

**Popup Workshop: Computationally Enhanced Paper
Engineering for Children**

by

Susan Lee Hendrix

B.A., University of Nebraska, 1969

M.S., University of Nebraska, 1981

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

2008

This thesis entitled:
Popup Workshop: Computationally Enhanced Paper Engineering for Children
written by Susan Lee Hendrix
has been approved for the Department of Computer Science

Michael Eisenberg

Tamara Sumner

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 #1205.17

Hendrix, Susan Lee (Ph.D., Computer Science)

Popup Workshop: Computationally Enhanced Paper Engineering for Children

Thesis directed by Prof. Michael Eisenberg

Computational enhancement of craft work has been attempted for a variety of crafts. These comprise an unusual branch of software development because of their relationship with physical objects produced by users. One craft which has seen no general computational enhancement usable by children is paper engineering. Paper engineering is the production of pop-ups, 3-dimensional forms that pop into shape when a page is opened, and that fold away when the page is closed. This is an interesting craft for children since pop-up books have become a mainstay of children's culture, and have many applications in teaching mathematics, writing, and art.

This dissertation describes the design, implementation and testing of a software application, Popup Workshop, that was designed to enable children to learn how to make pop-ups. Features of Popup Workshop include the ability to make a variety of pop-up elements, the automatic enforcement of the geometric constraints necessary to keep the elements smoothly foldable and allow for changing elements, and the use of a constraint system to allow animation of the 3D representation of the pop-up being designed. A framework of craft learning and practice is developed consisting of the competencies of knowledge, skill and appreciation. This framework is applied to paper engineering to guide the design and testing of Popup Workshop and to assess the changes seen in five young paper engineers who used the software.

Dedication

Growing up in small-town Nebraska, it was my good fortune to know many strong women who became my role-models.

I fondly remember Marie Rutledge, a small-town postmistress. Helen Shaw went to college at a time when few women would have, and became a local pharmacist. Her daughter, Ann Marie Shaw, earned a Ph.D. of her own. My grandmother Rachel Parker was a school teacher in a one-room schoolhouse at the age of 16. And my mother, Betty Hendrix, battled MS to live almost 20 years longer than the doctor's predictions.

These women worked hard and found joy in the small pleasures of life: children, books, food, nature, cats, and conversation with a friend. They survived the loss of husbands and children. Some lived through a depression and two world wars. They set high standards. I still remember my grandmother's raised eyebrow, or Helen's "by the gods" when I said something poorly thought out or phrased.

To all these women, and others over the years, I dedicate this work.

Acknowledgements

No work such as this is done alone. This author would like to thank the many people who helped.

The author thanks Mike Eisenberg for his advice, patience, time, and funding. The other members of my committee provided helpful comments and support: Clayton Lewis, James Martin, Mitchell Nathan, Tamara Sumner and David Webb.

Glenn Blauvelt provided invaluable help, encouragement and red ink. He was always there for me, and this dissertation could not have been completed without him.

My user testing subjects were a joy. A big thanks to: Daisy, Ursula, Richard, Peggy and Emily, and to their parents.

Ann Eisenberg gave the loan of her hypergami kids and much good advice. Craig Yager provided the delightful 5th grade students for informal testing.

Ann Montanaro of the Movable Book Society helped in locating references on paper engineering. Eric Scharff gave support and final editing help. Leysia Palen provided a kind word when it was most needed.

Also contributing assistance, editing and comments were Mitchell Resnick, Yasmin Kafai, Yvonne Rogers, Kirsten Butcher, Erich Hacker, Leah Buechley, Susanne Sherba, and Alena Sanusi.

The work described in this document has been supported by National Science Foundation grant REC0125363.

Contents

Chapter		
1	Introduction	1
1.1	Motivating Problem	2
1.2	Children and Paper Engineering	3
1.3	Pop-ups as a Domain for Computation	4
1.4	A Framework of Craft	5
1.5	Research Question	6
1.6	Research Approach	6
1.7	Reader's Guide and Road Map	8
2	Crafts, Children and Computing	10
2.1	What is Craft?	13
2.1.1	The Relationship Between Craft and Industry	14
2.1.2	The Relationship Between Craft and Art	15
2.2	The Value of Craft	19
2.3	Learning and Practicing a Craft	23
2.3.1	Knowledge	26
2.3.2	Skill	28
2.3.3	Appreciation	31
2.4	Adding the Computing Dimension	33

