

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 around the holes in their knowledge and over the rough spots 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 (Section 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 craftsman, 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.