

Sculpted Computational Objects with Smart and Active Computing Materials

by

Margaret A. Orth

B.F.A., Painting, Rhode Island School of Design, 1986
S.M.V.S., Massachusetts Institute of Technology, 1993

Submitted to the Program of Media Arts and Sciences,
School of Architecture and Planning
In Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

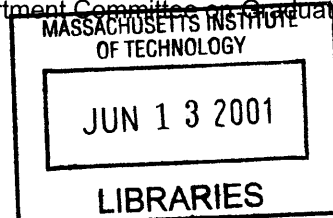
[June 2001]
May 2001

© Massachusetts Institute of Technology 2001. All rights reserved.

Author.....
Program of Media Arts and Sciences,
School of Architecture
April 30, 2001

Certified by.....
[Signature] / Tod Machover
Professor of Music and Media
Thesis Supervisor

Accepted by.....
Stephan A. Benton
Chairman, Department Committee on Graduate Students



ROTCH

Sculpted Computational Objects with Smart and Active Computing Materials

by

Margaret A. Orth

B.F.A., Painting, Rhode Island School of Design, 1986

S.M.V.S., Massachusetts Institute of Technology, 1993

Submitted to the Program of Media Arts and Sciences,
School of Architecture and Planning
In Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

Abstract

This thesis presents the creative, technological, and philosophical means and methodology, by which technology artists and researchers can materially and sculpturally transform physical computing technology from hard, remotely-designed, plastic shells, into intimately created, sensual computing objects and artifacts. It asserts that the rigid, square, and prefabricated physical materials of computing technology are a fundamental technological and artistic limitation to anyone who wishes to sensually transform physical computing technology, or develop a rich artistic vocabulary for it. Smart and active sculptural computing materials are presented as a solution to this problem. Practically, smart computing materials reduce the number of separate, rigid, and square prefabricated parts required to create physical computing objects. Artistically, active sculptural computing materials give artists and designers the ability to directly manipulate, shape, experiment with, and therefore aesthetically understand the *real*, physical materials of

computing technology. Such active design materials will also enable creative people to develop a meaningful artistic relationship between physical form and computation.

The total contributions of this thesis include a proposal for a future three-dimensional design/technology practice, a portfolio of sensually transformed expressive computational objects (including new physical interfaces, electronic fashions, and embroidered musical instruments), and the smart and active sculptural computing materials and processes (in this case smart textiles), which make that transformation possible. Projects from the design portfolio include: *The Triangles*, and its applications; *Electronic Fashions*, including the *Firefly Dress and Necklace*, *New Year's Eve Ball Gown*, and *Serial Suit*; *The Musical Jacket*; *Electronic Tablecloths*; and a series of *Embroidered Musical Instruments* with embroidered pressure sensors. Contributions from the supporting technical area include: the first fabric keypad (a row and column switch matrix), a new conductive yarn capable of tying and electrical/mechanical knot, an advanced process for machine embroidering highly conductive, flexible and visually diverse electrodes, an empirical model of complex impedance sensing, and a definition of and test for the machine sewability and flexibility of yarns. These contributions are presented in three sections: 1) the supporting arguments, and philosophy of materiality and computation behind this work, 2) the design portfolio, and 3) the supporting technical story.

Thesis Supervisor: Tod Machover
Title: Professor of Music and Media

Sculpted Computational Objects with Smart and Active Computing Materials

by

Margaret A. Orth

The following people served as readers for this thesis:

Reader _____
John Maeda
Associate Professor of Design and Computation

Reader _____
Neil Gershenfeld
Professor of Media Technology

Acknowledgements:

For my mother who taught me to sew and make things, and my father who told me I could do anything.

Many thanks to my committee members: John Maeda, whose work made me wish hardware was as expressive as software; Neil Gershenfeld, for letting me make a really big mess in his lab; and Tod Machover, for his undying creative and personal support, and his wonderful sense of humor.

Thanks to my many unbelievably talented collaborators: Matt Gorbet, Rehmi Post, Peter Russo, Emily Cooper, and Gili Weinberg. You have all contributed to opening my mind and imagination.

Thanks to Hiroshi Ishii for his support, generosity with ideas, and imagination.

There are not enough words to thank to my perfect and brilliant husband, Joshua Smith.

...and to my daughter Lily, who often asks, "Mommy, how is your thesis?" I can now answer, "Done."

Contents

SECTION I. SUPPORTING ARGUMENTS

Chapter 1. Introduction p.14

- Expanding the Problem p.16
- Expanding the Contributions p.19
 - A Future Three-Dimensional Design/Technology Practice p.19
 - My Artistic and Aesthetic Vision p.22
 - The Portfolio of Expressive Computing Objects p.23
 - Smart Textiles: Materials and Processes p.27
- Conclusion p.30

Chapter 2. An Oeuvre? p.31

- The Question Concerning Art p.32
- What's in a Demo? p.35
- Utopian Visions of Technology p. 38
- Expressive Objects p.39
- Everyday and Approachable p.40
- Multiples p.41
- Materials and Meaning p.43
- Functional Ornament: A Modern/Post-Modern Tension p.45
- Conclusion: *Bad* Materials p.47

Chapter 3. Physical Computing Technology: A Future Artistic Medium and Form p.49

- Beyond Chips in Boxes p.49
- Software as a Model for an Expressive, Computing Medium p.51
 - Plasticity, Shapeability and Expression p.53
 - Direct Manipulation of *Real* Materials p.54
 - An Intimate Relationship Between Form and Computation p.55
- Can Hardware become an Expressive, Computing Medium? P.55
- Sculpted Computational Objects: Properties and Materials p.56
 - A Closer Look at Commonly-Used Computing Materials p.58
 - Raw Materials p.59

Prefabricated Materials p.59
Structured Materials p.60
Where Do Physical, Computing Materials Belong? p.60
More Rigid than Stone p.61
Fixed and Rigid, Electrical and Mechanical Connections p.63
Conclusion p.63
Chart of the Properties of Computational Objects p.65

Chapter 4. A Sculptural Perspective p.66

The Unshapeable, Unsculptable and Persistently Square p.68
Square Displays and the Pictorial Tradition p.71
Shapeability p.72
Shaping in Industrial Design p.72
Shaping in the Fine Arts p.74
The Direct Manipulations of *Real* Materials p.75
More on the Decorative/Industrial Arts p.78
Ramifications p.79

Chapter 5. Related Work p.82

Robotics as Computational Assemblage p.82
Tim Anderson, *Painting Machines* p.84
Stellarc, *Robotics and the Body* p.85
Ken Goldberg, *Tele-Garden* p.86
Plastic Manipulation vs. Assemblage p.86
Dave Small and Tom White, *Stream of Consciousness* p.87
Meaning and Materials in Sculpture p.88
Joseph Beuys, *Materials Before Form* p.89
Merit Oppenheim, *Fur-lined Tea Cup* p.90
Symbolic Materials in Practical and Interactive Computing Objects p.92
Product and Industrial Design p.93
Apple Computers p.94
Durrell Bishop p.95
Human Computer Interface and Tangible Computing p.98
Hiroshi Ishii, *Various Works* p.98

Brygg Ullmer, *Strata* p.99
Electronic Musical Instruments p.100
Musical Controllers p.101
Stand-Alone Instruments p.102
Michael Waisvisz, *Crackle Synthesizer* p.103
Michael Waisvisz, *The Hands* p.104
Dan Truman and Perry Cook, *BOSSA, Bowed Sensor and Speaker Array* p.104
Curtis Bahn, *Bubbaball* p.105
Laurie Anderson, Interval Research and Bob Bilecki, *Talking Stick* p.106
Conclusion p.106

Chapter 6. Future, Smart and Sculptural Computing Materials p.108

Design Properties of Sculptural and Active Computing Materials p.108
Smart or Multi-Functional Computing Materials p.110
The Materials of an Acoustic Violin p.111
The Materials of its Physical, Computing Counterpart p.112
Small is *Not* Enough p.114
Networked Computing Materials p.115
Amorphous Computing, J. Sussman p.116
The Potential of Structured Computing Materials p.117
How My Portfolio of Projects Fits In? p.117

SECTION II. THE DESIGN PORTFOLIO

Chapter 7. Introduction to the Design Portfolio p.119

Motivating Design Work in Tod Machover's *Brain Opera*, 1996 p.120
Talking Trees p.122
Rhythm Tree Pads p.123
Digital Baton p.124

Chapter 8. *Triangles* as a Networked, Computing Material p.127

Overview of the *Triangles* p.127
How They Work p.128
Why Three Sides? p.129

As A Macroscopic Material p.129
Integrated Connector Design p.130
First Generation p.131
Second Generation p.132
Triangles Applications p.133
Galapagos; An Interactive Web-based Narrative p.135
Cinderella 2000: An Audio Comic Book p.139
Character Triangles p.140
Text Bubble or **Information** Triangles p.141
Event Triangles p.142
Narrative Conclusions p.142
The Digital Veil, Ars Electronica, 1997 p.144
Working Notes on Images, Sounds and Associations p.146
Toy Search p.149
Conclusion p.149

Chapter 9. Early Smart Textiles Projects p.151

Why Textiles? P.151
The Electronic Fashions p.154
Firefly Dress and Necklace p.155
Electronic New Year's Eve Ball Gown p.159
Serial Suit p.160

Chapter 10. Projects in Fabric Sensing: p.162

Spanning Fashions, Musical Instruments and New Physical Interfaces p.162
Piecework Fabric Keypad p.164
Musical Jacket p.165
Embroidered Keypad p.169
Electronic Tablecloth p.171

Chapter 11. Early Embroidered Musical Instruments p.175

Introduction to Embroidered Musical Instruments p.175
Physical Interdependency in the *Embroidered Musical Instruments* p.176
From the Generic to the Specific: Timeline of the *Embroidered Musical Instruments* p.178
Embroidered Musical Instruments as a Smart Materials System p.179

Early Embroidered Musical Instruments p.181
Squiggle Ball 1 with Composite Thread p.182
Squiggle Ball 2 with 100% Non-Continuous Stainless Steel Thread in Bobbin p.184
Diamond Ball 3 with 100% Non-Continuous Stainless Steel Thread in Bobbin p.186
Circle Ball 4 with 100% Non-Continuous Stainless Steel Thread in Bobbin p.187
Circle Ball 5 with Wrapped Thread p.188
Generic Ball 6: A Design Control Object p.189

Chapter 12. Shaped Embroidered Musical Instruments p.192

As Musical Instruments p.192
Music Shapers in Tod Machover's *Toy Symphony* p.193
Squeeziness and Shapeability p.195
Quick Demo, Commercial Toy or Practiced Instrument? P.197
A Natural Squeezing Style and Intimacy Sensing p.200
As Sculpted Computational Objects p.202
A Relationship Between Physical Form and Music Software p.202
A Hands-on Design Process p.204
A Few Essential Textile Advances p.206
Shaped *Embroidered Musical Instruments* p.209
Sound Sculpture Pyramid p.209
Melody Butterfly p.215
Melody Tube p.217
Big Ring p.220

SECTION III. THE TECHNICAL STORY

Chapter 13. Complex Impedance Sensing p.224

Introduction to the Technical Story p.224
Overview of the Sensing p.226
A Simple Capacitive Model p.227
Grounding Issues p.228
What is Pressure in the *Embroidered Instruments*? p.229
Black Art Sensing Factors p.229

- Test Circuits p.231
- Design Implications of Sensing Model p.235
 - Large Sensors for the Precise Control of a Limited Number of Musical Parameters p.236
 - Small Sensors for Intuitive Exploration of Numerous Interdependent Musical Parameters p.236
- Software Filtering p.237
- Beyond the Resistive Element p.237
 - Frequency Response Across Skin and Fabric Electrodes p.238
- Conclusions p.241

Chapter 14. Defining Sewability and Flexibility in Yarns p.243

- Background p.245
- Introduction to Flexibility in Textile Materials p.247
- Machine Sewing p.249
- General Characteristics of Machine Sewable Yarns p.250
 - High Tensile Strength or Tenacity p.251
 - Moderate % of Elongation at Breakpoint p.251
 - Denier of ~Under 400 p.252
 - Smooth Surface Finish p.253
 - High Flexibility p.253
- Curl Test for Flexibility of Yarns p.255
 - 1) Bending or Curling the Yarn p.256
 - 2) Reloading the Yarn p.257
- The Final Analysis p.258
- Individual Yarn Results p.259
- More on Flexibility in Fibers p.260
 - Flexibility in Conductive Fibers and Yarns p.263
 - Sewing with Conductive Yarns p.264
- Specific Yarn Analysis p.266
 - Metal Wrapped or Gimped Yarns p.266
 - Stainless Steel Yarns p.267
 - Staple or Stainless Steel Yarns p.268
 - Yarns with Continuous Stainless Steel Filaments p.270

Chapter 15. Materials Index p.271

Stainless Steel Fibers p.271

Materials List p.272

Gimped Thread, Wrapped with Metal Foil p.272

Metallic Silk Organza p.273

Conductive Hook and Eye Fasteners (Velcro) p.274

Stainless Steel and Polyester Blend, BK50/2 p.275

100% Continuous Stainless Steel p.276

70-100% Non-Continuous Stainless Steel p.276

Nylon Wrapped with Continuous Stainless Steel p.277

Mechanical and Electrical Knot Tying Braid of 100% Continuous Stainless Steel Core Wrapped with BK50/2 p.277

Snaps, Zippers, Earring Backs, and Other Mechanical Fasteners p.278

Chapter 16. Sewing Process Timeline p.279

Expansion of the Sewing Time-line p.281

Piecework Circuit Elements Sewn from Metallic Silk Organza p.281

Composite Stainless Steel Thread, (BK 50/2) Passes Through Needle of Commercial Sewing Machine p.282

High Impedance Circuit Elements Designed in CAD Environment and Embroidered on Commercial Machine with Composite Stainless Steel Thread, (BK 50/2) p.282

Electro Impedance Reduced by 10X by Using Composite Stainless Steel Thread, (BK 50/2) in Bobbin p.283

Electro Impedance Reduced by Improved Stitch Pattern and Continuous Stitch Path Between Objects p.283

Electro Impedance Dramatically Reduced by Using 100% Non-Continuous Stainless Steel in Bobbin, but Causes Short Circuits Between Close Elements p.285

Electro Impedance Dramatically Reduced by Nylon Wrapped with 3 Continuous Stainless Steel Fibers in Bobbin without Sewing Problems p.285

Sensing Stability and Resolution Improves when Electrode Area and Density are Increased p.286

Tying a Knot Creates a Simultaneous Mechanical and Electrical Connection with a Twine of Continuous Stainless Steel Core Wrapped with Stainless Steel and Polyester Composite Thread (BK 50/2) p.287

Contour Underlay Stitch Decreases Electrode Stiffness p.288

Contour Stitch Overlay Decreases Stitch Density and Increases Conductivity p.288

Chapter 17. Conclusion p.290

- Summary p.293
 - A Proposal for Future Design p.293
 - A Personal Artistic Vision p.294
 - Proof is in the Projects p.295
 - Technical Innovations p. 298
- Further Inquiry p.297
 - Art and Design p.300
 - Physical Form and Computation p.300
 - A Process for Exploring Physical Form and Computation p.301
 - Future Materials p.304
 - Smart Textiles p.304
 - Future Sculptural Smart Computing Materials p.305
 - Future Computational Objects p.311

Design Appendix. The *Big Thing* p.313

- Description of The *Big Thing* p.314
 - List of Kit Components p.315
- Description of Components p.315
 - Islands p.315
 - Chunks p.316
 - Poking Area p.316
 - Operator Poles p.317
 - Stack Connectors p.317
 - Stretchy Connectors (Conductive Bungee Cords) p.317
 - Feather Sensors p.318
- Implementation of *Big Thing* p.318
 - Overall Schematic of *Big Thing* Infrastructure p.318
 - Physical Chunk Design p.320
 - Chunk Communication and Electronic Design p.320
 - Bungee Cord Sensors p.323

Bibliography p.325

Chapter 1.

Introduction

Have you ever wondered why computers aren't pretty? Why they are hard? Why they are square? Why they don't feel good? Or why wearable computers are still unfashionable and unwearable? Is this a reflection of the aesthetics and priorities of the male dominated engineering world that creates them? Or are there more fundamental technological limitations that prevent people from having aesthetically¹ fulfilling, if not downright desirable computers and computing objects? And if artists and designers could take computing technology even further, physically transforming it into soft, furry and sensuous, tactile objects, would that material transformation also expand and change the role and meaning of computing technology in peoples' lives? This thesis asserts that there are fundamental technological limitations that prevent physical computing technology from becoming not only tritely

¹ By aesthetics, I am primarily referring to what the Oxford English Dictionary On-line, World Wide Web, (2001) defines as: "Of or pertaining to sensuous perception, received by the senses." At the same time I am loosely referring to its other definition aesthetics, "Of or pertaining to the appreciation or criticism of the beautiful."

pretty, but also from developing a sophisticated, sensual and visual, artistic language. These same limitations also prevent artists and designers from radically changing peoples' aesthetic, or gut response, to computing technology, and therefore its meaning and purpose in their daily lives.

In response to this problem, this thesis presents a portfolio of aesthetically transformed, expressive computing objects, the new technologies that enable that transformation, and the artistic and design theories that direct and describe this work. These contributions include electronic fashions, squishy, stuffed, embroidered musical instruments, new physical interfaces, and the new, smart textiles and processes, including fabric pressure sensors, keypads, circuits and connectors, that make these aesthetically unusual computing objects possible. Together, these artistic and technical contributions act as a proposal for a future, three-dimensional design/technology practice that seeks to transform computing technology, both aesthetically and technically, through smart and active, sculptural computing materials. And while the results of this thesis are multidisciplinary, integrating artistic theories, processes and artifacts with electronics, software, materials science, and manufacturing, the main contributions of this thesis are the portfolio of expressive computing objects and the design/technology proposal that these objects present. This proposal for a future design/technology practice combines hands-on design and artistic practices founded in the decorative and industrial arts, computing technology, and novel, physical, smart sculptural materials in attempt to truly change the

physical form and sensual properties of computing technology. My hope is that together, the technical, artistic, and theoretical results of thesis will ultimately point the way to a sophisticated, sensual and visual artistic language for physical and material computing technology; a language which will ultimately enable the power of computing technology to find a more expressive, sensual and creative role in peoples' lives.

Expanding on the Problem

Five years ago I came to the Media Lab to find myself surrounded by dreary beige boxes. I was a sculptor, artist, and designer of physical objects who was suddenly confronted with a world of neutral PCs. All around me people simply ignored the material presence of computers. Computers were literally *physically* invisible. People seemed to be aware of only the *virtual* space inside the computer's monitor. But a revolution was about to take place. Researchers in Things-that-Think² were taking computation out of its box, and into the world around us. No longer were computers bound to the desktop and invisible, suddenly they were "ubiquitous"³. Unfortunately, they were also ugly and physically ill suited to their tasks. I

² Things-that-Think is a research consortium that was begun in 1996 at the MIT Media Lab. According the [MIT Media Lab website](#), World Wide Web, (2001): "This consortium explores ways of moving computation beyond conventional sites, such as PCs or laptops, and adding intelligence to objects that are first and foremost something else."

