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.

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[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.