2.4.1	Computer Enhancement of Craft Knowledge	35
2.4.2	Computer Enhancement of Craft Skill	36
2.4.3	Computer Enhancement of Craft Appreciation	37
2.5	Summary	38
3	The Craft of Pop-ups	40
3.1	A Brief History of Movable Books	42
3.1.1	The First Mechanisms (pre-1700): Wheels and Flaps	45
3.1.2	The First Movable Books for Children (1700-1820): Harlequinades and Toilet Books	52
3.1.3	Early 3-Dimensional Effects (1820-1850): Slots, Panoramas, and Peep- shows	58
3.1.4	The Golden Age of Movable Books (1850-1914): Tabs, Scenes, and Transformations	61
3.1.5	True Pop-ups Emerge (1914-1979)	65
3.1.6	The Modern Pop-up Book (1979-present)	71
3.2	Pop-up Making as a Representative Craft	74
3.2.1	The Pop-up Maker's Knowledge Set	80
3.2.2	The Pop-up Maker's Skill Set	83
3.2.3	Appreciation of Pop-ups	84
3.3	The Value of Paper Engineering for Children	85
3.3.1	The Value of Pop-ups as Craft	86
3.3.2	Pop-ups in the Classroom	88
3.4	Summary	97
4	Pop-ups and Computation	99
4.1	The Composition of Movable and Pop-up Books	100
4.1.1	Movable Devices	101

4.1.2	Pop-up Elements	103
4.1.3	Combining Pop-up Elements	113
4.2	Previous Research on Computationally Enhanced Pop-up Design	116
4.2.1	Mathematics of Pop-ups	117
4.2.2	Computer Based Pop-up Design Tools	119
4.2.3	Viewing the Operation of Virtual Pop-ups	125
4.2.4	Creating Physical Pop-ups from Virtual Representations	127
4.3	Introduction to a System for Children’s Use in Pop-up Crafts	129
4.3.1	Supporting the Growth of Knowledge	130
4.3.2	Supporting the Growth of Skill	131
4.3.3	Supporting the Growth of Appreciation	132
4.3.4	Other Design Considerations	133
4.4	Summary	133
5	The Popup Workshop System	136
5.1	High-Level Design Considerations	137
5.2	Design History of Popup Workshop	140
5.3	User Interface	143
5.3.1	Editor Window	145
5.3.2	Viewer Window	151
5.3.3	Menu Operations	152
5.4	Program Design and the Nature of Pop-ups	153
5.4.1	Classes and Data Structures	154
5.4.2	File Formats	156
5.4.3	Geometric Constraints of the Elements	159
5.4.4	Constraint Methods in the Opening Algorithm	167
5.5	Summary	172

6	User Testing	174
6.1	Informal Testing	175
6.1.1	Observations of Children During Informal Testing	177
6.1.2	Influence of the Informal Tests	179
6.2	Formal Testing Methods and Environment	181
6.2.1	User Sessions and Environment	182
6.2.2	Pre- and Post-testing Assessment	183
6.2.3	Data Collection and Analysis	188
6.3	The Users	188
6.3.1	Users - Data About Sessions	190
6.3.2	Users - Prior Experience	191
6.3.3	Users - Results of Cognitive tests	192
6.4	Results	194
6.4.1	Craft Knowledge	194
6.4.2	Craft Skill	199
6.4.3	Craft Appreciation	206
6.4.4	Other Observations	210
6.5	User Testing in Context	218
6.6	Summary	222
7	Two Users of Popup Workshop	224
7.1	Overview	224
7.2	First Pop-ups	227
7.2.1	Peggy: Abstract Face	227
7.2.2	Emily: <i>Freddy Squarehead</i>	231
7.3	Later Pop-ups	234
7.3.1	Peggy: <i>Sun, Tree, and Cloud</i>	234

7.3.2	Emily: <i>Bart the Elephant</i>	239
7.4	Conclusions	245
7.4.1	Craft Framework	245
7.4.2	Software Interaction	247
7.5	Summary	248
8	Conclusions, Contributions, and Future Work	250
8.1	Conclusions	250
8.2	Core Contributions	251
8.2.1	Popup Workshop	251
8.2.2	Craft Framework	252
8.2.3	User Testing	253
8.2.4	Literature Survey	254
8.3	Future Work	254
8.3.1	Software Additions and Enhancements	254
8.3.2	Further User Studies and Curricular Applications	255
8.4	Final Remarks	257
	Bibliography	258
	Appendix	
A	Glossary	267
B	Resources for Pop-up Making Learners and Teachers	274
B.1	Instruction Books	274
B.2	Kit Books	275
B.2.1	Web Sites	276