³ Weiser, M., *The Computer for the 21st Century*, [Scientific American](#), (1991) pp 94-104.

was constantly confronted with computing objects that were rampant with physical paradoxes. Early wearable computers were *heavy, sharp, metal boxes*. Researchers also seemed to think that by simply sticking a piece of technology onto an object, the two would miraculously become integrated. Bulky commercial sensors were pasted onto sculptural musical instruments. Monitors were inserted into walls and onto doors to create smart rooms. Chips were stuck into coffee cups. I began to wonder if the makers of these new computing objects saw the physical aesthetics of their research as superfluous or were simply completely, visually unaware.

As an artist, I deeply felt that the act of creating a physical computing object *had* to be at some level about visual design, material processes and aesthetics. During my early work creating physical interfaces for the electronic musical instruments in Tod Machover's *Brain Opera*, I realized that the ugly computing objects around me were not simply the result of a lack of aesthetics and design training on the part of their makers. These objects were also the result of the poor and limiting physical computing materials with which they worked. Displays, chips, buttons, sensors, circuit boards and wires were not a particularly rich, broad or sculptural palette of physical materials. Moreover, when these materials were taken out of their plastic boxes, they became physically fragile and awkward. I began to believe that the only way I could physically and sensually transform computing objects was with new, physical computing materials. I also began to believe that the engineering goals of creating faster and smaller parts would not solve the artistic and

design problems I was facing. I had to create computing materials that would meet my aesthetic and practical goals as a designer. These materials had to be varied and rich in their mechanical properties and truly sculptural. They also had to integrate computing technology directly into the sculptural, design materials I wanted to work with, materials like textiles.

The creation of new, smart materials that allowed computing technology to exist comfortably in non-traditional physical contexts, like clothing and jewelry, *did* help overcome both the practical problem of integrating technology into everyday objects, and the formal boundary to aesthetic development. However, these were not my only artistic goals. Ultimately, I wanted people to feel differently about computing technology, to feel empowered over it, to question it, and to turn it toward creative and expressive ends. Industrial design and product design have demonstrated clearly that the physical form and material properties of an object can communicate its purpose and *function* to people. From my training in the fine and conceptual arts, I had learned that an object's materials could contribute to and transform its meaning *symbolically*. I believe that one important and unexplored way to change peoples' attitudes toward and use of computing technology is to transform its physical form and material properties *aesthetically*. By making technology physically and materially humorous, intimate and even strange, I ultimately hope to give it a more creative and expressive role in people's lives. By making technology from familiar and intimate materials like textiles, and with an everyday, down-to-earth

process like sewing, I also hoped to give people a more empowered feeling over technology.

Expanding the Contributions

The total contributions from this thesis include a proposal for a future three-dimensional design/technology practice, a portfolio of sensually transformed, expressive computational objects, and the smart and active, sculptural computing materials, in this case smart textiles, that enables that transformation.

A Future Three-Dimensional Design/Technology Practice

When today's artists and designers work with the physical materials of computers they usually work in a CAD-based process that is sculpturally remote. In fact, many designers of consumer electronics never even touch the *real* physical materials of computers, whether plastic or electronic, but instead work in models and through scenarios. And while visionary work in tangible computing⁴ by researchers like Hiroshii Ishii and Durrell Bishop has attacked both the inactive housing materials and some of the electronic guts of computers, there is still little work that integrates the design (housing) materials with electronic or active computing materials. There is also little work in which

⁴ Ishii, H. and Ullmer, B., *Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms*, Proceedings of Conference on Human Factors in Computing Systems, (CHI 1997), Atlanta, ACM Press, (1997).

designers sketch directly in electrically or computationally, active physical computing materials, or use them for a direct aesthetic and artistic exploration of physical form and computation. Moreover, there is almost no plastic shaping of active computing materials. Instead, most designers looking to materially transform or shape computing technology use unusual materials like wood and paper to cover existing chips and circuits, and additive methods to assemble a variety of prefabricated, rigid and square parts. But imagine being able to cut a piece of sensor/speaker plaid, sew it together, and create a musical instrument, a new computer mouse, or a soft computerized doll. Imagine picking up a piece of clay and shaping it into an object that interacts with software, and creates images related to its shape and size. Imagine directly and materially shaping a computing object, and immediately seeing the effect of that sculptural process on music, a story or an image.

In the tradition of the Media Lab, the future design/technology practice proposed in thesis lies at the crux of technology and culture, demonstrating how technology can change art and design, and how the needs of art and design can transform and drive technology. This proposal presents a material and process-oriented approach to technology design that integrates experimental technology research, the Media Lab's tradition of project-based research, and a hands-on design tradition that emerges from the industrial and decorative arts. This proposal asserts that without an aggressive and intimate, hands-on approach to the physical materials of computing technology, it is not possible to master, control or

understand their design, aesthetic and expressive properties. This proposal also insists that designers and artists create and invent new, sculptural and active, computing materials that meet their creative and aesthetic needs. Through both the direct creation and manipulation of the physical materials of computers, this new technology/design practice hopes to create computing objects that are both aesthetically and technically innovative.

The following tenets are presented as a guide for this future three-dimensional design/technology practice. While I believe these tenets have broad ramifications for any design practice dealing with physical computing or electronic technology, this summary is not meant as a prescription. Instead, it is meant as unique approach that can help designers of physical computing objects reach their practical and creative goals.

Deeply transform physical computing technology; sculpturally, materially and aesthetically.

- Do not accept prefabricated computing materials or allow them to determine the shape, form, sensual or tactile properties of your work.
- Create your own smart and active, sculptural physical computing materials. Make these materials meet your design and artistic needs, or turn your preferred design materials into active computing materials. Make your physical computing materials sculpturally and artistically manipulable in a direct, hands-on manner. Integrate as much computing functionality as possible into a single material.

- Understand the mechanical, electrical, sculptural and symbolic properties of your computing/design materials.

Explore the relationship of physical shape and computation formally.

- Create computational objects that are not physically neutral (like a mouse), but whose shape and material properties have meaning and relevance in software.
- Create cognitively clear and technically stable design control objects for initial formal exploration.
- Mix and match physical objects and software and to see what happens. Iterate between physical form and software.

Create new computing objects, don't just stick microchips in existing objects.

My Artistic and Aesthetic Vision

My personal artistic and aesthetic proposal is not about making computing technology pretty or tasteful. The ability to make computing technology pretty or even beautiful is only one incarnation of an artist's or designer's ability to truly change the meaning and physical properties of computing technology through novel computing materials. Moreover, my aesthetic is not about hating plastic. When I worked in a bronze foundry I wanted to make things that were materially opposed to bronze, things that were plastic. Now, I want to materially and sensually *invert* computing technology *away* from the hard and plastic. The motivations for this are simultaneously positive and perverse. Such an inversion is meant to make the computing objects in this thesis sometimes strange and

sometimes intimate. I hope that these transformations will make people see and feel differently about computing technology, make them question its use and turn it toward more expressive and creative ends.

As my personal artistic proposal, I do not believe that the following approach is necessarily applicable to other design or artistic practices. It is my own, a reflection of my training, goals and beliefs as a creative person.

Aesthetically *invert* the symbolic meaning of computational objects through antithetical and unexpected forms and materials.

Computing objects are hard, plastic, formal, square, heavy, smooth, remote and beige. Make them soft, fuzzy, desirable, sensual, round, light, squishy, elastic and colorful. Computing objects are square and industrial. Make them rounded and organic. Make computational objects more approachable and accessible through design and materials, not more elite or isolated. Make computational objects materially surprising and humorous.

The Portfolio of Expressive Computing Objects

Examined from the tradition of the visual arts and design, the portfolio of objects presented in this thesis can be understood as lying somewhere between the practices of industrial design, the decorative arts, technology design, and physical interface design. The objects presented in this thesis are simultaneously musical instruments, physical computer interfaces, fashions and other "everyday" objects that have been transformed through computation and smart materials.

The objects in this thesis are also "everyday" computing objects and physical interfaces that have been aesthetically transformed through unusual sculptural computing materials and an intimate craft/design process that finds its roots in the industrial and the decorative arts. These objects range from single hand-made objects, like the *Firefly Dress and Necklace*, to mass-produced objects like the *Triangles* and *Musical Jackets*. Together, they form a horizontal exploration of the expressive relationship of physical form, computation, the physical materials of computation, ornament, and three-dimensional design.

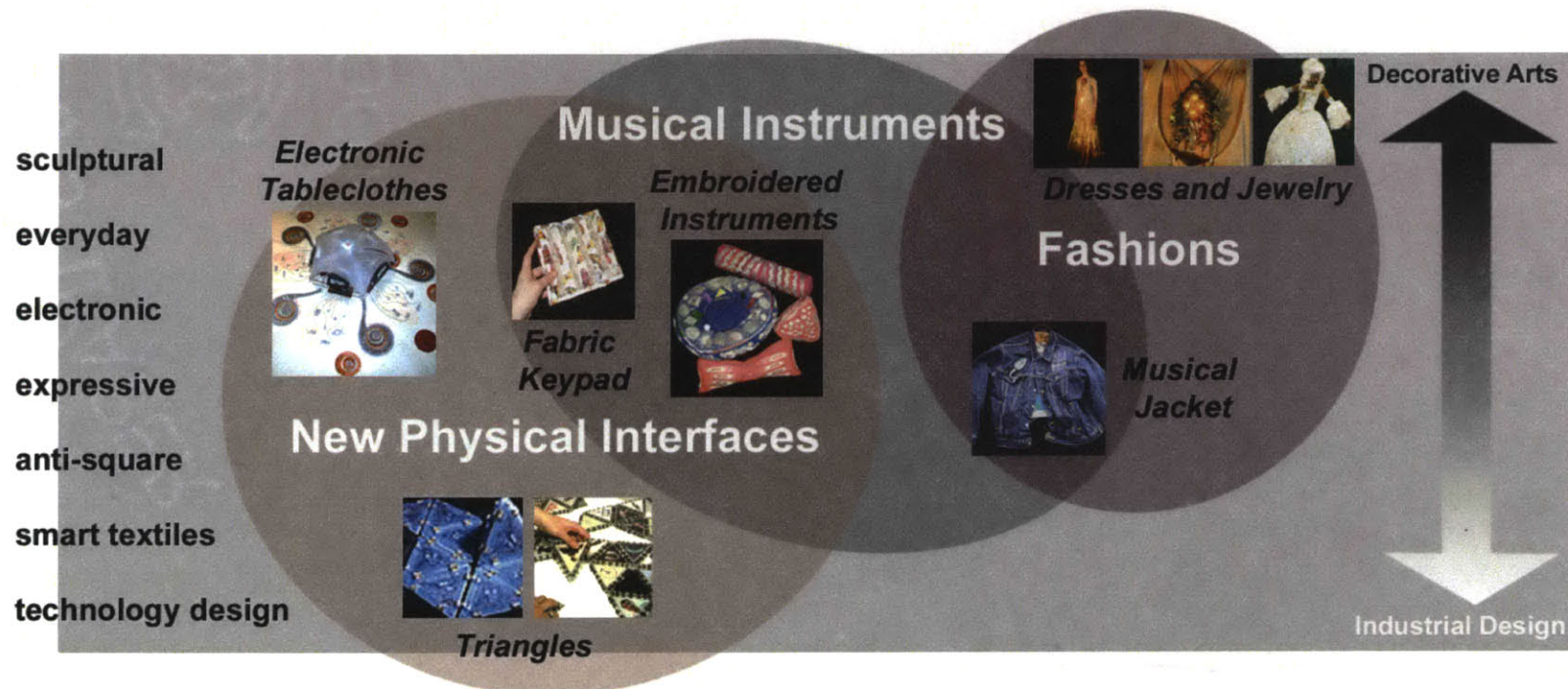


Figure 1.1 The Tree of Projects.

As both aesthetic objects and technology research, the computing objects presented in this thesis make the proposal for a future three-dimensional design/technology practice. But while these objects can be understood as *a proposal* for the future, it is essential to this proposal, that these objects and enabling technology are not merely theoretical. They are not unrealized design proposals that exist only on paper, and are unaware of the processes and materials necessary to create them. Nor are they merely scenarios, stories of how imaginary technology might change our lives. Instead, they are very real, working, expressive computational objects, their applications, and the working and innovative technology necessary to create them. Ranging from electronic fashions to musical toys, these everyday objects clearly demonstrate how new and unusual computing materials, like smart textiles, can allow computing technology to be transformed from plastic consumer electronic devices into aesthetic objects that are part of the rich material world around us. In fact, it is the very reality and functionality of the technology in these computing objects that makes the proposal for a hands-on approach to three-dimensional technology design involving the direct manipulation and invention of sculptural, physical computing materials.

Contributions from the design portfolio include:

The *Triangles* and its applications

A patented digital/physical construction kit.

- Version 1, with Matt Gorbet
- Version 2, with Matt Gorbet

- *Galapagos*, a web-based story application with Matt Gorbet
- *Cinderella 2000*, an audio comic book
- *The Digital Veil*, an artistic audioscape with Matt Gorbet and Mary Beth Back.
- *Toy Search*, an interactive web-based game

Electronic Fashions with Emily Cooper and design students

Fashions that use electrically active textiles as sensors, circuitry and design materials.

- *Firefly Dress and Necklace*
- *New Year Eve Ball Gown*
- *Serial Suit*

The Musical Jacket with R. Post, J. Strickon, J. Smith, and E. Cooper

A stand-alone, wearable musical instrument that contains a patented embroidered keypad, fabric communication bus, speakers, batteries and a miniature MIDI synthesizer in the form of a pin.

Electronic Tablecloths with A. Lippman, R. Post, P. Mukerji, P. Russo

An interactive cocktail-party jeopardy game, that contains an embroidered capacitive tag reader and keypad.

Early Embroidered Musical Instruments, with Peter Russo

Musical instruments with embroidered pressure sensors.

- *Squiggle Ball 1*
- *Squiggle Ball 2*
- *Diamond Ball 3*
- *Circle Ball 4*
- *Circle Ball 5*
- *Ball 6, The Generic Musical Ball*

Shaped Embroidered Instruments

Musical instruments with embroidered pressure sensors for Tod Machover's Toy Symphony.

- *Sound Sculpture Pyramid*
- *Melody Tube*
- *Melody Butterfly*
- *Big Ring*

Smart Textiles: Materials and Processes

The supporting technical contributions made by this thesis are essential to the achievement of my artistic and design goals. Without these smart textiles, fabric sensing devices, and sewing processes I could not have created the expressive, computing objects shown here. My motivation for working with textiles was multiple. On the one hand, I wanted to create flexible, and durable sensors for new digital musical instruments. As interest in wearable computers emerged at the lab, I also found that I was far more interested in making clothing compute than strapping a PC to my body. Using textiles as a computing material was a solution to both. Textiles are also a wonderfully, sculptural material. They are cuttable, bendable, shapeable and easy to make quick prototypes with. Finally, they are *feminine*. Traditionally, textiles have been considered women's work. I enjoyed using them to create computing technology, something that is normally considered within the realm of the male. In addition, they are soft and squeezy.

To truly make the proposal for sensually transformed computers, I needed to keep the computing objects created for this thesis as lightweight and soft as possible. Textiles were chosen because they are soft and squeezy. Ideally, smart textiles would create soft

computing objects by replacing all the hard, square materials of the computer, including monitors, sensors, chips, housings, and power supplies. The active, smart textiles presented in this thesis do not do this. They integrate housing materials, input sensors and wires, and are then used as part of a *smart material system*⁵ that is connected to a central processor or PC. The chips, speakers, power supplies and displays necessary for these objects are either located off board, or cleverly disguised. Integrating all these computing materials into a single textile is the next step towards creating truly "squishy" computers.

Because squeeziness, touchability, wearability and softness are central to my artistic vision, creating smart textiles with these properties was also one of my central technical goals. Consequently, I have tried to create smart textiles that are as flexible, durable and soft as most fashion-oriented textiles. Focusing on fibers and yarns that can work with the standard textile manufacturing processes and machinery, rather than developing new machinery, helped guarantee this. There are many industrial textiles that contain unusual fibers, like glass, that are not soft, flexible or appropriate for touch. These textiles are usually made with special machines that take into account their unusual mechanical properties. Using standard sewing machines guaranteed that the yarns I worked with had mechanical properties very similar to standard fashion-oriented yarns.

⁵ Ball, Phillip, Made to Measure: New Materials for the 21st Century, Princeton, University of Princeton Press, (1997) pp.107.

The conductive yarns and woven textiles used in this thesis are for the most part pre-existing, conductive threads and woven textiles that have been re-purposed to create sewn or embroidered electronic circuitry and devices. The *Firefly Dress and Necklace*, the row and column keyboard, and the fabric data and audio bus in the *Musical Jacket* all use a very old, decorative fabric known as metallic silk organza. The machine embroidered sensors and electrodes made for this thesis are sewn from a variety of composite stainless steel threads that are usually used for static or EMF shielding, or as mechanical composite reinforcements in products such as tires. The new materials developed for this thesis were developed at a composite level, and involve the braiding, weaving or sewing of existing yarns and textiles together.

The supporting technical contributions of this thesis include:

The first fabric keypad, a piecework row and column switch matrix.

A new electrically active, composite yarn capable of tying and electrical and mechanical knot.

An advanced process for machine sewing highly conductive and visually diverse embroidered electrodes.

An empirical model of complex impedance sensing in a smart materials system of smart textiles and central circuitry.

A definition of, and test for, the sewability and flexibility of yarns and threads.

A portfolio of electrically active textiles.

Conclusion:

All of the projects and the supporting technology presented in this thesis are the result of my overall artistic motivation to materially and physically transform computers, and to explore the expressive relationship between physical form and computation. At the same time, they are the result of my own artistic ideas and beliefs that I have developed for years, and of the research agenda and environment here at the Media Lab. All of these factors have combined to motivate the work in this thesis. The next chapter looks at how these factors combine to form the unique body of work presented in this thesis, and attempts to further describe the motivations and ideas behind this work.

Chapter 2.

An Oeuvre?

Ultimately, the objects presented in this thesis are both an artistic and technical, vision and exploration. They are a vision and exploration of how computers can transcend their persistent squareness and become a sculptural medium. They are a vision and exploration of how physical form and computation can interact to create a new expressive language. They are a vision and exploration of how smart materials can change computing technology into intimate and sensual objects. They are a vision and exploration of how computers might become materially *real*, and materially symbolic. They are a vision and exploration of how ornament and decoration can, through computer technology, actually become functional. They are a vision and exploration of how smart materials can change technology design from a remote CAD-oriented process to a more intimate, physical and hands-on process. They are a vision and exploration of how the needs of design and artistic practices can *technically* change computing technology. They are a vision and exploration of how unusual computing materials can change the role and place of computing technology in people's lives. Finally, they are a vision and exploration

of how computer technology can be turned toward the enabling of human expression.

The Question Concerning **Art**

The best answer that I know to the question of "Is it **Art**?" was given to me by a great artist and wise man, Krzysztof Wodiczko. He said, "This question is irrelevant. **Art** is defined by the **Artist**. The relevant question is: 'Is it successful?'"

