created with MachineShop, but the pieces necessary to build them can. Crank-sliders turn their rotary input into an elliptical output at the tip of the slider rod. The exact shape of that ellipse depends on two factors: the offset of the crank and the distance from the crank to the support bearing for the rod. In these examples, that bearing location can be changed by moving the bearing up or down along the slots seen in the backs of the support structures. Having the bearing near the crank will result in an ellipse that is wider than it is high, while having the bearing far from the crank will create a tall and narrow ellipse. Three styles of crank are show here. From left, an eccentric cam with ring follower, a disc with offset pin, and an offset crank.

Appendix E

Automata Resources

Contemporary automata were an almost perfect domain choice for the research described in these pages for a variety of reasons already enumerated. But in addition, there exists an abundant variety of resources to assist and inspire automata builders of all skill levels and artistic sensibilities. Collecting these resources into a single location is an impossible task that would be obsolete and incomplete almost before it was started. But as an aid to the reader, this appendix presents a "short list" of resources that every automatist should know about.

E.1 Contemporary Automata

Web resources that focus on contemporary automata. Many of these offer support to teachers using automata in the classroom:

- **Automata and Mechanical Toys**

  (http://automata.co.uk/)

  A source for information on constructing automata with a focus on their use in education in the United Kingdom. Interactive CDs and some excellent books are offered for sale.

- **Cabaret Mechanical Theatre**

  (http://www.cabaret.co.uk/)

  CMT is an excellent jumping off point for the budding automatist, from short biographies of some of the Cabaret artists to support for automata in education to virtual

gallery exhibits. The online shop sells a variety of kits, books, videos, and professionally constructed automata.

- **Chomick and Meder - Figurative Art and Automata**

  (http://www.chomickmeder.com/)

  A blending of contemporary automata sensibilities with golden age appearance.

- **Flying Pig**

  (http://www.flying-pig.co.uk/)

  Similar to the Cabaret website in structure, it offers a complementary mix of educational material and automata kits.

E.2 Automata Builders

A sampling of artists whose primary medium is automata in all of its variations:

- **Dug North**

  (http://www.dugnorth.com/index.aspx)

  Handmade wooden automata.

- **Fourteen Balls Toy Company**

  (http://www.fourteenballstoy.co.uk/)

  A collaboration of Paul Spooner and Matt Smith, both CMT artists.

- **Francois Junod**

  (http://people.timezone.com/mdisher/decorte/junod/junodpart1.htm)

  Large scale automata with intricate mechanisms.

- **Keith Newstead**

  (http://www.keithnewsteadautomata.com/)

  The personal automata site of one of the CMT artists.

- **Martin Smith**

  (http://www.smithautomata.co.uk/)

  Automata and mechanical sculptures.

- **Rodney Peppé**

  To call Rodney's work "moving toys" is to do him a disservice. His book *Automata and Mechanical Toys* (ISBN 1-86126-510-7) should be in the library of every automata builder.

- **Ron Fuller**

  Ron is a master toy maker, CMT artist, and author of *Simple Wooden Toys* (ISBN 0-7472-1288-0) which includes instructions for making his well known automaton, *The Lion Tamer*.

- **Walter Ruffler**

  (http://www.walterruffler.de/index1.html)

  Paper and card automata and kits.