

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

by

Glenn Raymond Blauvelt

B.Sc., Colorado School of Mines, 1997

M.S., University of Colorado, 2000

A thesis submitted to the
Faculty of the Graduate School of the
University of Colorado in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
Department of Computer Science

2006

This thesis entitled:
MachineShop: A Design Environment for Supporting Children's
Construction of Mechanical Reasoning and Spatial Cognition
written by Glenn Raymond Blauvelt
has been approved for the Department of Computer Science

Michael Eisenberg

Clayton Lewis

Date _____

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

HRC protocol #0201.20

Blauvelt, Glenn Raymond (Ph.D., Computer Science and Cognitive Science)

MachineShop: A Design Environment for Supporting Children's

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

Acknowledgements

Work like this never springs fully formed from the mind of the author, and MachineShop bears the imprint of many hands. In particular, I am indebted to Mike Eisenberg for his help in shaping the core ideas for this research and to Tom Wensch and Eric Scharff whose thoughtful and challenging discussions improved this work in every way. Carol Strohecker and Doug Smith were instrumental in bringing order from the early chaos. Valuable insights into the process of design came from Mark Gross. Robin Murphy worked me hard as an undergraduate and convinced me that I should follow my heart.

Everyone associated with Cabaret Mechanical Theatre has had a tremendous influence on the style and substance of this work. I am especially grateful to Sue Jackson and Sarah Alexander for their encouragement and kind hospitality, to the Cabaret artists Paul Spooner, Peter Markey, Tim Hunkin, Ron Fuller, and Keith Newstead for their remarkable bodies of work, and to Gary Alexander and Aidan Lawrence Onn for their excellent book that proved invaluable while shaping the experimental method.

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!

Finally, none of this would have been possible without the encouragement provided by my wife, Susan Hendrix. Without her support, this work might never have been started, much less completed. One down, one to go.

This work was supported in part by a gift from Mitsubishi Electric Research Laboratories.

Contents

Chapter

1	Introduction	1
1.1	Motivating Problem	1
1.1.1	Visuospatial Reasoning	2
1.2	The Research Domain	3
1.2.1	Automata	3
1.2.2	Contemporary Automata	4
1.2.3	Why are Contemporary Automata a Good Choice?	5
1.3	Why Create Computer Systems to Design and Build Automata?	5
1.3.1	Reduce Barriers to Entry	6
1.3.2	Make Mechanical Reasoning Explicit	6
1.3.3	What Do Beginning Automatists Currently Use?	6
1.4	Research Question	7
1.5	Research Approach	7
1.6	Reader's Guide and Road Map	9
2	Mechanical and Spatial Thinking: Concepts	11
2.1	Thinking and Reasoning About Machines	13
2.2	Visuospatial Reasoning	14
2.2.1	Spatial Cognition	15

2.2.2	Mechanical Reasoning	16
2.3	Research in Mechanical Reasoning	17
2.3.1	Industrial and Vocational Psychology Research	17
2.3.2	Cognitive Psychology Research	18
2.3.3	Educational Research and Practice	21
2.4	Constructing Mechanical Reasoning	23
2.4.1	Constructivism and Constructionism	24
2.4.2	A Constructionist Approach to Mechanical Thinking	25
2.5	Changes in Mechanical Thinking	27
2.5.1	Changes in the Use of Domain Specific Language	27
2.5.2	Changes in the Use of External Representations	28
2.5.3	Changes in Mappings from Structure to Motion	29
2.5.4	Changes in Discrimination and Integration Skills	29
2.5.5	Changes in the Ability to Deal with Complexity	29
2.5.6	Changes in Design Abilities	29
2.5.7	Changes in Confidence Levels	30
2.6	Summary	30
3	Mechanical and Spatial Thinking: Tools	32
3.1	Design Software for Children	33
3.1.1	LEGO CAD and Derivative Software	33
3.1.2	The Incredible Machine	37
3.2	Design Software for Adults	38
3.2.1	AutoCAD	39
3.2.2	Pro/DESKTOP	40
3.2.3	Working Model	41
3.3	Construction Kits	42

3.3.1	LEGO	42
3.3.2	K'NEX	45
3.3.3	Metal Construction Toys	46
3.4	Automata Software, Kits, and Resources	48
3.4.1	Cabaret Mechanical Theatre	48
3.4.2	Flying Pig	52
3.4.3	Software 4 Teachers	52
3.4.4	MouseWorks	53
3.5	Summary	53
4	Automata as a Domain for Exploring Mechanical Reasoning and Spatial Cognition	55
4.1	A Brief History of Automata	56
4.1.1	Automata in Antiquity	56
4.1.2	Automata come to Europe	58
4.1.3	The Golden Age of Automata	59
4.1.4	The Contemporary Automata Period	63
4.2	What Makes the Design and Construction of Automata an Appropriate Task?	64
4.2.1	Automata Tell a Story	66
4.2.2	Separation of Story and Mechanism	66
4.2.3	Domain Knowledge and Constraints	66
4.2.4	Unexpected Results	67
4.3	Contemporary Automata	68
4.3.1	The Camel Simulator	70
4.3.2	Celia the Sea Lion	71
4.4	Automata in Education	72
4.5	Summary	73