When I came to the Media Lab it was because I was no longer interested in creating **Art** for galleries. I wanted to explore the role of art, design and images in the world outside the gallery, in worlds like commerce and mass production. There is a famous statement in conceptual art, "To search for the GOOD and make it matter"¹. This is related to much of the ethical, conceptual and social art being practiced in art schools today. After years of being a practicing artist (going from a formalist painter to a more conceptual, feminist performance artist), I had reached the conclusion that making art with a strong social and ethical message did not have much relevance in the context of the gallery or museum. I did not believe it mattered. I wanted to take that statement and invert it: "Take what MATTERS and make it good." Technology MATTERS. I wanted to make it good. I also believed that technology was a vast unexplored realm for artistic three-dimensional development outside the square and pictorial. Finally, I

¹ Majozo, E., *To Search for the Good and Make it Matter*, from, Lacy, S. (ed.), *Mapping the Terrain, New Genre Public Art*, Seattle, Bay Press, (1999).

was interested in creating multi-disciplinary and collaborative work that was applicable in many contexts outside the gallery.

Never, from the time I entered the doors of the Media Lab, was I asked to create **Art**. Frankly, if I had wanted to create personal **Art**, or **Art** for galleries, I probably would not have come to the Media Lab. I would have gone to the Whitney program in New York and continued my feminist performance work there. Instead, I participated wholeheartedly in many of the research agendas of the lab, including, the Hyperinstruments group, Things-That-Think, and Toys of Tomorrow. In this context I produced many effective demos, research projects, papers, shows in galleries, performances and patents. My research was successful in many contexts, both as working technology and as a proposal for future technology/design.

Don't get me wrong I am not saying that the work presented in this thesis is not art, nor am I saying that I have been cheated out of making art. I am merely saying that this is not a particularly relevant question for me for two reasons. After years of worrying about what **Art** is, I had decided, that indeed, **Art** was not definable, and that the question for me to concern myself with was "Is it successful?" I had also come to believe that **Art** with a capital **A**, or **Art** for museums and galleries, was often a highly rarefied practice that was limited in its scope. Through the course of my own artistic development, I had gone from being a strongly formalist painter, to a more conceptual artist, attempting to make the content or social message the

main focus of my feminist performance work. Before I came to the lab, the last **Art** I created was designed to examine how women participated in their own "feminine" construction. This work was meant to be critical and transformative, to help women see other possibilities in their psychic development. Over time, I began to realize that as long as I practiced my **Art** in galleries I could not reach any audience, but other feminists, who were already aware. I felt I was preaching to the converted. I tried to free my work from galleries but found it difficult. I found myself consistently meeting the attitude that the gallery was where **Art** was supposed to be and where I was supposed to practice.

The Media Lab gave me an opportunity to make work with broader boundaries, work that is relevant in more places than the gallery. I see my work today as art and design with a little "a": art that engages and transforms objects that are part of everyday life, whether fashions, toys, musical instruments or computers. While I ultimately believe the distinction between high **Art** and art is an historical anomaly; within the terms of this distinction, my work is clearly in the tradition of the practical and everyday arts. Moreover, my work is not the product of an individual maker and his or her personal "expression" as fine **Art** (after the 19th century), is often defined to be. Like many contemporary art forms that engage with technology (for instance film and theater), my work is the product of a highly collaborative process.

My work takes a post-modern position of the question of **Art** vs. art, asserting that art with a little "a" is

relevant based on its position in everyday life and its social context, while at the same time engaging in more formal questions. On the one hand, my desire to use unusual and unexpected computing materials to transform the meaning of computational objects comes out of a post-modern desire to make meaning and content the focus of artwork. On the other hand, I have found that meaning and content cannot be transformed or even controlled without both the materials and the formal language to do so. Because the physical media and materials of computers are such new territory for artists and designers, my work has often focused on fundamental questions about the formal language of physical form and computation, and on creating the materials necessary to control that meaning and content.

What's in a Demo?

While I am reluctant to draw a box or category around the work I have done at the Media Lab, I can say with little reservation that all the work that I have created, invented and designed at the Media Lab shares the distinction of being a live demonstration of working technology, or what is known at the Media Lab as a "demo". I make no apologies for this. In many ways, creating a demo is one of the most challenging forms of communication, and a truly unique technology design problem.

A demo must tell a highly captivating, clear, and believable story about the future of technology to a diverse audience made up of corporate sponsors,

media, and research or intellectual peers. This story usually needs to reflect at least two or three separate research agendas of the lab. To communicate this story, a demo must be technologically functional. In fact, it is the very functionality of the technology in a demo that enables people to see possibilities that they did not before. Moreover, the ideal demo will invent and demonstrate *new* technology. A demo must then use some sort of sophisticated language, whether visual, audio or narrative to communicate this story. Finally, a demo must function or engage in some external context or sphere of practice outside the lab, like engineering, scientific research or art. It might achieve this by being mirrored elsewhere in the culture, like the fashion world, the toy industry or the world of musical performance. A demo might also achieve this by having an "other" purpose that reflects the alternative or even subversive goals of its maker, as in my case art and design. Achieving and balancing all these disparate goals with one technology project is a truly challenging and creative *meta* design problem.

I believe that the research I made functioned as successful demos. Just as product design endeavors to use physical form and visual information to communicate the purpose of the object, my demos used form and visual information to communicate their story. My research was also unique because of the visual design and artistic background I brought to problems that had normally been confronted from the perspective of engineering, science, social science and HCI.

Making demos provided me with the opportunity to create work that was meaningful in many contexts and to many people with different perspectives. When I was officially an **Artist**, I felt that my work was limited to the gallery and ultimately seen only by those in the gallery. Demos provided me with the potential to reach and influence diverse industry sponsors (from toy makers to chip manufacturers), media, academics, and researchers in many fields. But more importantly, demos can go out into the world and reach people in many different forms. The demos that I made at the lab were meant to function in interactive musical performances, installations, fashion shows, galleries, and as models for new toys or other commercial items.

Creating demos that could function as both far-flung artistic and technology research, and real-life, working objects is incredibly challenging. For instance, the *Embroidered Musical Instruments* presented in this thesis were designed to be part of larger project, *Toy Symphony*. The goal of this project is to provide kids with electronic music toys that would help them learn about, create and ultimately perform music with a symphony orchestra in a professional performance. Creating these instruments meant balancing a number of disparate criteria. These instruments needed to sound great, and also be meaningful design and technology research. They needed to be durable enough for public performance, relatively cost effective and reproducible in *at least* a limited number. Finally, they were meant to inspire, if not become, actual commercial products.

Frankly, fulfilling all these criteria was not possible. While it is extremely challenging to transform demos from the Lab into permanent public installations, making the transition to product is far more challenging. In the case of the *Embroidered Instruments*, the smart textiles that allowed us to create reasonably cost effective and durable "limited series" items for the performances, were too expensive for actual toys. Moreover, the technology that is cheap enough for actual toys, injected molded plastic, is too expensive for limited run items, and not research oriented. In addition, the process for making a real toy at an established company like Mattel involves a number of marketing tests. Few toys ever make it past these tests, and the reasons seem as much a result of the process and people involved as of the toy itself and the kids reaction to it. For research to truly suggest the future it needs to focus on creating the improbable, both intellectually and practically. Making a product involves creating the probable. Consequently, the path from demo to product is rarely clear.

Utopian Visions of Technology

As a vision for the future, a demo can be a profoundly positive action. Personally, I have found that as a *positive* proposal for the future, the making of demos stands against much of the purely *critical* art practices of today. This is not to say that the making of a demo is not the result of a critical design or thinking process, or that a demo cannot have a critical message. Nor should demos rely on an implied *neutrality* of technology, examining none of the negative aspects of

new technology. Nor should they be a blind vision of technology changing the world. But under any critical message in a demo there must be some new *possibility or proposed solution* to a problem. As a positive proposal, creating demos offers artists and designers a means to making something that is actively forward looking and hopeful and does not rely on the vocabulary of critical theory that dominates the art academy today.

This may put the research presented in this thesis squarely in the line of many unfashionable, utopian design visions of the future, like those of the 1964-1965 New York World's Fair or the design work of Buckminster Fuller. Despite the *extensive* criticism of this type of work, I can live with that. I would rather make a positive design proposal than be relegated to the practice of making art or objects whose main function is to be critical. Like Buckminster Fuller, my work actively uses technology to make a proposal for the future. And like Fuller, some of it manages to be produced in limited run productions and reach the outside world, while some of it exists as working prototypes and suggestions. Unlike Fuller, my work is not geared toward using technology to create a sustainable environment. It is geared toward using technology to enable what I believe is a fundamental human activity, aesthetic and artistic expression.

Expressive Objects

One of the main goals of this thesis has been to turn the powerful and extensive tools of computing

technology toward enabling human expression in everyday life. I firmly believe that putting computing technology in the service of human expression will make that technology better, and further human expression. Because I believe that the desire for aesthetic and artistic expression is a fundamental human activity, this is ultimately, a strongly humanist approach.

In a broad sense, all of the objects and materials in this thesis are designed to enable human expression. This can be done in many ways. There are tools and instruments, like paintbrushes and violins, which enable both professionals and everyday people to play music or create a painting. There are aesthetic objects, like pieces of clothing, jewelry or furniture, that enable people to express themselves simply through a choice of style, design and ornament. And there are creative materials, like clay that enable artists to express their ideas. This thesis has produced objects and artifacts in all of these areas, including musical instruments for kids, fashions, and materials for artistic expression.

Everyday and Approachable

One major goal of my research has been to emotionally empower people in relation to computing technology. I have attempted to do this by making computing technology more physically approachable, rather than rarefied or isolated. I have chosen to create computing objects that are part of everyday life, like fashions, tablecloths and instruments. I have also chosen to create objects that speak to people in

aesthetic styles that technology usually does not. My use of visually organic and romantic, decorative elements has been aimed at subverting the standard aesthetics of the beige box and the hard, weapon-like, business-oriented, style of commercial technology. I have also attempted to make technology more approachable through its materials. I have chosen to work in textiles, a material that through its physical intimacy, softness, and warmth is antithetical to the hard plastic of most computing objects. Finally, I have used humor to make computing technology more approachable. I have attempted to create computing objects that are visually surprising and make people laugh.

Multiples

Since coming to the Media Lab, I have always endeavored to create objects that could be mass-produced at some level, and were not single entities or individual works of **Art**. The history of using the processes and images of mass production to question "what **Art** is" is extensive. Controversy over the legitimacy of multiples as true art works can be seen in multiple bronze casting of August Rodin². Warhol used what is considered a lesser **Art** medium, printmaking and the images of mass media (for instance Campbell's soup cans), to question the meaning of the single, handmade piece of **Art**.

² Krauss, Rosalind E., *Narrative Time; the Question of the Gates of Hell, Passages in Modern Sculpture*, Cambridge, MA, MIT Press, (1977).

The objects in this thesis are for the most part multiples; they are almost all reproducible and manufacturable on some small scale. In fact, one reason I was anxious to work with textiles is that they are a wonderful material for producing objects that are both the result of a hands-on material-oriented process, and are capable of being reproduced in a limited series. And as multiples, rather than single *precious* objects, most of the work in this thesis can easily go out into the world and be touched and handled, an essential part of interactive art. The use of multiples has also made my work unique as a demo. Multiples make great demos because people can see that the technology is robust enough to be reproducible. Making multiples also means that the research or project must be created with an awareness of the manufacturing processes by which it is made, something that I believe is essential to any design process.

I have also used multiples to explore a basic artistic question made possible only by computers and mass production. Networking and the mass production of electronic objects are allowing creative people to explore the artistic and expressive potential of a large group of communicating objects. The *Triangles*, with their numerous narrative applications, was an early example of this exploration. Further explorations into the expressive possibilities of networked objects were also done both by Kelly Heaton (both *Nami* and

Peano)³, and with Gili Weinberg⁴ in the networking of the *Embroidered Musical Instruments*. The potential of networked objects remains a large area of expressive exploration yet to be tackled.

Materials and Meaning

My interest in unusual materials and the meaning that they impart to an object has always been fundamental to my work as an artist. My desire to use antithetical or "bad" materials has also always been important for me artistically. When I worked in a bronze factory I longed for plastic. Consequently, it is no surprise that the objects created for this thesis use unusual computing materials to subvert and transform the meaning of computing technology.

My work with computing technology has demanded new computing materials for both practical and symbolic reasons. New sculptural materials are necessary to achieve the practical integration of computing technology into many everyday objects, like clothing. These materials are also necessary to allow artists a hands-on sculptural experience with computing technology. But these are formal and practical issues. New computing materials also bring to

³ Heaton, Kelly, Physical Pixels, Thesis for the Degree of Masters of Science of Media Arts and Sciences at the Massachusetts Institute of Technology, Cambridge, MA, (2000).

⁴ Weinberg, G., Lackner, T., and Jay, J., *The Musical Fireflies - Learning About Mathematical Patterns in Music Through Expression and Play*, Proceedings of XII Colloquium on Musical Informatics, A'quila, Italy. (2000).

the table the ability of an artist to change the meaning of computing object *symbolically*. Artists like Joseph Beuys have put "materials before form"⁵, using the chemical properties of their materials to create the meaning of the whole work of art. My reason for using unusual computing materials is not to create *nicer* or *prettier* computers. Instead, my goal has been to invert computing technology and its meaning with antithetical materials. Consequently, one of the specific, sensual, material and sculptural transformations that dominates the work of this thesis is the pursuit of the soft and squishy. I have always seen my work as aligned with the project of *Surrealism*, with conflating reality and dreams⁶. Undeniably, I have been attracted to materials that are organic, squishy, and even transparent because these are sensually opposed to most computing technology. But I have also been interested in working with textiles because they are symbolically *female*. Most people associate fashion and the textile arts with women. Sewing is traditionally seen as women's work. Sewing computers and technology subverts the idea that technology is a man's work and a man's territory.

⁵ Borer, Alain, *The Essential Joseph Beuys*, Cambridge, MA, MIT Press, (1997) pp. 15.

⁶ A more detailed description of Surrealism and the work of Joseph Beuys is provided in Chapter 5.

Functional Ornament: A Modern/Post-Modern Tension

The computing objects presented in this thesis use smart materials to create ornamental and decorative elements that are actually *functional*. The creation of computationally active ornamental elements for this thesis, brings to the fore, the tension between Modernism and Post-modernism that I believe exemplifies the objects created for this thesis. Beginning with Adolph Loos' infamous "Ornament and Crime",⁷ published in 1908, modernism scorned the ornamental and decorative as criminal, depraved, and bourgeois.⁸ The modernist Bauhaus espoused pure *functionalism* and created what has been since been called *the machine aesthetic* or the square, ornament-free objects and architecture which are associated with the modern design. (Of course, the machine aesthetic has been criticized for being itself a form of superficial ornament or style, while presenting itself as a social solution.⁹) In architecture, Post-modernism revived the ornamental and decorative, looking to non-functional elements to bring meaning and context, if not irony and fantasy, to its work. In Post-modernism, ornament and decorative style were seen as indeed *functional* by virtue of the meaning it added to a piece of design.

⁷ Loos, Adolf, *Ornament und CVerbrechen in Trotzdem 1900-1930*, Innsbruck, Verlag, (1931) pp. 79-92.

⁸ Newman, Lenore and Spak, Jan L., *Is Ornament a Crime?*, Idleberg, Martin (ed.), *Designed for Delight*, New York, NY, Flammarion and the Montreal Museum of Decorative Arts, (1977) pp. 177.

⁹ Reyner Banham, *Theory and Design in the First Machine Age*, MIT Press, Cambridge, MA, (1996).

The objects presented in this thesis have taken what has been criticized as superfluous (ornament) and made it computationally and practically *functional*. While I have a strong love of ornament and decoration for aesthetic reasons, and for the meaning it can bring to an object, I also have a strong desire to have some functional purpose to my design decisions. *Functional ornament* has given me an opportunity to do both.

A number of computing objects in this thesis clearly use *functional ornament*. For instance, the *Embroidered Musical Instruments* presented in this thesis use electronic embroidery to create ornamental patterns that are not merely visually expressive, but that also function as pressure sensors. When touched and squeezed these sensors play music. Decorative elements and unusual materials like tortoise shell and mother of pearl, have historically played a strong role in the visual design of musical instruments. For example baroque guitars have often used elaborate inlay, painting and color to communicate the status, personal preferences of their owners, or the place and period where they were made. But these designs generally had little influence on the sound of the instrument. Even the elaborate rosettas of early guitars had no acoustic function.¹⁰ *My Embroidered Musical Instruments* are decorated with embroidered ornament that is actually musically *functional*; it is essential to how the instrument creates music. Moreover, the design of these ornamental sensors is an intimately

¹⁰ Kuronen, Darcy, *Dangerous Curves, The Art of the Guitar*, Boston, MFA Publications, (2000).

linked reflection of both the visual, tactile and the technical needs of the sensor. For instance, the “bumpy” sensor from the *Sound Sculpture Pyramid*, is a huge, embroidered resistive network that functions as a pressure sensor. The decorative swirl underneath creates a broad, flexible, conductive, plane. The bumps and interconnects tie that plane electrically together and also provide an excellent mechanical surface for the player to couple to and a tactile indication that the player is touching the sensor. In this way, both the technical, ergonomic and visual needs of the sensor are intimately tied together.

Conclusion: *Bad* Materials

The ability of what are normally considered the housing materials of computing objects, (the materials that artists and designers of physical computing objects are most concerned with), to participate in computation captured my imagination. To fully understand how making the housing materials of computing objects active, sculptural and smart will improve the design process and aesthetically transform physical computing objects, we must have a better understanding of what the current, commonly-used and *bad* physical materials of computing objects are. It is significant to understand that what I am referring to here is not necessarily the microscopically engineered materials of computers, like silicon. Instead, I am referring to all the human-scale materials that must be assembled to create any physical computing object. After all, it is the sensually perceived that is ultimately the concern of the artist and designer. These human-scaled computing materials

include; output media like speakers, lights and visual displays, input media like buttons and sensors, chips and circuits, wires, power supplies and of course, the housing material that holds it them together, (usually plastic). I refer to them all as computing materials because any designer needs them to make any physical computing object. Active computing materials include anything electrical, and for the most part include everything but the housing material of a computing object. The next chapter of this thesis will take a closer look at these materials and their ramifications for physical computing technology as an artistic material, medium, and form.

Chapter 3.

Physical Computing Technology: A *Future* Artistic Medium and Form

This chapter presents an overview of the goals for physical computing technology as both a future artistic *medium* and *form*, and the limitations that physical computing technology must overcome to achieve those goals. This overview provides an important conceptual framework for a deeper analysis of the process and materials of sculpting computing objects from the perspective of visual art and design practices, i.e., industrial design, decorative arts practices and sculpture, which is presented in Chapter 4.