B.2.2	Web Sites of Paper Engineers	277
B.2.3	Other Web Sites	277
B.3	Resources for Teachers	279
B.3.1	Making Pop-up Books in the Classroom	279
B.3.2	Using Commercial Pop-up Books in the Classroom	282
C	Popup Workshop Documentation	284
C.1	Introduction	284
C.2	System Requirements	285
C.3	Downloading, Installing and Running Popup Workshop	285
C.4	General Information	286
C.5	Adding Elements	287
C.6	Changing Elements	290
C.7	Deleting Elements	291
C.8	Replicating Elements	291
C.9	Decorating Elements	292
C.10	Saving and Printing Your Popup	293
C.11	Finishing Your Popup	294
C.12	Trouble Reporting	295
C.13	For Further Reading	295
C.14	Known Bugs in This Version	297
C.15	Changes in Version 2.0	297
C.16	Acknowledgements	298
D	User Testing Materials, Books, and Tools	299
D.1	Tools	299
D.2	Materials	300
D.3	Instruction Books	301

	xii
D.4 Pop-up Books	301
E User Testing Questionnaires	304
E.1 First Session Questions	304
E.2 Final Session Questions	305
E.3 Email Follow-up Questions	305
F Pop-ups Created by User Test Subjects	307
F.1 Daisy	307
F.2 Ursula	313
F.3 Richard	320
F.4 Peggy	325
F.5 Emily	331
G Test Subject Pop-up Analysis	343

Tables

Table

2.1	Teacher perceptions of value of craft in education	21
4.1	Elements Used in Three Commercial Pop-up Books	113
6.1	Demographics of Users	189
6.2	Test Extent for Users	191
6.3	Cognitive Test Results	192
6.4	Element Names in User Tests	195
6.5	Total Numbers of Each Element for Each User	204
G.1	Daisy: Software-Produced Elements	344
G.2	Ursula: Software-Produced Elements	344
G.3	Richard: Software-Produced Elements	345
G.4	Peggy: Software-Produced Elements	345
G.5	Emily: Software-Produced Elements	345
G.6	Decorative Features of Pop-ups Produced by Daisy	346
G.7	Decorative Features of Pop-ups Produced by Ursula (Sessions 1-3)	347
G.8	Decorative Features of Pop-ups Produced by Ursula (Session 4)	348
G.9	Decorative Features of Pop-ups Produced by Ursula (Sessions 5-8)	349
G.10	Decorative Features of Pop-ups Produced by Richard (Sessions 1-3)	350
G.11	Decorative Features of Pop-ups Produced by Richard (Sessions 3-5)	351

G.12 Decorative Features of Pop-ups Produced by Peggy 352

G.13 Decorative Features of Pop-ups Produced by Emily (Sessions 1-4) 353

G.14 Decorative Features of Pop-ups Produced by Emily (Sessions 5-9) 354

G.15 Decorative Features of Pop-ups Produced by Emily (Sessions 10-13) 355

Figures

Figure

2.1	A Framework of Craft Learning	25
3.1	Volvelles	46
3.2	Lullian Circle	47
3.3	Apian Volvelles	49
3.4	Examples of Flaps	50
3.5	A Harlequinade	56
3.6	A Toilet Book	57
3.7	A Panorama	58
3.8	A Carousel Book	59
3.9	A Peep-show or Tunnel Book	60
3.10	Scenic Books	64
3.11	A Transformation	65
3.12	A Pull-tab	66
3.13	Bookano	68
3.14	The Tournament Castle	69
3.15	A Modern Pop-up	72
3.16	A Fractal Pop-up	92
4.1	A Partial Taxonomy of Movable Devices	101

4.2	A Gatefold Producing Side-Pages	102
4.3	Parts of a Pop-up Elements on the Base Page	103
4.4	Constraints on the Step Element	104
4.5	A Partial Taxonomy of Pop-up Elements	105
4.6	Five Commonly Encountered Pop-up Elements	106
4.7	Box, Pyramid, and Platform Elements	108
4.8	Boat and Coil Elements	109
4.9	Attached Planes	110
4.10	Moving Arm Element	111
4.11	Slotted and Noisemaker Elements	112
4.12	Three Step Elements Combined into One Pop-up	114
4.13	Terms Describing a Pop-up Element at Level 2	114
4.14	An Inverted Element	115
4.15	The Relationship Between V-fold, Angled Tent, and Parallel Tent	118
4.16	Examples of Origamic Architecture	120
4.17	Making a Pop-up with Pop-Up Card Designer	121
4.18	Pop-up Assistant Interface	123
4.19	Animation of the Pop-up with Pop-Up Card Designer	126
4.20	Printing a Final Pattern with Pop-Up Card Designer	128
5.1	Popup Workshop Windows and Palettes	144
5.2	Popup Workshop Palette Buttons	146
5.3	Popup Workshop: Adding an element	147
5.4	Popup Workshop: Changing an Element	148
5.5	Popup Workshop: Replicating elements	149
5.6	Popup Workshop: Deleting elements	150
5.7	Popup Workshop: Viewer Window	151