5	The MachineShop System	75
5.1	The MachineShop Software	75
5.1.1	High Level Considerations	76
5.1.2	Exploring Movement	80
5.1.3	Component Editors	82
5.1.4	Browsing Libraries of Components and Mechanisms	92
5.1.5	Designing Mechanisms	94
5.1.6	File Types	100
5.2	Output Devices	101
5.2.1	The Landscape of Computer Controlled Machine Tools	101
5.2.2	The Kern Laser	104
5.2.3	The VersaLaser	106
5.3	Ancillary Materials	108
5.3.1	Example Automata and Mechanisms	108
5.3.2	Kits and Instructions	109
5.3.3	Videos	110
5.3.4	Posters	110
5.4	Summary	110
6	Experiment and Assessment	112
6.1	The Experimental Method	113
6.1.1	The Users	113
6.1.2	The Experimental Procedure	115
6.1.3	Assessment	122
6.2	Results	123
6.2.1	Talking About Automata	123
6.2.2	Using External Representations	124

6.2.3	Components, Motion, and Complexity	125
6.2.4	Confidence Levels	127
6.2.5	MachineShop System Usage	127
6.3	Discussion	129
6.4	Summary	132
7	A Case Study in MachineShop	134
7.1	The Soccer Player	135
7.1.1	Designing the Soccer Player	135
7.1.2	Prototyping the Soccer Player	142
7.1.3	The Soccer Player as Science Project	144
7.2	The Carousel	148
7.2.1	Designing the Carousel	151
7.2.2	Prototyping and Constructing the Carousel	154
7.3	Discussion	157
8	Conclusions, Contributions, and Future Work	160
8.1	Conclusions	160
8.1.1	Children and Automata	160
8.1.2	Automata and Mechanical Thinking	161
8.1.3	Undiscovered Richness in the Domain	162
8.2	Core Contributions	163
8.2.1	MachineShop	163
8.2.2	A Design Process for Creating Automata	164
8.2.3	A System for Using Novel Output Devices	165
8.2.4	A Survey of Research into Mechanical Reasoning	166
8.3	Future Work	166
8.3.1	Technology for Children	166

8.3.2	Meta-design	167
-------	-----------------------	-----

Bibliography		169
---------------------	--	-----

Appendix

A	Observations on the User Testing	179
A.1	The Use of Language During Testing	179
A.1.1	Abbie	180
A.1.2	Dylan	184
A.1.3	Iris	190
A.2	What Users Found Difficult in This Domain	194
A.2.1	Size and Scale	195
A.2.2	Simplification and Generalization of Mechanisms	198
A.2.3	Considering Alternative Mechanical Solutions	199
A.2.4	Reorienting Extant Mechanisms	199
A.2.5	Mechanical Dependencies	200
A.2.6	Lack of Mechanical Education or Experience	200
A.3	User's Experiences with the MachineShop System	201
A.4	Apprenticeship in Practice	203
B	Automata Created with MachineShop	206
B.1	Abbie - Drowsy Dragon	206
B.2	Calum - The Commute	209
B.3	Dylan - The Leaping Lion	212
B.4	Dylan - Busy Beehive	215
B.5	Frank - Evil Cat	218

B.6	Iris - Globe Trotter	222
B.7	Sam - Soccer Player	225
B.8	Sam - The Carousel	228
C	The MachineShop User's Manual	232
C.1	Getting Started with MachineShop	232
C.1.1	System Requirements	232
C.1.2	Getting the Software	234
C.1.3	Assumptions	234
C.1.4	Installing MachineShop	234
C.2	Starting the Program	234
C.3	Exploring Movement	235
C.4	Designing and Editing Components	237
C.4.1	Designing Cams	237
C.4.2	Designing Gears	241
C.4.3	Designing Levers	244
C.5	Assembling Mechanisms	247
C.6	Working with Files and Libraries	247
C.7	Fabricating Components	248
D	Sample Automata and Mechanisms	249
D.1	Ralphie's Dream	249
D.2	Nessie the Sea Serpent	250
D.3	Big Top Celia	251
D.4	Example Mechanisms	253
E	Automata Resources	257
E.1	Contemporary Automata	257