Beyond Chips in Boxes

Over the past few years computers *have* begun to escape their neutral, beige boxes. Today, we have a myriad of *industrially designed* electronic devices,

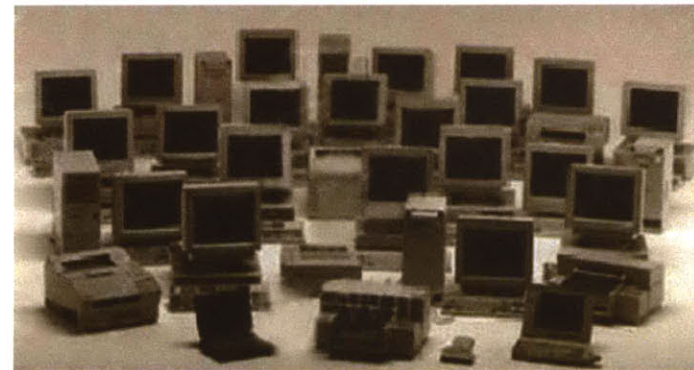


Figure 3.1 The beige and square ancestors of today's more shapely, consumer, computing devices.

including PDA's and cell phones, programmable picture frames and the beautiful new Apple computers. Design and technology research agendas, like Ubiquitous Computing and Things-that-Think, want computers to disappear into the rich, material world around us. Sciences like MEM's and nanotechnology are promising microscopic engines, sensors that can float inside our bodies, and miniature machines that can build themselves. At the same time there is a materials revolution taking place. New visions of quantum, biological and chemical computers all promise ways to create faster and smaller computers.

Yet despite these research visions, faster and smaller materials, and ergonomic and colorful designs, most new computing objects remain no more than poor grandchildren of their neutral beige ancestors. They are still merely chips and circuits in plastic boxes. In fact, their physical form and material properties still remain a highly *superficial* reflection of their square, prefabricated guts, which may include chips, buttons, speakers, displays, wire, circuit boards and speakers. The process that creates them is also remote and industrial, leaving little room for the direct manipulation and aesthetic exploration of active, physical computing materials. Moreover, the relationship of these objects physical form to computation, or what happens inside them, is also highly superficial. And finally, the sensual and material properties of physical computing objects, are still limited in the extreme. There is only one tactile vocabulary for computing objects, square, smooth and hard. All of these artistic problems are an artifact of the square, prefabricated, physical computing materials

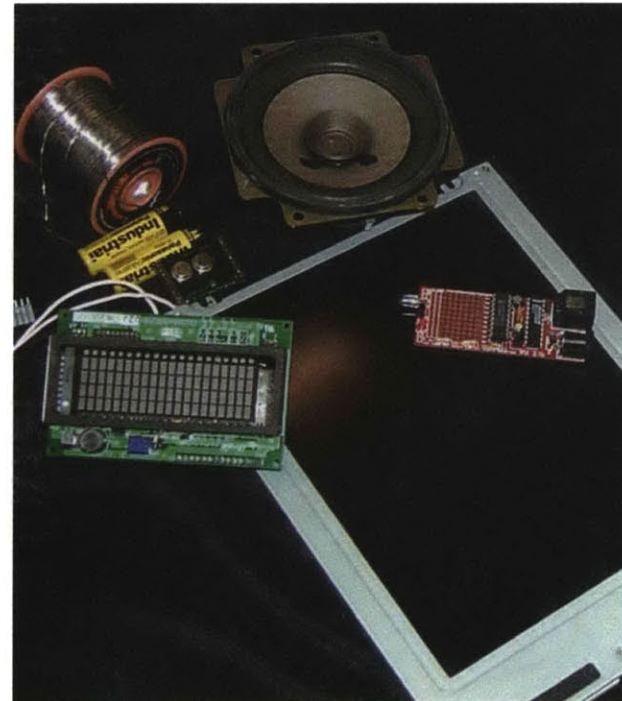


Figure 3.2 The typical palette of physical computing materials, including speakers, screens, IR boards, solder and batteries.

that are commonly available to most artists and designers today.

I believe that computers and computing technology have the potential to become a truly sculptural, materially rich, and directly expressive artistic medium, which will allow artists to explore more than just the relationship of a plastic housing and a circuit board. The beige computers shown in Figure 3.1 recall a time when computers were physically neutral and figuratively invisible. No one cared what they looked like or felt like. Moreover, their shape and material properties has no effect in software, (changing the shape of the monitor, or the mouse makes no difference in any application). But I believe that there can be a relationship between the physical properties of a computing object, (its shape and tactile qualities), and computation that is artistically expressive, evocative and necessary.

Software as Model for an Expressive, Computing Medium

Computer technology presents artists and designers with two types of artistic media to shape; the *physical* materials of computers (circuits, displays, buttons, silicon and plastic), and the *virtual* media of computers (light, images, and sounds.)¹ As an artistic medium,

¹ In this chapter, I use of the word medium to refer to something, like paint or film, which artists manipulate to create their message. Perhaps the most appropriate definition of *medium* in regards to computers comes from a 19th century understanding of *medium* as an "intervening or intermediate agency or substance" through which

software, and the *virtual* media it controls, (sound, images, light), have been highly successful, as can be seen by the revolution that computer graphics has created in film, computer music and much algorithmically generated art. Because of this success, software and the *virtual* media of computers provide an excellent model for what artists and designers should expect from the *physical* materials of computing technology. This may seem odd, because virtual media might be seen as the antithesis to the material and physical design practice I am advocating. But it is not. The expressiveness and directness of the virtual media of computers provide artists and designers with a level of control and intimacy that is an excellent model for the physical materials of computers.

The expressive properties of software and the virtual media it creates and controls include:

- It is highly plastic or shapeable, and therefore expressive.

people express an idea. {Taken from: Williams, Raymond, Keywords, A Vocabulary of Culture and Society, Rev. Ed., New York: Oxford UP, (1983)}. In my comparison of the virtual and physical media of computers, it may seem that I have conflated the word medium with materials. I describe the virtual, untouchable, light, sound and images of computers as media, and compare them to the touchable materials of computers, screens, plastic and speakers. I think this is an appropriate comparison because the physical media of computers are indeed materials. Moreover, for my philosophy, it is essential that I use material to refer the physical medium of computers, because the material reality of this medium is what I believe is being artistically ignored.

- It allows for the direct manipulation of the *real*² or final materials of the thing or object being made.
- It allows for an intimate relationship between visual form, artistic process, and computation.

Plasticity, Shapeability and Expression

Computer artist John Maeda's description of expression is highly relevant to understanding why *the plasticity* of a medium or material is essential for artistic expression.³

media: there is some external vessel that can hold the concept outside the expresser's mind, such as paper, clay, etc.

tools: there is some way to shape the media in a conscious manner, such as with one's bare hands, a paintbrush, etc.

skills: the expresser understands the physics and metaphysics of his media and tools, and his experience with them allows him to mold forms of superior craftsmanship. Through his experience he possesses a basic vocabulary by which he can express himself.

concept: there is something that the expresser wishes to express; most importantly, he has the will to express (this can include the to express no concept at all). The expresser has an imagination within which the concept is nurtured and brought to reality with technique, tools and media.

Central to Maeda's concept of expression is the ability of the artist to convey his or her ideas by shaping and

² See Chapter 4 for a more thorough discussion of what I mean by the *real* medium.

³ Maeda, J. and McGee, K., *Dynamic Form*, International Media Press, (1994).

controlling his medium. Without the ability to shape their medium an artist cannot be expressive. The visual and virtual media of computers, i.e. images on screens, are highly plastic. This is clearly demonstrated by the amazing development of special effects in film, where software has created dinosaurs, animated toys and spaceships. In HCI, the plasticity of software has allowed designers to represent information in images, icons and word. In fact, this classic and highly iconoclastic argument about how to best represent computer information, in image, icon or word, is a direct result of the shapeability of software.

Direct Manipulation of *Real* Materials

Software has also provided artists and designers with the ability to *directly* manipulate their materials. This may seem strange, as software is a *mediation* through which artists and designers can reach the images it creates. However, software allows artists and designers write a piece of code, and immediately see what it does in the *real* or *final* medium,⁴ for instance the light and images on the computer screen. They do not just see some materially remote, design or facsimile of what they are making. In addition, despite compiling time, this can be a very quick or not immediate, process. Through software, artists and designers can sketch, experiment, iterate and create a final product all in the same material or medium. This fast and direct process is essential to any design process or aesthetic investigation.

⁴ See Chapter 4.

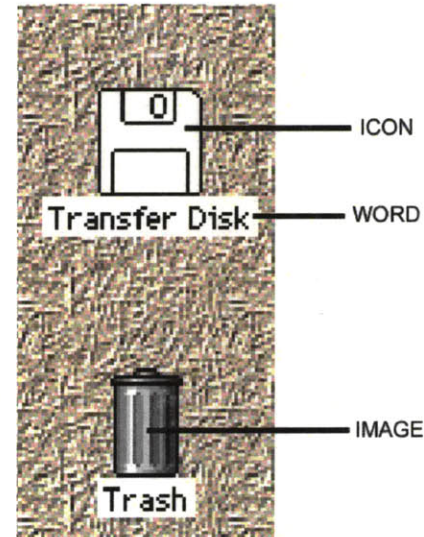


Figure 3.3 GUIs can represent ideas as images, words and icons.

An Intimate Relationship Between Form and Computation

Software and the virtual media it controls also have an intimate relationship that has allowed artists and designers to explore the artistic and aesthetic relationship of computation and visual form. This is because software is computationally active. Artists and designers working with software can ask questions like "What images do certain algorithms make?" Visual artists and designers working in software have carefully examined the expressive relationship of computation in software to the images and sounds it creates. Artists like Karl Simms (Figure 3.4) have used genetic algorithms to create a whole phylum of virtual creatures. Designers like David Small (Figure 3.5) have used software to explore new forms of text with dynamic motion. Moreover, software allows artists to create their own tools as alternatives to the pre-fabricated software tools of Photoshop and other consumer graphics programs.

Can Hardware Become an Expressive, Computing Medium?

Hardware, or the physical materials of computers contain no real analogue to software and the *virtual* media of computers. There are no physical computing materials that artists and designers can plastically shape, directly manipulate, and that allow them to investigate the artistic relationship of physical form and computation. This has severely limited the expressive exploration of computers and three-dimensional design and artistic practices. Without materials that are

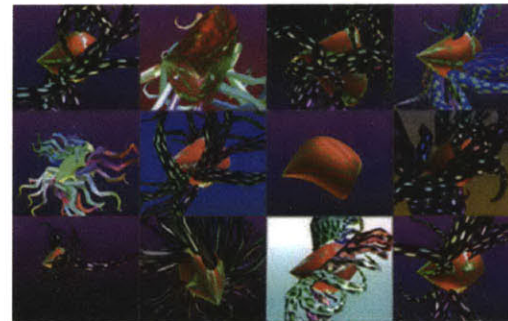


Figure 3.4 Karl Simms, *Galapagos*, 1997.



Figure 3.5 David Small, Yin Yin Wong, *Minski Melodies*, 1996.

shapeable, directly manipulable and computationally active, like software, computers and computing technology will never reach their full potential as a physical and visual arts medium. Moreover, the physical materials of computers possess a property their virtual counterparts do not; they are tactile. To explore this property the physical materials of computers must become tactilely diverse and rich. Physical computing materials that are tactilely rich, shapeable and directly manipulable will also allow physical computing technology to participate in many three-dimensional, artistic and design practices that they are currently uninvolved in. Fields like the decorative and industrial arts, and certain types of "fine arts" practices, simply require these types of materials and processes. With sculptural, and active computing materials, physical computing technology also has the potential to become a truly unique future artistic form, *sculpted computational objects*.

Sculpted Computational Objects: Properties and Materials

As a potential artistic form, *sculpted computational objects* have a unique set of properties that each require a physical material. Understanding these properties and the materials that enable them will help us also understand both the artistic, practical and material challenges facing any creative person who wants to make a computational object.

I have defined computational objects as having five properties. Computational objects *must* have a unique

physical form (this sets them apart from neutral computing objects like PC's and mice), be programmable, display dynamic reaction to either internal or external stimuli (be interactive), and receive some sort of power (in most cases this is electricity). Computational objects *may* also possess the ability to sense their environment and be networked.⁵ Every one of these properties *requires* some sort of physical material to enable it. For anything to fulfill the three minimum properties of a computational object, (have a unique physical form, be programmable, and display dynamic reaction), it must be made from at least a physical substrate material (usually plastic), a processor, and some sort of output device. It may also have an input device and/or a network device.

I have defined all these materials as *physical computing materials* because they are what any designer must use to build a computational object. I have defined the input, output, sensing, and power related materials of computational objects as *active* because they all share and require the ultimate agency of computation, *electricity*. (I realize that new types of computation may involve active sources other than electricity, but today, it is dominate.)

To create a computational object, designers and artists usually assemble these materials together inside a CAD designed plastic shell. For the active materials of computational objects to share and exchange electricity, they must be electrically and mechanically

Properties of Computational Objects	Enabling Materials
<p>Unique Physical Shape (required)</p> <p>Runs Software (required)</p> <p>Displays Dynamic Reaction (required)</p> <p>Can Sense (optional)</p> <p>Can be Networked (optional)</p> <p>Needs Electricity (required)</p>	<p>* necessary materials</p> <p>* Housing Material Like plastic</p> <p>* Chips, Processors or Circuit Boards</p> <p>* Output Devices, Displays, Speakers</p> <p>Input Devices Mice, buttons, etc.</p> <p>Network Devices Wired or unwired</p> <p>* Power Supplies and Wires</p>

Figure 3.6 Abbreviated chart of the properties of computational objects and the materials necessary to enable them. An expanded chart of these properties is located at the end of the chapter.

⁵ See the chart at the end of this chapter for a more detailed discussion of these properties and materials.

connected together. This usually involves using large, electrical connectors that are mechanically rigid to ensure that leads and solder joints don't break and that there is electrical continuity between the parts. (Wireless communication still cannot overcome the need for power and ground distribution between parts.)

A Closer Look at Commonly Used Computing Materials

So what is so limiting about these *physical computing materials*? How do they prevent artists and designers from developing computers into an expressive, visual and physical medium? Why aren't they shapeable and directly manipulable? Why can't they be cut, bent, molded or applied like paint? And why don't they provide artists and designers a means to explore physical form and computation?

material (me-tir-e-el) *n.* **1.** The substance or substances out of which a thing is or may be constructed: "*Simple ideas, the material of all our knowledge, are suggested to the mind only by sensation and reflection.*" (Locke). **2.** A precursory element, such as an idea or sketch, to be refined and made or incorporated into a finished effort: *material for a comedy.*⁶

I have set up a loose classification for understanding how different types of materials are used to create objects. It divides the materials of computing objects into three categories, raw, structured and prefabricated. This system is not all encompassing, but is meant to provide a framework for understanding the limitations of current, physical computing materials.

⁶ American Heritage Dictionary On-line, World Wide Web, (2000).

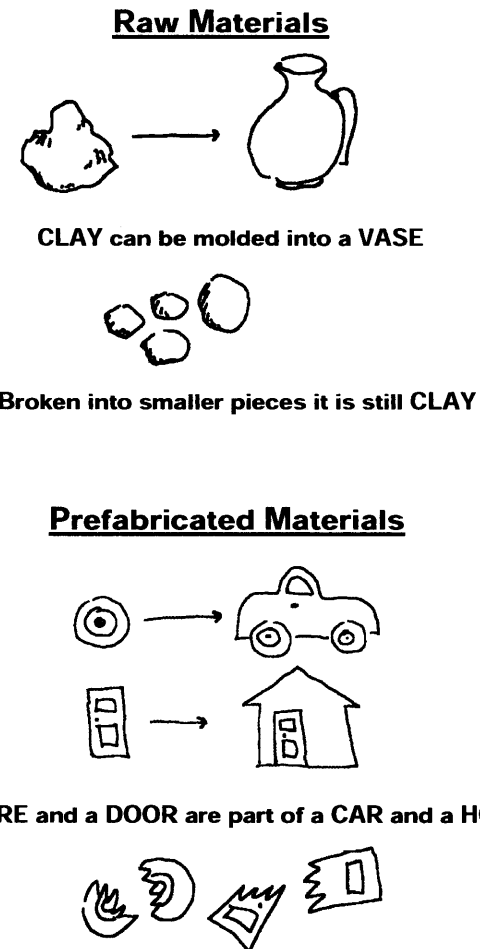


Figure 3.7 Diagram of raw and prefabricated materials.

Raw Materials

Materials like clay and ink can be understood as raw materials. These materials have no pre-defined shape, and are usually highly shapeable. Moreover, their properties do not change if they are broken apart and reshaped. If you take a hunk of clay and break it in two, you still have two hunks of clay. If you shape it into a bowl, it still behaves like wet clay, until it is dried or fired. Clay, paint, ink, pencil lead, and steel are all amorphous materials. Raw materials can be easily manipulated in both an additive and subtractive manner, in other words one can easily break them apart and stick them back together. This provides a very high level of shapeability and *plastic* control. Raw materials also provide a means for direct manipulation.

Prefabricated Materials

Prefabricated materials are precursor elements or manufactured parts that are assembled from other materials, and then used as part of a larger object. For example, a tire, a door, and a stretched canvas are prefabricated materials that can be incorporated into larger objects, like a car, a house or a painting. Because precursor elements are generally manufactured from many different other materials, they usually cannot be randomly resized or plastically reshaped without losing their fundamental material properties. Break a door in two and it is no longer a door. Bend canvas and it is no longer suitable for painting on. Of course a tire is rubbery, so you might bend it. But normally, a precursor element or prefabricated material has a structural integrity that prevents it from being radically, physically reshaped.

Structured Materials

Between the two extremes of raw materials and precursor elements are structured materials. Usually, these materials are natural or manufactured composite materials that are *sculpturally anisotropic*, or can only be shaped in a specific direction without destroying their fundamental properties. For instance, a steel beam is a manufactured, structured material that can be cut perpendicular to its length, and it will still be a beam. However, if a piece is cut out of one of its flanges, or it is cut lengthwise, it will no longer function as a beam. Paper is a structured material that is almost as shapeable as an amorphous, raw material. It can be cut, glued, folded and bent. But, it cannot be pulled out, or cut down its width, without destroying it. Textiles are also a structured material. They can be cut, bent and sewn. Structured materials, like textiles, wood and paper provide an excellent level of plastic and direct control.

Where Do Physical Computing Materials Belong?

Most physical computing materials, including almost all input and output devices, chips, circuits and network devices, are prefabricated materials that cannot be directly reshaped or cut apart without destroying their electrical properties. As a result, designers and artists looking to reshape or physically transform computing objects must usually accept the shape, size and form of prefabricated elements. This shape, size and form inevitably determines the form of their work. Thus many computing objects remain *reflections* of the

square and rigid prefabricated materials from which they are made.

Of course, a designer might specify the shape of these items before manufacturing, but this is a remote, rather than, a direct process⁷. One could also imagine a prefabricated element that might be bent, but in the case of most *common* computing materials this is highly unusual because they must conduct electricity. For instance, commercial force sensors must be used on a rigid flat surface or they will crack, electrical continuity will end, and they will fail. Wires are structured materials, and as such wires can be bent and twisted fairly directly and easily. The only truly amorphous or raw physical material of computational objects that artists can freely reshape is the mechanical substrate material or housing, which is usually plastic. Designers can shape these plastic housings in CAD, have them manufactured and then integrate the active computing materials into them. But this tends to be a *remote* process that isolates the physical design from the electronic or computing design and discourages an exploration of the relationship between form and computation. Moreover, the plastic shells tend to be highly constrained by the shape of the circuits, buttons and displays they must hold.⁸

More Rigid than Stone

There are raw electronic materials, such as semiconductors, conductors, piezoelectric materials,

⁷ A more detailed discussion of this is in Chapter 4.