5.8	Popup Workshop: A Collision Between Elements	151
5.9	Tags in a Popup Workshop Save File	158
5.10	The Step Element in Popup Workshop	160
5.11	The Beak Element in Popup Workshop	161
5.12	The Angled Step Element in Popup Workshop	162
5.13	The V-fold Element in Popup Workshop	164
5.14	The Tent Element in Popup Workshop	166
5.15	Example of Anchored and Unanchored Points	169
5.16	Algorithm for Placing Opened Pop-up Points	170
6.1	Pop-ups Made During the Informal Studies 1: 5th Grade Students	175
6.2	Pop-ups Made During the Informal Studies 2: Summer Program Students	176
6.3	Pop-ups Made in Informal Studies: Adults	177
6.4	Comparison of Viewer Window in Software Versions	179
6.5	Assessment Pop-up 1	185
6.6	Assessment Pop-up 2	185
6.7	Assessment pop-up 3	186
6.8	Assessment comparison pop-up 1	186
6.9	Assessment comparison pop-up 2	187
6.10	Two Pop-ups Made at Home by Emily	212
6.11	Two Pop-ups Made at Home by Ursula	213
7.1	Peggy's First Pop-up Complete	227
7.2	Peggy's First Pop-up As Printed	230
7.3	Emily's First Pop-up Complete	231
7.4	Emily's First Pop-up As Printed	233
7.5	Peggy's Final Pop-up Complete	235
7.6	Peggy's Final Pop-up As Printed	236

7.7	Brad Holding the Sun on Peggy's Final Pop-up	237
7.8	Emily's Eighth Pop-up Complete	240
7.9	Emily's Eighth Pop-up As Printed	242
C.1	Popup Workshop Starting Windows	286
C.2	Popup Workshop with design in progress.	289
C.3	Popup Workshop with design in progress that includes multiple pages	290
C.4	Two pop-ups made with Popup Workshop	293
C.5	Other pop-ups made with Popup Workshop	295
F.1	Daisy Session 2 Pop-ups	308
F.2	Daisy Session 3 Pop-ups	308
F.3	Daisy Session 4 Pop-up	309
F.4	Daisy Session 5 Pop-up	310
F.5	Daisy Session 6 Pop-up	311
F.6	Daisy Session 7 Pop-ups	312
F.7	Ursula Session 1 Pop-ups	313
F.8	Ursula Session 2 Pop-up	314
F.9	Ursula Session 3 Pop-ups	315
F.10	Ursula Session 4 Pop-ups	316
F.11	Ursula Session 5 Pop-ups	317
F.12	Ursula Session 6 Pop-up	318
F.13	Ursula Session 7 Pop-ups	319
F.14	Ursula Session 8 Pop-up	319
F.15	Richard Session 1 Pop-up	320
F.16	Richard Session 2 Pop-ups	321
F.17	Richard Session 3 Pop-ups	322
F.18	Richard Session 4 Pop-ups	323

F.19	Richard Session 5 Pop-ups	324
F.20	Peggy Session 1 Pop-up	325
F.21	Peggy Session 2 Pop-ups	326
F.22	Peggy Session 3 Pop-up	327
F.23	Peggy Session 4 Pop-up	328
F.24	Peggy Session 6 Pop-up	329
F.25	Peggy Session 7 Pop-up	330
F.26	Emily Session 1 Pop-up	331
F.27	Emily Session 2 Pop-ups	332
F.28	Emily Session 3 Pop-ups	333
F.29	Emily Session 4 Pop-ups	333
F.30	Emily Session 5 Pop-ups	334
F.31	Emily Session 6 Pop-ups	335
F.32	Emily Session 7 Pop-ups	336
F.33	Emily Session 8 Pop-ups	337
F.34	Emily Session 9 Pop-ups	338
F.35	Emily Session 10 Pop-ups	339
F.36	Emily Session 11 Pop-ups	340
F.37	Emily Session 12 Pop-ups	341
F.38	Emily Session 13 Pop-ups	342