E.2 Automata Builders 258

Tables

Table

6.1 Demographics of the MachineShop Test Users 114

Figures

Figure

2.1	A Test Question about a Pulley System	19
3.1	A LEGO CAD Machine	34
3.2	The LEGO Digital Designer Interface	36
3.3	One Puzzle from the Incredible Machine	38
3.4	A Volvo XC-90 Replica Made from LEGO Bricks	44
3.5	A Sample of LEGO Technic Gears	44
3.6	The K'NEX Gear and Crank Set	45
3.7	A #10 Erector Set from 1932	47
3.8	Contraband Cat Card Cutout Automaton Kit	50
3.9	The Cabaret Mechanical Theatre Designing Automata Kit 2005	51
4.1	Hercules and the Dragon	59
4.2	Three Automata by Vaucanson	60
4.3	Vaucanson's Duck	61
4.4	Three Automata by Jaquet-Droz	62
4.5	Cat Drinking Someone Else's Milk	64
4.6	Press-up Anubis	68
4.7	The Camel Simulator	70
4.8	Celia the Sea Lion	71

5.1	The Machine Shop Opening Screen	79
5.2	The Movement Explorer Interface	80
5.3	Lift and Dwell for a Snail Cam	84
5.4	A Four-lobed Snail Cam and an Eccentric Cam	84
5.5	Designing a 3-lobed Snail Cam	85
5.6	Spur Gears and Pinwheel Gears	87
5.7	Designing a Set of 3 Spur Gears	89
5.8	The Three Orders of Levers	90
5.9	Designing a Lever of the First Order	92
5.10	Browsing Cams in the Component Library	93
5.11	Assembling Components into a Mechanism	98
5.12	The Kern Laser Cutter	105
5.13	The VersaLaser	107
5.14	Examples of Simple Movements	109
7.1	The Soccer Player	136
7.2	The Mechanism for the Soccer Player	137
7.3	The Soccer Player's Leg	139
7.4	Refinement of the Soccer Player's Leg	141
7.5	Building the Support Structure	143
7.6	Testing the Speed of the Returning Ball	144
7.7	The Gears and Cam for the Mechanism	145
7.8	Checking the Kick	146
7.9	The Soccer Player Automaton	149
7.10	The Mechanism for the Carousel	152
7.11	The Carousel Prototype	155
7.12	The Carousel Drive Mechanism	156

7.13	The Animal Lifting Mechanism	157
7.14	The Completed Carousel	158
B.1	Abbie's Sketches for the Dragon	207
B.2	The Drowsy Dragon	208
B.3	The Mechanism of the Dragon	208
B.4	Calum's Initial Sketch for a Commuter	210
B.5	The Commuters	210
B.6	Prototype and Pieces for the Commuters	211
B.7	Dylan's Sketch for the Lion	213
B.8	The Leaping Lion	213
B.9	The Jaw of the Leaping Lion	214
B.10	The Beehive Sketch	216
B.11	The Busy Beehive	216
B.12	Beehive Details	217
B.13	Sketches for the Evil Cat	218
B.14	The Evil Juggling Cat	219
B.15	The Mechanism of the Evil Juggling Cat	220
B.16	Prototyping the Evil Juggling Cat	221
B.17	Sketch of the Globe Trotter	222
B.18	The Globe Trotter	223
B.19	The Mechanism of the Globe Trotter	224
B.20	The Soccer Player Sketch	225
B.21	The Player and Mechanism	226
B.22	Mechanism Detail and the Science Project Poster	227
B.23	The Mechanism for the Carousel	228
B.24	The Carousel	229

B.25	The Carousel Mechanism	230
C.1	Checking Your Operating System Version	233
C.2	Checking the Java Version	233
C.3	Welcome to MachineShop	235
C.4	MachineShop Menus	235
C.5	Exploring Movement	236
C.6	Using the Cam Editor to Design a Snail Cam	238
C.7	Using the Cam Editor to Design an Eccentric Cam	239
C.8	Designing a Ratchet	239
C.9	Using the Gear Editor to Design Sets of Spur Gears	242
C.10	Using the Gear Editor to Design a Set of Pinwheel Gears	242
C.11	Designing a Lever of the First Order	245
C.12	Designing Levers of the Second and Third Order	245
C.13	Designing Crank and Pawls	246
C.14	Browsing the Libraries	247
D.1	Ralphie's Dream	250
D.2	Nessie	251
D.3	Celia the Sea Lion	252
D.4	Example Spur Gears	254
D.5	Example Pinwheel Gears	254
D.6	Example Snail Cams	255
D.7	Example Eccentric	255
D.8	Example Ratchet and Pawl	256
D.9	Example Crank-Sliders	256