⁸ *Ibid*

optoelectronic materials and dielectric or insulating materials. But few people in the world can actually manipulate the raw materials of computational objects, nor is it a particularly direct or plastic process. The silicon and the other materials required to create chips are processed in clean rooms with exacting and hazardous processes that are unavailable to most people. With the exception of basic conductors (metals and wires), and basic insulators (plastic and glass), the raw electronic materials that most creative people encounter, are already built into prefabricated, precursor elements. *These elements are more rigid than stone.* If you cut them or bend them they simply stop working. This is because most raw, electronic materials have limited mechanical properties and cannot be bent or flexed or exposed to the environment without destroying their electrical properties. To preserve the electrical continuity of these materials, a complex array of other materials must usually be used. Take, for example, sensors made from an electronic piezoelectric material. For this material to be useful as a sensor it must be addressed electrically, which requires the addition of metal conductive leads to contact other materials or components. To isolate and protect the conducting and piezoelectric material, an insulator must be wrapped around it. For it to remain electrically stable, it must be placed on a rigid physical substrate. Almost immediately this raw material is a fully designed and rigid, *system* of materials, or a precursor element, that cannot be reshaped in a direct or plastic manner.

Today, we are beginning to see flexible, raw electronic materials, including conductors make their way into the

market. The result of these flexible raw materials is the production some relatively flexible circuit boards, and displays. These materials are like structured materials in that they are directly flexible and bendable in some orientation. But they cannot be reshaped or resized accept through a CAD or remote design process. They generally have a finite edge or physical space that must be accepted in the process of making an object.

Fixed and Rigid, Electrical and Mechanical Connections

But the mechanical rigidity of most individual precursor elements is not the only limiting quality of the physical materials of computing objects. The fact that all these materials must be electrically and mechanically connected is ultimately incredibly limiting. Think about how a seamstress works. He or she cuts off a piece of fabric and then sews it to another piece of fabric. The two are easily joined, and the joint is strong because the two have similar mechanical properties, and no unusual physical stress (like hard meeting soft,) is introduced at the connection. In furniture making, glue can easily attach wood to wood. But what if glass is attached to fabric? When two materials with different mechanical properties, like expansion due to heat, are joined, that process becomes more complex because the materials may not be easily glued, or may damage each other with repeated contact. For instance, glass cannot be glued to wood, or sewn to fabric. It can be sewn into a fabric pocket, but if this process is not very carefully done, the hard glass will cut into or wear out the fabric. It is not that joining two different materials is

impossible, just far more complex than attaching fabric to fabric.

And computing materials present more than just the need to integrate many different materials mechanically. These materials must also be electrically connected and maintain that connection. This usually necessitates that the connection between these parts be fixed and rigid. The need for fixed and rigid connections between the materials of computational objects, also means that these objects must be rigid and hard as well.

Conclusion

For *physical* computing technology to become a truly expressive medium and artistic form new computing materials must be developed. These *physical* materials must provide artists and designers with the same level of control and expressiveness that the *virtual* media of computers provide. They must give artists and designers the ability to *directly and plastically shape* their computing materials. Finally, they must provide a means to explore physical form and computation. To do this, the plastically shapeable materials of computing objects, or design materials, must become computationally active. As *real*, physical and tactile media, physical computing materials must also develop tactile and sensual qualities that virtual media do not possess. Chapter 4 will look at three-dimensional practices in the visual arts and design, and their relevance for the materials and processes that shaping computing objects.

The Properties of Computational Objects

Have a Unique Physical Shape or Material Property →

This must influence events in software, physically reflect the function of the object, or convey a special meaning through design. Ideally, there should be a direct interaction between physical form and computation. Desktop computers are general-purpose tools and their neutral physical form reflects that. If you change the form and shape of the computer or its input devices, it has no effect on the software inside. In contrast, computational objects can be fuzzy, flat, hard or soft, and those differences in design can both reflect and change the function and meaning of the object inside the computer. (ESSENTIAL PROPERTY)

Are Programmable, and Run Software →

This can change their practical function and symbolic meaning. Non-computing objects often have many functions, from magical (as a charm or fetish), to symbolic or practical. Usually, the physical form and markings on the object remain fixed. Software can actually change these forms, markings and functions. The addition of software and sensors to a hammer can change its practical function from driving nails to playing music. Through software, an icon on a screen can change from a GUCCI symbol to a Barbie symbol to cross, transforming its symbolic meaning. (ESSENTIAL PROPERTY)

Display Dynamic Media, i.e., Sounds, Images, Light, Motion and Text →

They do this in reaction to a change in their environment or their internal state. This sets computational objects apart from traditionally static media, like sculpture or painting, and relates them more strongly to time based media, like film or music. Through software, the dynamic media of computational objects can also be interactive, rather than fixed and linear, as in film. (ESSENTIAL PROPERTY)

May Sense Their Environment and the People Using Them →

They do this through sound, light, touch and temperature. They can do this simply, with the discrete information of a switch or on/off button, or they can do it more complexly, using continuous information about factors like touch, pressure, or temperature. (NOT AN ESSENTIAL PROPERTY)

May be Networked and Communicate with One Another →

This lets computational objects to know each other's physical state, (i.e. where they are), and identity. Communication between objects can also facilitate communication between people, either as mass media, like the web, or as personal media, like a cell phone. Using networked, computational objects as an artistic medium is a tremendous creative challenge in itself. (NOT AN ESSENTIAL PROPERTY)

Uses Electricity (ESSENTIAL PROPERTY) →

Enabling Materials

Substrate Materials

Like plastic, to integrate and support all other physical materials.

Electronic Components

Integrated circuits, circuit boards.

Output Devices

Speakers, displays, lights, and or mechanical devices that create motion.

Input Devices

Keyboards, buttons, force sensors, motion sensors, and light sensors, etc.

Network Devices

Wires, card or chip, infrared transmitters, radio transmitters and antennas.

Power Supplies and Wires

Chapter 4.

A Sculptural Perspective

Looked at from the point of view of three-dimensional visual art and design practices, much can be said about the way that today's computing objects are made, shaped, and physically transformed. Because the physical materials of computers are prefabricated and cannot be plastically reshaped, the making of computing objects today is primarily an additive process which involves the bringing together or joining various parts, including buttons, displays, chip and plastic shells. Consequently, most fields of visual artistic exploration that use the physical materials of computers, including the fine arts, physical HCI and industrial design, all use an additive processes or *assemblage*¹ to create physical computing objects. The additive manipulation of physical computing materials has led to the creation of a range of objects, from industrially designed and superficially, curvy, hand-held

¹ A more detailed discussion of sculptural assemblage is provided in Chapter 5.

devices, to successful robotic sculptures, like Tim Anderson's painting machines.²

But despite the range of computing objects that additive manipulation can create, this process still limits the development of computing technology as a truly sculptural medium. Absent from the artistic exploration of physical computing materials is any work that involves the hands-on, direct, plastic, manipulation of *real* and active *physical computing materials*. As a result, many types of three-dimensional, visual art and design practices simply do not work with computing technology. For instance, both the decorative arts and certain types of sculptural and artistic practices demand the hands-on, plastic manipulation of *real* physical materials. Because these practices dominate the design and creation of very specific types of objects (like fashions or house-wares), computing technology simply will not meaningfully become part of these types of objects. Moreover, the artistic development of computing technology as a three-dimensional medium is still limited. Just as assemblage transformed sculptural and artistic practices in the 20th century, so will the plastic manipulation of physical computing technology transform both artistic practices and computers. This kind of direct, hands-on plastic manipulation of *computationally active* materials will also allow artists to truly investigate the artistic relationship between physical form and computation.

² A more detailed description of these works is provided in Chapter 5.

This chapter looks at the design and creation of computing objects from the perspective of the visual arts. It expands on the importance of shapeability and direct manipulation for physical computing materials, by looking at the role of these qualities in three-dimensional artistic and design practices, like industrial design, sculpture and the decorative arts.

Unshapeable, Unsculptable and Persistently Square

Throughout history, artists, designers and craftsmen have expressed their ideas and emotions in three-dimensional form through the inspired manipulation of a wonderful palette of physical materials. The results include a broad range of expressive forms, which can function aesthetically, practically and culturally. Artists, craftsmen and designers have fashioned stone into human form, clay into beautiful, yet practical vessels, and steel, rubber and glass into curvaceous, mechanical automobiles. And while the goals of these expressive activities have differed from the practical to purely aesthetic, each activity has been *sculptural* because it involved the physical shaping of materials. And in many cases, this process was highly plastic and direct one, involving the hands-on cutting, bending or molding of the material into a desired shape.

Artists seeking to reshape computing technology physically, or even sculpt computing technology face a visual medium that is both unshapeable and *persistently square*. Computing materials are prefabricated, rigid, and hard, and for reasons of

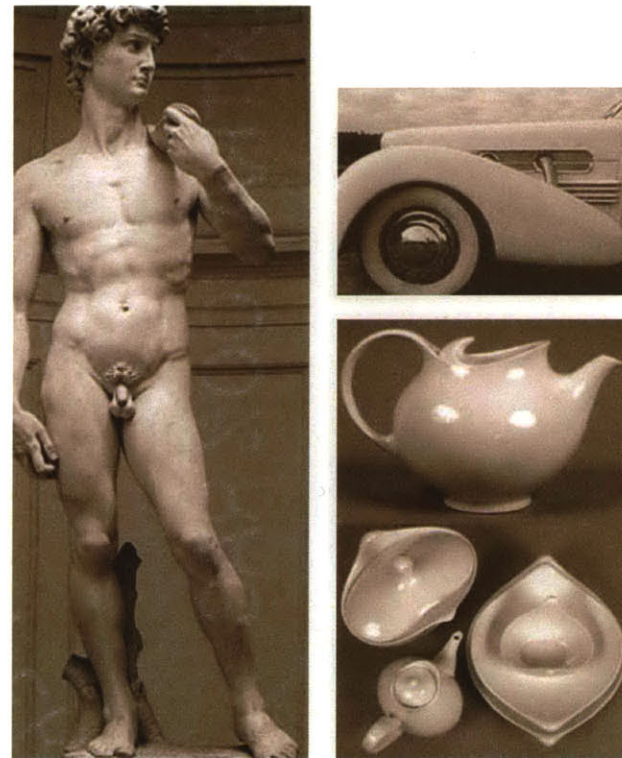


Figure 4.1 Michelangelo's *David*, 1501, carved from stone; Eva Zeisel's *Hallcraft*, 1949, slipcast clay; Detail 1920's sports car, metal and glass.

convention are usually square. They cannot be bent, shaped, or cut, which prevents them from becoming truly sculptural. In addition, because they are conventionally square, they remain strongly rooted in the pictorial, a visual arts tradition that is usually considered anti-sculptural.

The urge to break from the square in the tradition of western sculpture is strong and old. It can be traced to the history of stone carving in early Greece. The archaic stone figures in 6th century B.C. Greece were straight, linear and four sided, reflecting the block of stone they were carved from. Throughout the 5th century B.C. classical period, and into the later Hellenistic period, Greek sculptors fought to break away from these linear shapes and create fluid forms that did not reflect the square block of stone from which the figures were cut, but instead conveyed the complexity of the human body and its movement³. In more modern and contemporary times, the urge to break from the square and the pictorial tradition of painting can be seen in a broad sculptural tradition that includes works of assemblage, the built paintings of Frank Stella⁴, installation art and site specific sculpture. In this way, getting the computer out of its box is more than a call for ubiquitous computing or new markets for chips. It reflects the artistic imperative to explore shape and form in a means that transcends the square.

³ Carpenter, Rhys, Greek Sculpture: A Critical Review, Chicago, University of Chicago Press, (1960).

⁴ Stella, Frank, Working Space, Cambridge, MA, Harvard University Press, (1986).

The *persistent squareness* of computing materials is complex; it is both a cultural and technical artifact⁵. Technically, it is based on the both the mechanical properties of the rigid prefabricated physical computing, and the fact that by convention, these materials are usually square. Buttons, chips, circuits, displays and speakers, are all prefabricated, rigid, bulky, and square items that simply cannot be reshaped, or cut, stretched, bent or joined. Sometimes, these materials can be specified through industrial design processes, but they are still hard an immutable once you have got them. Culturally, the conventional *squareness* of the monitor and visual displays, has kept most visual expression with computers firmly in the realm of the pictorial. This is because the virtual media of computers, (the images on the screen), have provided visual artists with such a rich and expressive medium, that they have gravitated toward the area of computer graphics, creating everything from special effects in films to photographs and computerized portraits. All these visual artworks take place on square monitors, and consequently much of the visual and artistic exploration of computers remains firmly grounded in the pictorial tradition. And monitors are square because the pictorial tradition, and the convention of displaying images on squares is so old and so strong. Painting, photographs, film, video and television all demonstrate the strength and

⁵ Bishop, D., from an interview in, Abrams, R., *Adventures in Tangible Computing, the Work of Interaction Designer, Durrell Bishop, in Context*, *Masters Thesis for the Royal College of Art*, (1999).

development of the pictorial tradition in our culture today. So while there are strong technical reasons for the development of computer expression within the rectangle, the cultural strength of the pictorial tradition has also contributed to the acceptance of the square frame of computers.

Square Displays and the Pictorial Tradition

Until very recently, visual displays have been perhaps the most physically fixed part of the computer, (new flexible display technology and even projectors are changing this.) Monitors are simply square and rigid. That is how they are made and how they come. Their aspect ratio is even determined. When people look into a computer display, they look into this square, and consequently at art or design work firmly rooted in the pictorial traditions of painting, photography, theater and filmmaking. This is not to say that computers have not, through interactivity, created many new artistic forms. It is only to say that that these visual forms have tended to remain strongly), related to the pictorial tradition. Some of the best descriptions of what goes on inside the computer are strongly pictorial. Interface design has been famously compared, by Brenda Laurel⁶, to the frame of the proscenium theater. This innovative way of looking at what goes on inside the computer is wonderful if one wishes to work in the realm of the pictorial, but also demonstrates how the materials of computers can be limiting to anyone seeking to transcend the square.

⁶ Laurel, Brenda, Computers as Theater, Reading Massachusetts, Addison-Wesley Publishing Company, (1991).

Shapeability

Learning to shape the hard material of stone into fluid human forms that transcend the original square block took Greek artisans centuries.⁷ Artists and designers wishing to explore the sculptural possibilities of computers are faced with prefabricated materials that can be even more limiting than stone. At the very least, physical force could reshape stone. Physical force used on the prefabricated materials of the computer will only destroy their electrical properties and render them useless. Thus, artists and designers working with these materials must preserve their physical integrity, rather than alter it. Usually, artists and designers attempting to transform the shape of computers have had to work around these square materials, building curvey or furry housings to hide them. And while the size of these materials can be "specified" through remote CAD and design processes, this usually does only a little to truly transform their squareness. Moreover, artists who want to work in a more direct manner than CAD, simply can do little to physical computing materials but accept them as is or cover them up with other materials. Consequently, the *persistently square* materials of computing technology have left most computational objects sculpturally superficial, a mere reflection of their square interiors.

Shaping in Industrial Design

Industrial and product designers working with the physical materials of computers have been able to



Figure 4.2 An extreme example of the results of covering square computers with fur, and the sculpturally superficial results of such a process.

⁷ Carpenter, Rhys, Greek Sculpture: A Critical Review, Chicago, University of Chicago Press, (1960).

remotely and plastically, shape and design the plastic shell, boxes and peripherals of many computers and computing objects. But this operation is also often superficial, because industrial designers rarely have control over the prefabricated electronic *guts* of computing objects. These *guts* usually consist of buttons, circuits and displays that are physically rigid, bulky and square. Designers may be able to specify the size and arrangement of parts; they may even design the shape of a circuit board, but there are some parts, like displays, that they simply cannot make *unsquare*. They must work around these parts, trying to hide their squareness under a curvey shell. The direct result of this is that the objects they are designing get bigger. In Figure 4.3 the inner circle and the square contain approximately the same area. Imagine that the square is a display. To make a truly round housing for the display, without violating the its structural integrity, that housing would have to be the size of the outer circle, which is *over 50% as large in area*. Consequently, the external form, or housing, of most computing objects usually remains a rounded square, which is squished around the square interior parts.

In addition, this form of plastic manipulation does not actively engage with computation. The plastic housing is the one material of computational objects that is non-computing. It is only structural. Consequently, reshaping it provides little opportunity to investigate physical form and computation.

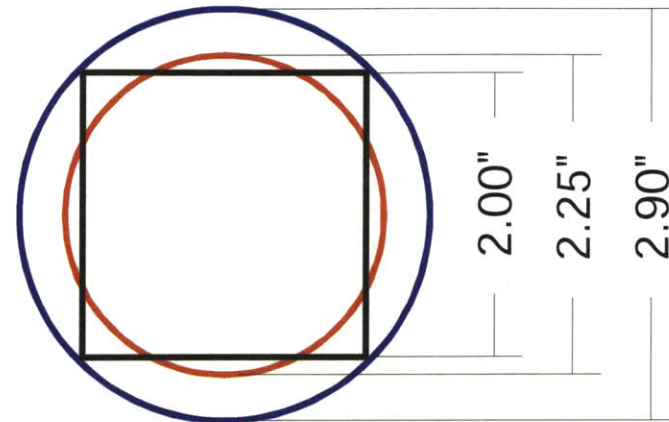


Figure 4.3 Diagram of how the housing of fundamentally square computing materials must grow in size to become curvey or round. The inner circle has the same area as the square. The outer circle, which is big enough to contain the black square, is 50% larger in area.

Shaping in the Fine Arts

In simplistic terms, artists and sculptors who are working towards personal artistic expression with the physical materials of computers generally have little control over the shape of those materials, because they tend to work in a direct, hands-on manner with materials that are at hand; and in general, the materials of computers are shaped through industrial processes. Working additively from materials at hand as led to many successful assemblage/robotic works⁸ that do not use the plastic manipulation of physical materials. It has also lead to the artistic covering square computers with unusual materials like wood or fur, or simply giving in and accepting what they've got. In no way has it let artists plastically shape active, computing materials.

For most individual artists working with the physical squareness of PC's and monitors, the transformation of these shapes has either been sculpturally superficial, or just NOT. An extreme example of how superficial the attempt to change the shape of PC's can be is the fur covered PC shown in Figure 4.2. An example of a inoffensive, kind of acceptance of square monitors is the installation of Karl Simms, *Galapagos* (Figure 4.3). While Simms valiantly works to create organic and fluid forms inside the monitor, the installation of this software is somehow contradictory, accepting the cold, square, and fixed monitors it must be shown on. This definitely shows better taste than covering it them with fur, but it outlines the limits of individual artists trying to reshape physical computing media.

⁸ See Chapter 5 for a more detailed description of works in robotic assemblage.



Figure 4.3 Installation of Karl Simms *Galapagos*.

The Direct Material Manipulation of *Real* Materials

As previously outlined, the most successful means for reshaping computing materials is through CAD specification, or remote design. For certain areas of three-dimensional design and artistic practice this is fine. But there are certain design and artistic practices that demand the direct, hands-on manipulation of the *real* materials of an object. For instance, architecture and industrial design often rely on model making and drawings to understand, see, sketch, and design their final products. The hands-on tactile manipulation of the materials of the object is not always essential to the design process. Designers in these areas usually use prototype materials to mimic the final result. Architects build small models of wood, cardboard and metal screen to create the final "look" of a building's *real* materials. In other words, architects usually do NOT sketch in buildings, or *real* building materials, but instead make models of them. Industrial designers and product designers often create "looks like models" from drawings. These models may be made from a variety of materials, like plaster, and then painted to look like the final material. These materials and objects are often non-functional. In fact, the final materials of such objects are usually specified by an engineer *after* the design process.

But there are certain three-dimensional artistic and design practices that *do* require the hands-on manipulation of the *real* materials of an object. Both decorative arts practices, and many more purely **Artistic** sculptural practices often require the direct

hands-on manipulation of the *real* and final materials of an object. In these practices, the objects that are created have a certain *material reality* that is the result of a process that involves sketching, exploring and creating in the materials of the final product. In more purely high **Art** practices, (like sculpture or painting), an artist usually works with a material that is shaped directly into his or her final product. An artist takes a piece of stone and makes a sculpture, or uses paint and canvas to make a painting. Significantly, the physical presence of paint on canvas brings a material reality to a painting that a print cannot imitate. (This not to say that multiple work, like Warhol's, that explores the meaning of the individual art object, is not art, just that many forms of artistic practice rely on the hands-on manipulation of *real* materials towards the final product.) In the decorative/industrial arts practice, the hands-on manipulation of the *real* materials of an object is an essential part of the manufacturing and design process. Ceramic artists may initially make sketches on paper, but they also work and sketch directly in clay, perfecting the final shape, material and tactile properties of their products by directly manipulating the clay itself. This process can lead to the direct creation of a single hand-made, final product or to a design for a mass-produced product.

This kind of sketching and aesthetic exploration through the hands-on manipulation of physical materials, has been severely limited by the physical materials of computers. What this kind of hands-on manipulation provides artistically, is a sort of knowing through action that requires a quantitative knowledge of a material and medium, which ultimately leads to a

qualitative understanding. A jewelry maker must know at some level the quantitative mechanical properties of the metals they work in, for instance how ductile a certain metal is, or what its melting point is. At the same time, the artistic and aesthetic ramifications of those quantitative properties, or the qualitative properties of that material, must be understood by the craftsmen to achieve his or her artistic and aesthetic goals. Achieving that kind of qualitative understanding, for instance what kind of curve and resolution a certain metal can have when bent in a certain process, is an aesthetic understanding of the material that can only be achieved through the direct hand-on use of the *real* material.

Of course, an artist might work in silicon, but assuming he or she could gain access to these materials, it not clear how they provide the same ability to experiment *aesthetically* that the hands-on manipulation of traditional sculptural materials provide. In many ways, this is an issue of scale. Artists and craftsmen have relied on things that they can feel and touch with their senses. The world of micro and nano-technology does not provide such *sensual* access to materials. (Of course, there are mediated ways to access and understand these materials visually, like with a microscope or a robot. these may someday be so successful that they do not fall outside of the hands-on approach I am speaking about.)

It this kind of knowing and aesthetic exploration through the direct manipulation of *real* physical computing materials, that will ultimately lead to a

meaningful artistic relationship between physical form and computation.

More on the Decorative/Industrial Arts

When we talk about the decorative arts, we talk refer to a wide range of artistic practices that create *everyday* objects, such as jewelry, textiles, glassware, fashions and even musical instruments. While it is impossible to draw a rigid boundary between the decorative arts, industrial design, product design and even traditional sculpture, there are quite a few aspects of decorative and industrial arts practices that generally separate them from these other fields. Decorative and industrial arts are generally concerned with the creation everyday objects that have some root in the functional, but are aesthetically transformed through ornament or materials. Despite Modernist calls for a union of "form and function" the idea of transforming the everyday through ornament and materials has remained a central practice in object making throughout the 20th century and in the decorative arts today. Today's decorative arts practices also find strong roots in Post-modern ideas. They seek to "subvert the expected notions of form and challenge our traditional assumptions about the behavior of materials."⁹ Thus aesthetic transformation in decorative arts practices relies heavily on the direct, hands-on, artistic exploration and manipulation of physical materials.

⁹ Newman, Lenore and Spak, Jan L., *Inversion and Transformation*, Eidleberg, Martin (ed.), *Designed for Delight*, New York, NY, Flammarion and the Montreal Museum of Decorative Arts, (1977).

It is important to note that the hands-on relationship of decorative arts practices to physical materials does not require the final product to be a singular, hand-made item. Before the industrial revolution, the decorative arts referred clearly to the fabrication of a single, handmade "everyday" objects that ranged from jewelry to musical instruments and household items. Today's decorative and industrial arts may produce anything from a single, individual hand-made vase to an industrially mass-produced piece of furniture. What is common to these objects is that their production or design process was not *materially abstract*. The touching or manipulating of the *real* materials of each of these objects plays an essential part in their fabrication or design. For instance, a contemporary designer making a lamp from an industrially produced translucent plastic tube must experiment with this material to determine what happens when light passes through it. Once the designer achieves an effect that is desirable, he or she can then reproduce it, either in a small series or through a larger scale industrial process. In this way, the hands-on manipulation of *real* materials in a decorative/industrial arts process can lead to either a single final object, or to a design that can then be reproduced. In contrast, an industrial designer may never have to touch the materials of his design at all. He or she may just sit at a computer and only CAD his final product.

Ramifications

Without new active, physical computing materials that are tactilely and mechanically diverse, and that allow for hands-on aesthetic and plastic exploration,

computers simply cannot become part of this incredibly broad field of aesthetic practice. Practices in the decorative arts create a myriad of household objects, clothing and tools, and bring to these types of everyday objects an aesthetic transformation that is more than practical. It is cultural, symbolic and sensual. Computers are currently isolated from this type of transformation and from becoming part of the wide range of objects that decorative arts practices produce. Moreover, this kind of hands-on, plastic, investigation of computationally active physical materials is important to any visionary technology or design practice. These types of directly manipulable, plastic materials are necessary to explore a meaningful artistic relationship between form and computation. Without materials that can be directly shaped, bent and formed, and that have an effect in software, artists will not be able to understand the meaning of either shape or tactile properties, in relation to software.

While the limitations of physical computing materials do have significant artistic and aesthetic ramifications, they also have a dramatic effect on the direction of many more *practical* fields of computer development and research. Technology researchers, from visionary product designers like Durrell Bishop to nanotechnology scientists, dream of computers that can cover our walls, lie in the carpets underfoot, or be worn comfortably on our backs or fingers. Technology visions like Ubiquitous computing, Tangible Media, Things-that-Think and Wearable Computing ALL call for the incorporation of computing technology into the very objects that the decorative/industrial arts are centrally concerned with. These objects are necessarily

materially rich and diverse. But the same material limitations that prevent an aesthetic exploration of computing technology in such objects, are also preventing the fulfillment of these technological and design visions. For despite the shrinking size of microprocessors and the promise of wireless technology, shaping and imbedding technology into the rich material world around us remains technically difficult and elusive. No matter how small computer chips become, they must still be housed in plastic packages, and connected to in a rigid manner. Consequently, integrating computer technology into objects that are not rigid and plastic (like clothing) is still incredibly awkward and impractical. For computers to truly emerge from their plastic boxes their humanly sensed, physical materials must change.

Chapter 5.

Related Work

This chapter provides a detailed description of relevant work from visual art and design practices, human computer interface and electronic musical instruments. Because the portfolio of projects presented in this thesis falls into many categories, like fashions, jewelry and computer interface, it would be possible to present an unlimited amount of related work from many various fields. I have attempted to pick work from the visual arts and design that is related to the portfolio work through its process and materials. Some of this work involves computing materials and some does not. I have also shown electronic musical instruments, because I believe, they are excellent models for any expressive, computing and interactive object.

Robotics as Computational Assemblage

As previously discussed, additive processes are ideal for manipulating the current physical materials of computing technology. In fact, that is how most computing objects are made; they are a group of

mechanically attached buttons, chips, circuits and displays. Consequently, most three-dimensional works of computer art, or sculpture, are what is called in the field of sculpture, an *assemblage*.

An *assemblage* is the result of an additive process that juxtaposes many disparate materials or found objects to create an artifact with new meaning. In the 20th century, an *assemblage* was radical both formally, and within artistic practices that were more content driven. In Futurism, Surrealism and Dadaism, *assemblage* was considered artistically radical because it allowed artists to create new content and social messages. Raoul Hausman's *Mechanical Head* is an early example of the reassembly of found materials for the purpose of dramatically changing their meaning. Marcel Duchamp used industrially produced objects he called *readymades* to draw into question both the assumption that sculpture was the hand-made and the assumption that an work of art was the result of personal aesthetic investigation. Duchamp's *Fountain* placed a urinal, an industrially produced object, on the wall as art. This was a radical move, and dramatically changed the meaning of the art object, by drawing into question what it meant to be a hand-made object in an industrial age.¹ Today, sculptural works in conceptual arts practice use materials that are chosen for their symbolic meaning, like the use of raw meat in Jana Sterbak's *Meat Dress*.

¹ Krauss, Rosalind E., *Forms of the Readymade: Duchamp and Brancusi, Passages in Modern Sculpture*, Cambridge, MA, MIT Press, (1977).

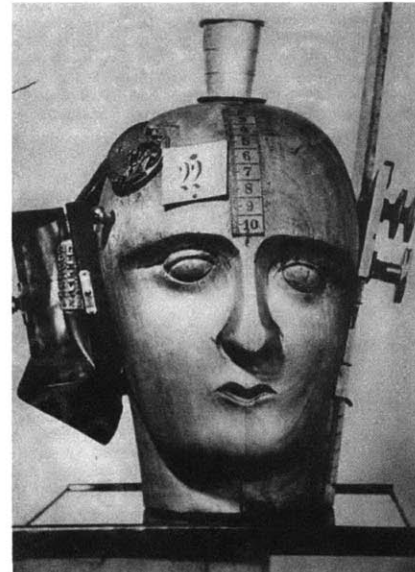


Figure 5.1 Raoul Hausmann, "Mechanical Head", 1919-20.

Looked at from a more formal point of view, *assemblage* has also been seen as radical. Until the 20th century certain materials simply were not seen as appropriate for sculpture; they were seen as poor materials. But the freedom of *assemblage* and working with poor materials radically changed 20th century art. Picasso used *assemblages* made from paper and cardboard to create many of truly sculptural works. The acceptance of *assemblage* has also encouraged artists in the 20th century to be resourceful; to work from any materials that are at hand and that meet their artistic needs. For instance, Louise Borgeois chose the wooden and other various materials of her large assemblages as a result the unavailability of steel and bronze during WWII.

Fine artists working with physical computing materials have also shown a real resourcefulness, creating a myriad of additive objects, or *assemblages* from found or purchased computing materials. Usually, these *assemblages* have tended toward the robotic. In some cases, artists have stuck together pieces of old computers and transformed them into new mechanical entities. In fact, the scope of robotic artworks has been well documented in Ken Goldberg's recent book, *Robot in the Garden*.²

Tim Anderson, Painting Machines

Tim Anderson's painting machines (from the early 1990's) relied on the reassembly of old junk computers and printers into robotic painters. These painting

² Goldberg, Ken, (ed.), *Robot in the Garden*, Cambridge, MA, MIT Press, (2000).

machines created abstract expressionist paintings on canvas. In this work, Tim Anderson completely re-purposed computing technology by reassembling the parts of old printers and PC's into his abstract expressionist painting machines. These works were particularly successful because they re-purposed pieces of existing printers and computers, and turned them into *art* making machines. The motion (or dynamic display) of the robotic painting machines themselves was often more expressive and beautiful than the paintings that they created. I have seen many of these machines personally, and can attest to the fact that their motion is truly beautiful and highly expressive.

Stelarc, Robotics and the Body

Australian born performance artist, Stelarc has wired his body to a whole series of robotic devices, including his piece the *Third Arm*.³ In this piece Stelarc sets up a feedback loop between a third robotic arm that is connected to his real right arm, the muscles of his legs and the muscles of his left arm. Stelarc uses the motors of the arm for audio output as an intentional part of his performance with this robotic device. Stelarc's work has always been of interest to me because it questioned the limits of bodies and "the self" and the role of technology as an extension of the self. In this work, it is the motion of the body and its relation to the motion of the robotic arm that makes for an intriguing performance and juxtaposition of the mechanical to the natural.

³ Stelarc, homepage, <http://www.stelarc.va.com.au/third/third.html>, World Wide Web, (2001).



Figure 5.2 Stelarc, *Third Arm*.

Ken Goldberg, *Telegarden*⁴

Robotic works like Ken Goldberg's *Painting Machines*, and his *Telegarden* are excellent examples of robotic, computing sculpture. Like much socially motivated assemblage from the early 20th century, these robotic art works do re-contextualize computing technology. Ken Goldberg's *Telegarden* juxtaposes computing technology, robotics, and the Internet, with nature. This robotic garden allows a web-based community of gardeners to remotely plant and tend a real garden, through a single, central robot. What I enjoy about this piece is the relationship of the strong and industrial robot, to the planting and care of the tender plants. When the robot moves it seems frightening and dangerous. The robot makes for a strange and jarring "avatar" for the human community on the other end of the computer.



Figure 5.3 Ken Goldberg, *Telegarden*, 1995-ongoing.

Plastic Manipulation vs. Assemblage

All of the previously described works use mechanical motion to *display dynamic reaction*⁵. Creating these works involved a direct, hands-on, *additive* process. This direct process *did* lead to an understanding of physical materials, computation and robotic motion. So how are additive hands-on works different plastic ones? Why doesn't robotic sculpture fulfill the need for the direct hands-on manipulation of computational materials that leads to an artistic understanding of physical form, materials and computation? Once

⁴ Goldberg, Ken, homepage, <http://www.ieor.berkeley.edu/~goldberg/>, World Wide Web, (2001).

⁵ See properties of computational objects, Chapter 3.

assemblage works like Louise Borgeois' were considered radical. Critics wondered if an assembly of found parts could be truly "sculptural" in the *formal* sense. Today, these works are accepted *formally* as both **S**culpture and **S**culptural. Mechanical works like Calder's circus characters have become classic sculptural items in the 20th century. So why can't robots, mechanical assemblages of computer parts, be truly sculptural? Certainly, they are. And many robots *are* becoming more and more human-like in their form. So who cares if there can be no plastic or clay-like manipulation of active computing materials?

I believe that just as the assemblage of prefabricated materials revolutionized the traditional world of sculpture (which had previously relied on plastic manipulation of raw materials like clay and stone), so will the plastic manipulation of active computing materials revolutionize the form, function and ultimately, symbolic *meaning* of computing objects. Until now, computing designers and artists who wished to work with physical computing materials in a *plastic*, direct, and sculptural manner, had to work with materials that are *inactive* and *non-computing*.

Dave Small and Tom White, *Stream of Consciousness*⁶

David Smalls' interactive garden, *Stream of Consciousness* uses non-computing, *plastic* materials

⁶Small, D., White, T., *An Interactive Poetic Garden*, (short paper), *Proceedings of Conference on Human Factors in Computing Systems*, (CHI 1998), Los Angeles, ACM Press, (1998) pp. 303-304.

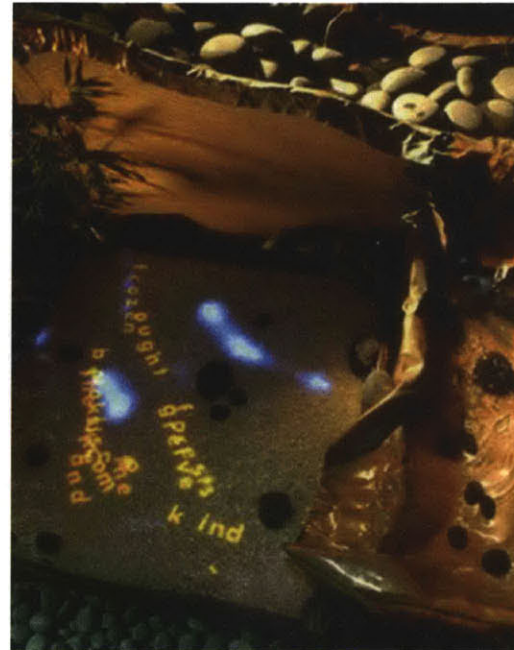


Figure 5.4 Dave Small, Tom White, *Stream of Consciousness*, 1997, with shaped copper and stones.

in a sculptural manner to create an interesting backdrop for his interactive software images. But these materials remain separate from the computational activity of the piece, they are just a back drop or screen for the projected text. But imagine what might happen if the shaping of the copper in this *Interactive Garden* had some real effect in software, or some effect on what words were seen or displayed. The material would then be sculpturally plastic and computationally active, leading to artistic possibilities we cannot yet imagine.

Meaning and Materials in Sculpture

The possibility of *plastically* using active physical computing materials that have unique *sensual* properties will also truly change the possible form, sensual properties and therefore *meaning* of computers. Artistic choice of materials and the effect they can have on form and meaning is what is essential here. There is a certain type transformation of meaning through the plastic shaping of diverse physical materials that is not possible with the current physical materials of computing. The following examples of both Joseph Beuy's and Merit Oppenheim's work, demonstrate the relationship between meaning and materials that is possible when a range of materials can be plastically used by artists.

Joseph Beuys, (1921-1986) Materials Before Form

One of the main themes of artist Joseph Beuys' work was to put materials and before form.⁷ His works used non-traditional, "indeterminate, raw materials to suggest energy potential, investigate alchemical meaning and stimulate senses like smell and touch. These 'poor' materials included felt, fat dead animals, copper, sulphur, honey blood and bones"⁸ The alchemical language of these materials recognizes that "felt is an excellent insulator, just as beeswax is a good insulator but poor conductor of heat, or that copper is an excellent conductor of heat and electricity."⁹ When Beuys juxtaposed these materials, with different properties, he suggested their energy potential. By placing these materials in "determinate" containers, like vats or jars, or in physical configurations with energy potential, (such as a wedge), Beuys suggested and referred to the power of sculpture to transform entropic materials into shapes with mechanically stored, potential energy. In *Chair with Fat*, the entropic fat, a material with stored energy is shaped into a wedge. The wedge shape imparts additional energy to the material. Beuys' "Fond III" (Figure 2.8) juxtaposes copper and felt. The copper rests on nine piles of felt. This piece juxtaposes two materials with antithetical energy properties, copper (conductor), and felt (insulator). The placement of the heavy copper sheets



Figure 5.5 Joseph Beuys, *Chair with Fat*, 1963.



Figure 5.6 Joseph Beuys, *Gelatin Object*, 1968, gelatin, wax and part of a transformer.

⁷ Borer, Alain, *The Essential Joseph Beuys*, Cambridge, MA, MIT Press, (1997).

⁸ Ibid.

⁹ Ibid.

high on top of the soft, stacked felt, physically and structurally reinforces the energy potential of materials.

Beuys' use of materials for their alchemical properties and differences in energy potential has always been a great influence on my work. My interest in the electrical and material properties of computing materials, like silicon and metal, finds much of its roots in Beuys. But unlike Beuys, I have been interested in exploring the energy potential of computing materials not just symbolically, but *functionally*. The desire to understand and functionally use the different properties of computing materials has led me to an investigation of material science.

In *Infiltration Homogenous for Grand Piano* and *Fond III*, Beuys uses the contradictory properties of materials to create a symbolic piece about energy potential. In *Infiltrations*, the energy of a piano, (an acoustic resonator), is contained by a wrapping of felt (an acoustic insulator). In *Fond III*, stacks of electrically insulating felt are topped with highly conductive copper plates to emphasize energy potential. This work inspired me to think about turning textiles, which are acoustic, and electrical insulators, into electrically and musically active materials, and to create both electronic textile objects and musical textile objects.

Merit Oppenheim, *Fur Lined Tea Cup*

Surrealism has always sought to recontextualize meaning, to make the ordinary strange through the juxtaposition and assemblage of incongruous objects

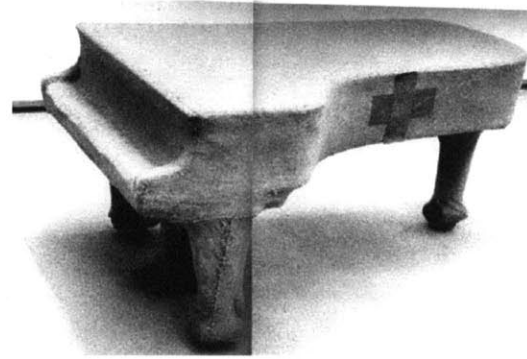


Figure 5.7 Joseph Beuys, "Infiltration Homogenous for Grand Piano", 1966. A piano, wrapped in felt.

and materials. This juxtaposition has sought to combine reality with the world of dreams.

I believe in the future transmutation of those two seemingly contradictory states, dream and reality, into a sort of absolute reality, of surreality, so to speak. I am looking forward to its consummation, certain that I shall never share in it, but death would matter little to me could I but taste the joy it will yield ultimately.¹⁰ (Andre Breton)

In 1936, Merit Oppenheim covered a teacup with fur. The result is the quintessential Surrealistic object.

Oppenheim had decorated a bracelet with fur, and Picasso jokingly commented that fur could cover anything. Her response was another joke: a fur-covered cup, saucer, and spoon, *Le Déjeuner en Fourrure*, its official name.¹¹

By covering a teacup with fur, Merit Oppenheim created an entirely new object, whose meaning does not derive simply from its functionality. Her *Fur Lined Tea Cup* triggers unexpected, subconscious feelings in the viewer, perhaps sexual feelings, or feelings of desire. Her use of antithetical materials asks us to rethink our preconceived ideas about reality.

This use of materials to transform an ordinary object into something evocative inspired me to believe that transforming the computer *materially* could have a similar affect. Antithetical materials could bring new



Figure 5.8 Merit Oppenheim's *Fur-lined Tea Cup*.

¹⁰ Breton, Andre, *What is Surrealism, Selected Writings*, NY, Monad, (1978).

¹¹ Barlow, Margaret, *Women Artists*, Levin, Hugh Lauter Associates, (1997).

and other meaning and purpose to computers, extending the function of technology beyond the limits of practical purpose.

Symbolic Materials in Practical and Interactive Computing Objects

Just as materials can transform meaning, and ultimately function, in sculptural practices, so can they in computing design. Designing with antithetical computing materials, like textiles and rubber can bring new meaning and purpose to computers. Sculptors have achieved this by having access to, and adopting a diverse range of material that are unusual and outside established sculptural materials. Computer artists might take a similarly aggressive tack toward this type of material use. They might cover a cell phone with honey to transform its meaning. I suppose within the rarefied space of the gallery this might work. But computing objects are interactive, often demanding that people touch them, and that they are functional and durable. In fact, if computing objects don't work, they are not successful. Materials that relatively are durable, can become part of everyday life, and artistically meaningful, are then, essential for artists and designers who want to transform physical computing and interactive technology. And just covering a cell phone with honey contributes nothing toward the investigation of the expressive language of physical form and computation. Materials that are *plastic*, symbolically diverse and computationally active will allow for this type of investigation.

Product and Industrial Design

Creating a commercial computing object or product is almost an entirely additive process, (as opposed to *plastic* process), which requires the integration of many prefabricated parts, like input sensors, displays, and/or speakers into a plastic shell. It is this plastic shell, which most industrial and product designers get to plastically, albeit remotely, shape. The Palm Pilot is shaped to fit in your hand. Cell phones are shaped to fit in your hand and be spoken into. Many mice and keypads have been designed to be more ergonomic, fitting into a user's hand more comfortably. With the current onslaught of Repetitive Stress Syndrome, creating a variety of ergonomic physical computing devices has been essential. In general, all these objects are the result of a process that is materially remote and CAD-driven.

It is important to recognize that, in general, the additive design process of industrial and product design cannot be equated with sculptural *assemblage*. In sculptural *assemblage*, objects and materials are purposefully taken out of context to create new meaning. But there is no such recontextualization in commercial computational objects or consumer electronic devices. These kinds of computational objects contain elements that are *intended and designed* to become part of a single object. For example, the standard PC is a mix and match of separate prefabricated parts. But this construction of pieces does nothing to recontextualize them or challenge their established meaning or function. Thus, in traditional industrial design and product design, an assembled group of standard

computational materials does not behave in an active symbolic manner. It simply repeats and reinforces the expected meaning and role of computers and technology.

Apple Computers

Recently, industrial design has begun to transform the plastic shells of computers and other computing devices into more aesthetic and stylishly designed items. The new Apple computers and many of today's more funky pagers and PDA's are great examples of this. This aesthetic emphasis involves changing the shape, color and transparency of the plastic housing. Apple's in house design team achieved the look of the iMac and iBook by creating elegant new plastics and even designing the shape of certain circuit boards to be visually appealing inside the transparent housing.¹² While this approach has been truly innovative in the design of the personal computer, a careful look at the new iBook shows the limitations of using the plastic housing to attempt to transform square, prefabricated parts into rounded, sculptural objects. In order to accommodate the size of the screen and be curvaceous, the laptop has had to dramatically increase in size.¹³ Mac designers have also been very clever about disguising generic PC parts, like the CD-rom drive, behind a more aesthetic and rounded exterior. This process has also led to an increase in size.

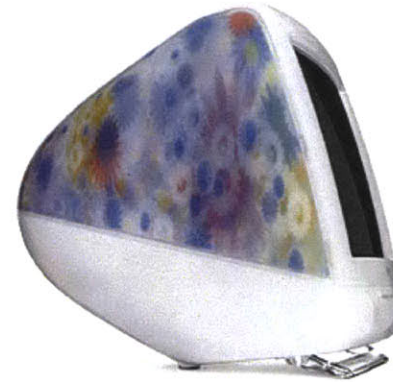


Figure 5.9 iMac, 2000.



Figure 5.10 Sketches of new Apple computers, iMac design team.

¹² Hirasuna, Delphine, *Sorry No Beige, Apple Interview*, [Apple Website](#), World Wide Web, (2001).

¹³ See Chapter 4, for a detailed description of this phenomena.

Durrell Bishop

Product design is often scenario driven, based on stories about the future of technology. These scenarios are often then used to drive the design for physical prototypes. Through scenarios, visionary designers like Durrell Bishop have suggested through many wonderful ways that computer technology can become more three-dimensionally interesting and functional (including his classic *Marble Answering Machine*¹⁴). Bishop has also created working prototypes of his scenarios with the active computing materials. In fact, he spends an enormous amount of time working with physical materials, as in his working prototype of the *Marble Answering Machine* incorporated into a broader intelligent environment,¹⁵ which allowed users to associate pieces of audio information with different physical objects. In this prototype, Bishop used resistive IDs and other computationally active materials to actualize his idea. This project actively worked to incorporate the functional materials of computing technology, like the resistive ID's and new materials like wood. He even uses the conductive properties of paper clips to read their resistive ID through DC current.

At the same time this project demonstrates how existing computing materials encourage scenario driven research and can limit the actual making of physical objects. The idea of these digitally augmented objects was excellent, realizing them, however,

¹⁴ Bishop, D., *Marble Answering Machine*, Director Animation, (1992).

¹⁵ Bishop, D., Still Images, reprinted with his permission, (1994).

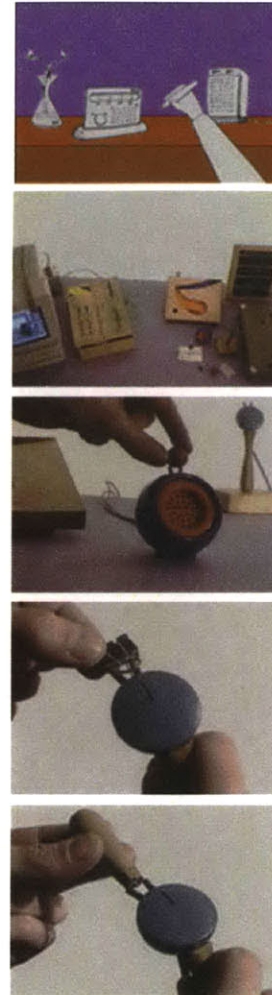


Figure 5.11 Durrell Bishop, stills.

involved working with limited materials the led to a sort of baroque interaction with the objects. For his *real* system to read the resistive ID's of objects, the user had to go through an elaborate physical process of connecting different objects to a sort of magical ID wand. This process became almost an elaborate ritual that was not present in the original director based scenario. If his physical computing materials had allowed him to directly sketch the way his sketchpad did, this problem might not have occurred. Physical computing materials that are part of the sketching and idea process can help overcome the scenario/working prototype separation that often occurs when designing computing objects.

Bishop himself is fully aware of the limits of physical computing materials, and at a Media Lab colloquium (October 27, 1999), he referred to the limiting, generic, palette of materials he faces as a designer of computing objects. He presented a palette that was a demoralizing bunch of buttons and screens. Bishop has faced this palette aggressively. One successful way that he has faced these materials is to accept them, and then use them in entirely unusual ways and create innovative objects with them. In fact, he has acknowledged the importance of materials in his work *Monitor as Material* (1996, with Michael Field). This work uses a screen to "enhance and define the functions of the whole object, like cartridges in a



Figure 5.12 Durrell Bishop, Michael Field, *Monitor as Material*, 1996.

Gameboy.”¹⁶ Bishop himself says of the square monitor:

“*Monitor As Material* cleverly demonstrates that the prevailing screen aesthetic results as much from cultural convention as any intrinsic technical properties.”¹⁷

“Monitor as Material” tries to change the role of the monitor as material, not by changing its physical properties, but by changing its function.

While I agree with Bishop that there is a strong pictorial tradition (painting, photography, and film), which has culturally directed the artistic development of computing technology into the realm of the square and the screen, I also believe that the technological limitations of physical computing technology have severely limited their development as an artistic medium. Changing those materials, will I believe, lead to a more in depth artistic exploration of physical form and computation. Thus in many ways, what separates my work from Bishop’s is the desire to change the physical materials of computers, rather than re-appropriate or re-purpose them.

¹⁶ Abrahms, R., *Adventures in Tangible Computing, the Work of Interaction Designer, Durrell Bishop, in Context, Masters Thesis for the Royal College of Art, (1999).*

¹⁷ Owen, W., *Monitor as Material, Expo supplement, ID Magazine, New York, August, (1996) taken from above.*

Human Computer Interface and Tangible Computing

Hiroshi Ishii, Various Works

Hiroshi Ishii's desire to make computers *tangible* has led to innumerable fascinating, experiments in tangible computing¹⁸. While human computer interface research *usually* focuses on making computers more useable, Ishii's research also displays a strong desire to make computers more physically and tactilely aesthetic. A few projects from his Tangible Media agenda stand out as *materially* transforming computing technology. *inTouch*¹⁹ (Scott Brave, Victor Su, Phil Frei, Rujira Hongladaromp, Andrew Dahley, and Hiroshi Ishii) allowed people to tactilely communicate through two computer controlled sets of rollers. This project, which required people to rub their hands over it, was made of wood, and gave people a far different tactile experience of computing technology than the usual plastic of computers. The groups' paper *Pinwheels* (Sandia Ren, Phil Frei, Seye Ojumu, Rujira Hongladaromp and Hiroshi Ishii) took computing technology into the realm of the materially ephemeral and delicate. Ali Mazalek, Jay Lee, and Hiroshi Ishii also created *Music Bottles*, which allow people to turn



photo: Webb Chappell

Figure 5.13 Sandia Ren, Phil Frei, Seye Ojumu, Rujira Hongladaromp and Hiroshi Ishii, *Pinwheels*, 1999.



Figure 5.14 Scott Brave, Victor Su, Phil Frei, Rujira Hongladaromp, Andrew Dahley, and Hiroshi Ishii, *inTouch*, 1997.

¹⁸ Ishii, H. and Ullmer, B., *Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms*, Proceedings of Conference on Human Factors in Computing Systems, (CHI 1997), Atlanta, ACM Press, (1997) pp. 234-241.

¹⁹ Brave, S. and Dahley, A., *inTouch: A Medium for Haptic Interpersonal Communication*, (short paper), Extended Abstracts of Conference on Human Factors in Computing Systems, (CHI 1997), Atlanta, ACM Press, (1997) pp. 363-364.

off and on musical voices by handling glass bottles and removing their stoppers. All of these projects use highly aesthetic and transformative *housing materials* to give computing technology a new tactile identity.

Brygg Ullmer, *Strata*

More recently, Brygg Ullmer's work in *Strata*²⁰ starts to incorporate computing functionality directly into his design materials. Ullmer laser cuts acrylic to create both shapes and cavities for electronic circuitry and components, which he then uses to create a model of a building. Ullmer describes an early version of *Strata* as taking the "form of a five-layer, translucent acrylic model woven with embedded lights, sensors, and computation."²¹ Using the laser cutter lets Ullmer sketch and create, both electronic "place holders", and shapes, through the same manufacturing process. The results of this process have led to unusual aesthetic items, like the curvaceous electronic base for *Strata* (Figure 5,15). In *Strata*, Ullmer is starting to create acrylic sheet material with electronics or computational functionality built right in. While this material is still hard plastic, it certainly suggests a manufacturing and design process which simultaneously engages with physical form and the materials of computation.

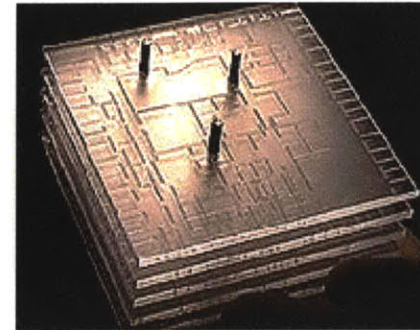


Figure 5.15 Brygg Ullmer, *Strata*, layers of plexigalss with cut grooves for circuitry, 2001.

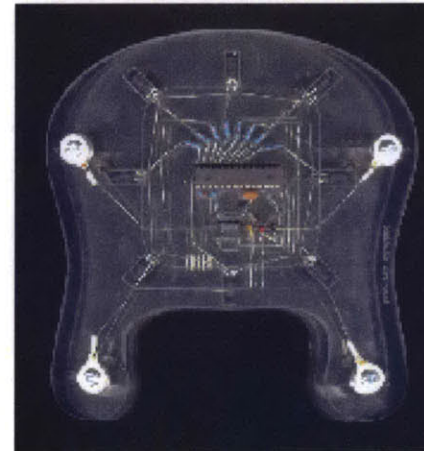


Figure 5.16 Brygg Ullmer, layer from *Strata* with integrated chips, wires and resistors.

²⁰ Ullmer, B., Kim, E., Kilian, A., Gray, S. and Ishii, H., *Strata/ICC: Physical Models as Computational Interfaces*, Extended Abstracts of Conference on Human Factors in Computing Systems, (CHI 2001), Seattle, Washington, ACM Press, (2001).

²¹ Ullmer, Brygg, The Tangible Media Homepage, <http://tangible.media.mit.edu/projects/strata/strata.html>, World Wide Web, (2001).

Electronic Musical Instruments

Live musical performance has almost always involved the live, on-stage, manipulation of some *physical* object or musical instrument. People play a violin, hit drum or even just bang a stick on the floor. Digital and electronic musical instruments often aspire to recreating this kind of intimate, expressive relationship with a physical object. Consequently, they must be incredibly sensitive, robust and ergonomic. They must be able to be touched and preferably held by the performer, if not easily moved around the stage with. And of course, they should also sound good. While this may seem like an easy task, given today's technology, it is not. Most digital and electronic musical instruments are physically, incredibly crude, when compared to their analogue counterparts. They are often fragile, bulky, and difficult to play, and build.

To become sensitive, ergonomic and expressive performance objects, electronic and/or digital instruments have utilized a few basic strategies. One strategy is simply to eliminate the need for a player to touch a physical object, as both the Theremin and its grandchild, Tod Machover's *Sensor Chair* (Joe Paradiso, Tod Machover, Ed Hammond, and Neil Gershefeld), with capacitive sensing, do.²² Physical instruments that require the touch of their player, have made themselves playable (light and ergonomic), by being either controllers (basically just sensors that are connected to off-board multimedia computers, synthesizers, samplers and speakers), or stand-alone

²² Paradiso, J., *Electronic Music Interfaces: New Ways to Play*, *IEEE Spectrum Magazine*, Vol. 34, No. 12, pp. 18-30 (Dec., 1997).



Figure 5.17 Tod Machover performing the Sensor Chair in a 1997 performance of the *Brain Opera*.

objects with limited musical functionality. The ideal stand-alone instrument would have built in sensors, musical synthesis or sound generation and speakers. Barring the analogue Theremin, few electronic instruments do this. Instead, most digital or electronic instruments are controllers, with music and sound generation happening off-board.

Historically, there has been extensive work in all sorts of novel physical devices and instruments for performing live electronic or computerized music. In general, there has been trend in the design of these electronic and digital instruments to copy the form factors of the past; to make electronic keyboards, violins, and guitars. At the same time many creators of controllers have attempted to truly depart from the forms of the past and the square. In discussing her latest instruments, the *Talking Stick*, Laurie Anderson said:

"The *Talking Stick* thing has been very satisfying. I'm on a campaign against rectangles. Let's get away from keyboards - typing and musical. It's a digital sampling machine, shaped like a harpoon."²³

Musical Controllers

Musical controllers are a great example of the advantages and disadvantages of using a multimedia computer when working with novel physical computing objects. These computing, musical instruments

²³ Takiff, Jonathan, Laurie Anderson Interview, Philadelphia Newspapers Inc, World Wide Web, (1998).

separate the sensing or input of the instrument, from the speakers, processing, power source and synthesis engine. This allows controllers to be far smaller, lighter and more finely designed than their stand-alone counterparts. Controllers can also control a range MIDI devices and software, giving them broad musical possibilities and allowing creative people to really experiment. While this can be powerful, it can also lead to a mix and match pairing of music with a controller whose design has little to do with the musical needs or output of the instrument. Another drawback of controllers is the physical separation of the player from the speaker or acoustic source. This separation denies the player tactile feedback, and the audience spatial understanding of the music. Musical controllers that are both arbitrarily linked to musical content, and that have a physically remote sound source, can be confusing and unbelievable to the audience.

Stand-Alone Instruments

Stand-alone computing objects have all their computing functionality on-board, including processing, input sensing and output devices like screens or sensors. Because getting all the functionality of a full sized PC into a handheld object is nearly impossible, stand-alone computing objects tend to focus on taking advantage of the constraints of their materials or parts. Small objects need small prefabricated materials, and prefabricated materials usually have functional constraints related to size. For instance, small speakers are limited in their audio output. Applications for stand-alone musical instruments are specifically designed to take advantage of the limited functionality

of on small board devices like processors or speakers. As a result, stand-alone objects generally have a more specific relationship between their physical design and software. They also, however, leave little room for redevelopment or reprogramming. In performance, stand-alone computing instruments have many compelling advantages. They allow the sound to emanate spatially from the player, as it does in an acoustic instrument. This can provide the player with a sense of personal and physical control similar to what they might find in a violin. They can also allow for freedom of movement and physical intimacy. Unfortunately, creating instruments with a full acoustic range can also require these instruments to be bulky, heavy and constrained by their materials.

Michael Waisvisz, *Crackle Synthesizer*

Waisvisz's *Crackle Synthesizer* is a wonderful example of a successful integration of all the parts required to make an electronic, stand-alone instrument. His instrument integrates all the classic elements of electronic instruments, like those found in classic room-sized synthesizers, into a human-scaled instrument. These elements include buttons and knobs (switches and continuous sensors), speakers, and circuitry for synthesis. But even when reduced to this human-scale, his ability as a performer to manipulate the object freely is sorely limited by its bulky array of parts. While Waisvisz's solution to these limited materials is excellent, he is still hampered in creating his instrument by the conventionality, size, weight and shape of its prefabricated parts.



Figure 5.18 Micheal Waisvisv, *Crackle Synthesizer*, 1976.

Michael Waisvisz, *The Hands*

Michael Waisvisz's *The Hands* is an excellent example of many of the positive and negative aspects of a controller. This instrument consists of two electronic keyboards strapped to his hands. By relating its design to the form and functionality of the piano, *The Hands* builds on a familiar and playable instrument. At the same time it creates a new kind of instrument by redefining its relationship with the body and the hands. The keyboards of *The Hands* are smaller than an both actual piano, or stand-alone digital instrument, could ever be. This means they can be strapped to his hands like no piano ever could. But while he has created a new relationship between the keyboard and his body, Waisvisz's *The Hands* is still severely limited by the circuit boards and sensors that are mounted on them. *The Hands* consist of two stiff boards that must be strapped onto his hand, rather than an instrument integrated into a glove on his hand, or easily held in his hand. *The Hands* is also a generic MIDI controller, so the sound and music it controls can change as easily as the synthesizer to which it is attached. It's design reflects that generic state. Finally, its speakers are off board, which can lead to a real disconnect between performer and sound.

Dan Truman and Perry Cook, *BOSSA, Bowed Sensor Array*

On board speakers placed directly on this controller overcome what is often a perceptual disconnect between the sound source and the player of digital instruments. This performance instrument combines a unique spherical speaker array (Dan Truman and Perry

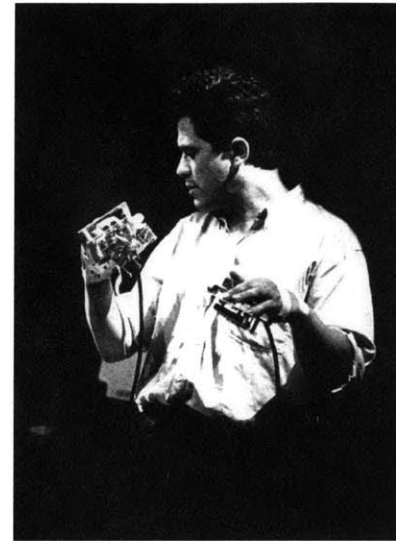


Figure 5.19 Micheal Waisvisv, *The Hands*, 1984.

Cook), with five commercial pressure sensors, and a rotating sensor stick that can detect the angle and the placement of the player's hand. Putting the speakers inside the instrument makes the performance of this object far more intimate. At the same time, the weight and size of the speakers prevent it from being held in the players hands, and limit its physical relationship with the player. According to Truman himself, the sensors on the instrument break regularly and have to be replaced. The sensors are arranged in a familiar violin-like format for bowing.

Curtis Bahn, *BubbaBall*

The *BubbaBall* uses a 22 inch spherical speaker array (Dan Truman and Perry Cook), combined with "five force sensitive resistors (FSR's) under squishy foam, a dual axis accelerometer for tilt and shake data, and five latching switches. The dodecahedron form for the *BubbaBall* comes from a gutted children's toy."²⁴ This is all connected to an off-board music system. By putting sensors right on the speakers, this ball becomes a handheld instrument. (Though given the 22 inch speaker array Bahn must be physically quite large.) Because the *Bubbaball* makes its own sound, the player gets wonderful tactile feedback from the acoustic vibrations. The ball-like form and pressure sensors make for a successful handheld instrument that the player squeezes. In this way, this is similar to my embroidered instruments. However, I think it is safe to say that this instrument is not really very squeazy. It

²⁴ Bahn, Curtis, [Homepage](http://www.music.princeton.edu/~crb/Activities/bubba%20ball.html), <http://www.music.princeton.edu/~crb/Activities/bubba%20ball.html>, World Wide Web, (2001).



Figure 5.20 Dan Truman and Perry Cook, *BOSSA, the Bowed Sensor Array*, 1998.



Figure 5.21 Curtis Bahn, *BubbaBall*, 2000.

is a hard plastic shell that has some foam rubber over its surface where the sensors are. Moreover, there is not a correspondence between the physical design of the instrument and the music it plays.

Laurie Anderson, Interval Research and Bob Bielecki, *Talking Stick*

Laurie Anderson's *Talking Stick* is in many ways the ultimate performance controller that truly emphasizes form factor and performer mobility. This lighted six foot long, musical stick is wirelessly connected to a central MAX controlled MIDI system. It has no on-board music making capabilities. It contains a linear potentiometer, one pressure sensor and six switches. It transmits sensor data wirelessly to a remote computer and sound system.²⁵ The instrument was designed for Anderson's performance of *Moby Dick*, so its harpoon-like shape has a clear relationship to the story. Moreover, Anderson dances with it and moves freely about the stage, something she could not do if it were not light and wireless. This instrument was designed by Anderson and a research team at Interval and mechanically engineered by REM Design.²⁶

Conclusion

This chapter has presented a number of areas, including robotic assemblage, industrial and product

²⁵ This information was provided by Geoff Smith, former Interval Researcher.

²⁶ [REM Design Homepage](http://www.remdesign.com/port4.html), <http://www.remdesign.com/port4.html>, World Wide Web, (2001).



Figure 5. Laurie Anderson, Interval Research and Bob Bielecki, *Talking Stick*, 1998.

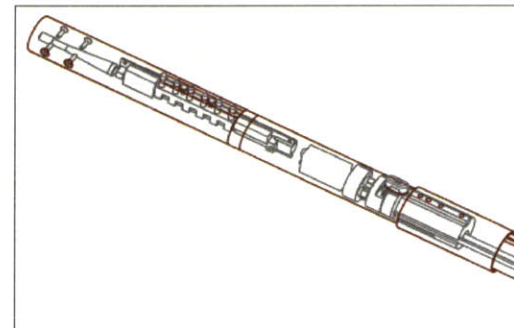


Figure 5. REM Design, CAD image of *Talking Stick*.

design, and tangible human computer interface, in which the physical and aesthetic transformation of computing technology is taking place. It has also presented electronic musical instruments as a model for that transformation. Despite the great advances that these areas of research are making in transforming physical computing objects, there is still much room for the use of smart and active, sculptural computing materials, in both the sketching and design process, and final creation of physical computing objects. Smart computing materials that provide artists with the ability to directly sketch will enable a different type of design process where the *actual* aesthetic possibilities of the materials play a role in the final proposal. Computing materials that are shapeable and that possess unusual tactile properties will also allow designers fuller range of symbolic expression. Finally, smart and shapeable computing materials will allow designers to directly investigate the relationship of physical form and computation.

Chapter 6.

Future, Smart and Sculptural Computing Materials

For computers to truly become sculpturally, materially, and symbolically transformed, and play new roles in peoples' lives, the generic palette of computing materials that designers and artists work with must expand and change. No longer will plastic, buttons and little screens suffice. New computational materials must emphasize *design* properties that are human-scaled, or capable of being sensed by people. Currently, most emphasis on developing new materials for computing technology occurs at a microscopic scale. Engineers work to make ever faster and smaller transistors and chips. But smaller technological materials do not necessarily solve the problems many designers are facing. New computing materials must provide artists and designers with more plastic control and immediacy, allowing artists to experiment and iterate. They must also provide artists and designers with visual, tactile and mechanical variety. Finally, they must enable artists and designers to truly explore the relationship between physical form and

Design Properties of Sculptural and Active Computing Materials

Enable the simultaneous investigation of physical form and computation. New sculptural and active computing materials must allow artists to simultaneously investigate physical form and computation. To do this, these materials must function simultaneously as physical design materials and active computing materials

Provide tactile, visual and mechanical variety. New sculptural and active computing materials must offer designers and the people who experience computers a variety of tactile, visual and sensual experiences. Industrial designers have always chosen their materials to communicate something about the object. Fabric is soft, warm and intimate. Metal is colder and more formal. Wood can be warmer. Most physical computing objects demand an input device that usually responds to touch. Yet people have almost NO sensual incentive to touch their computers, and designers have almost no choice in what the people who use computers touch. New physical computing materials must possess a variety tactile qualities, visual qualities (including transparency and opacity), and a variety of colors. Finally, they must provide artists and designers with a variety of mechanical properties to choose from, such as stiffness, elasticity, strength, and softness.

Be directly shapeable or sculptable. New sculptural and active computing materials must be shapeable so that designers and artists can create objects that physically reflect their artistic vision. They must provide designers and artists with immediacy so they can experiment and iterate with the physical properties of computational objects as quickly and easily as they can with software.

computation through direct manipulation. To do all this, these design materials of computing objects must be more than inactive, hard, plastic shells or housings; they must be computationally active.

The ideal sculptural and active computing material might be a sort of computer clay which designers or artists could use to form monitors, speakers and even processors into any *shape*. But there remains a lot of work to do before we have this magical computational clay. In the meantime, scaled back, smart or multi-functional computing materials can help us begin to physically transform computing, as well as to explore the relationship between physical form and computation.

The projects presented in this thesis use two strategies to suggest the possibilities of future sculptural and active computing materials. The first strategy is to use smart or multi-functional materials. Smart materials take on multiple functions, reducing the number of separate *prefabricated* materials necessary to create a computing object. The second strategy is networked computing materials. These are ultimately *raw* materials that are formed from many networked *prefabricated* computing devices. Like the bonds between atoms, network connections can let many prefabricated devices become a raw material.

Smart, or Multi-Functional Computing Materials

Phillip Ball, in *Made to Measure*¹ describes smart materials in the following ways:

"Smart materials can be thought of as materials that replace machines..."

"Smart materials have the potential to simplify engineering considerably. Moving parts have a tendency to break down, whereas smart devices in which the *materials* themselves do the job of levers, gears and even electronic circuitry, will contain less potential for malfunction.

"smart material systems... are materials that are hooked up directly to microprocessors."

The essence of what Ball is saying here is that smart materials *integrate* the functionality of various separate parts into a single material. This is mechanically efficient because it eliminates the need for parts to be physically connected or to interact. It is artistically efficient for the same reason. Making any object from a single material is almost always simpler than integrating multiple materials. As long as a piece of furniture is all wood, you can cut and glue it together relatively easily, and as long a piece of furniture is made of all metal you can cut and weld it easily. But making a piece of furniture from both metal and wood is far more complex. Mechanical fasteners between the two must be used. The properties of the wood (for example how much it expands with temperature and how soft it is) and their interaction with the properties of the metal must also be taken into

¹ Ball, Phillip, *Made to Measure: New Materials for the 21st Century*, Princeton, University of Princeton Press, (1997) pp.103-110.

account. Add more materials to this hypothetical piece of furniture, and it becomes even more complex. IF one can integrate the role of these multiple materials into one material, the designer will have a far simpler, and more direct building and manufacturing process.

The Materials of an Acoustic Violin

The materials of an acoustic violin provide an excellent model for the potential of smart or multi-functional, computing materials. An acoustic violin is an interactive object of incredible precision, ergonomic design and beautiful musical output. Like a computational object, an acoustic violin has an input device (strings), an output device (an acoustic cavity that makes music), and a means to transform the input (the form and properties of the instrument), into the output, music. The major material of an acoustic violin is wood. It performs many functions. (While there are additional materials, like string, horse-hair and steel, what I am getting at here is the *multi-functional* nature of wood in the violin.)

Wood is the waveguide, or the means of transporting the input signal, (the vibrations from the strings), to the output device, (the resonant cavity). It is also the output device; it amplifies and creates sound waves. It transforms the input signal into music, by controlling the frequency and timbre of the music output with the shape and size of the cavity. It is also the major mechanical substrate and design material of the instrument. It holds all the parts together, and is shaped to fit easily into the player's hands.



Figure 6.1 A violin is made mostly from the smart material of wood.

The wood of the acoustic violin is also truly sculptural. It can be shaped, cut, bent, drilled and glued quite precisely. The process of shaping the wood of a violin allows its designer to control both the ergonomics and musical output of the violin, because both the shape of the violin, and the material properties of the wood, have a direct relationship to its musical output. A violins size is related to its frequency range (for example cellos make deeper sounds). The shape of the arch of the back of the violin can be used to create subtly different vibrations. The shape of the sound holes also directly affects the sound of the violin. And the wood itself creates a very different timbre than metal would. In fact, different types of wood are used for different parts of the violin to create different vibrations.² In this way, we can understand the violin as an interactive object whose physical form and materials is directly related to its sound output, or *computational function*.

The Materials of its Physical, Computing Counterpart

So what would it take to create a physical, computing version of this instrument? Assuming one could actually create a computing instrument that was as responsive and sounded as good as an analogue violin, building it would require *MANY computing materials*. A physical, computing violin would need:

- **Sensors** to translate the mechanical energy of playing into electricity that communicates with a CPU.

² Johannsson, Hans, [Violin Making](http://www.centrum.is/hansi/), <http://www.centrum.is/hansi/>, Iceland, World Wide Web, (2001).

- **Wires** to send electricity to a chip.
- **A computer chip** on a circuit board processes the information from the sensors and creates an audio signal.
- **More wires** to send that signal to a speaker driver.
- **A speaker driver** to translate the signal back to the mechanical vibrations of sound.
- **A resonant cavity** to amplify the sound, (this may or may not be made from the substrate material.)
- **A mechanical substrate material** to hold it all together.
- **A power supply** (a battery or wire) to power it all.

Almost every one of these materials is a *prefabricated* material, and cannot be reshaped for either ergonomic or musical reasons. Moreover, an instrument created from these materials will be neither light, nor easy to play. The physical requirements of creating a mechanically stable object that can translate mechanical energy from the sensors, to electrical energy for the processors, and back to mechanical energy at the speaker, guarantee, that the digital and physical violin would need obtrusive wiring throughout, and a sturdy and inevitably bulky way to support it all.

When compared with its computing counterpart, the materials of an acoustic violin are unbelievably concise. In fact, if the acoustic violin had come *after* the computing version, we would think of the wood in the violin as the ultimate *smart* material. The wood of the acoustic violin replaces the speaker, amplifier, CPU, wires and housing material of the digital version. The wood is smart or multi-functional material, performing many acoustic and mechanical functions simultaneously.

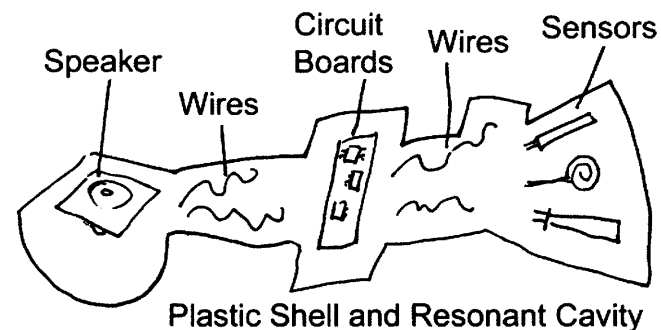


Figure 6.2 Diagram of the materials necessary to create its digital/physical counterpart.

Ideally, smart or multi-functional materials would perform as many functions as the wood of the violin. While creating a computing material that can perform as many functions as the wood in a violin is still far off, a single material, that can perform even a few computing functions simultaneously, can make a big difference in both the design process and its results. A scaled-down approach to creating smart computing materials might integrate least two of the following functions: sensing, mechanical substrate, electrical transport, visual output, audio output, and computing. And like the wood of the violin, smart computing materials should be wonderfully sculptable, able to be molded, sized, joined or bent to the shape appropriate for the object they forming.

A silicon chip is, itself, a highly integrated or smart material, which might serve as a model for a smart, sculptural, computing material. Silicon chips replaced complex logic circuits that had been made from many transistors and electronic components parts. Silicon is a remarkable material because it can be transformed into conductor, insulator or semiconductor. A smart sculptural computing material might also be transformable into different functions, like speaker, monitor or CPU.

Small is *Not* Enough

The need to mechanically simplify computing objects by integrating the functionality of many different parts into a single material is why simply making silicon chips SMALL is not enough. Today's computational objects are a system of mechanically attached, *human-scaled* materials, and microscopic silicon chips are just a part of

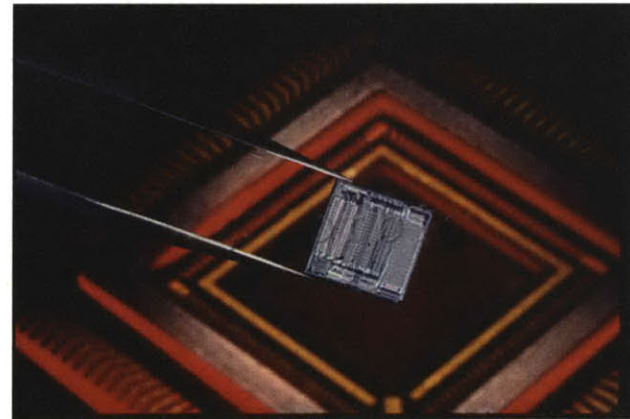


Figure 6.3 Miniature microchip compared to giant housing and pins around it

that system. These tiny chips are themselves only the core of a larger and more rigid package, which is designed to preserve their electrical properties, and allow them to communicate with other parts of the object. To send and receive electrical signals to other components, the electrical leads of these tiny chips must scale up; their microscopic pins must "break out" to reach large pins, which in turn reach the wires and connectors, on larger sensors and output devices. All these wires and connectors must then be held on a rigid surface, or inside a plastic box so that the electrical connections do not break.

Networked Computing Materials

It is possible to understand a network of many *prefabricated* computing devices or elements as an *raw*, networked material. While raw materials are capable of being divided into smaller chunks that still retain their material properties, they are ultimately composed of many individual elements (atoms or molecules), which, like precursor elements, cannot be broken down. It is the connections between these molecules or atoms that give a *raw material* its sculptability or shapeability. In this way, a mass of *prefabricated computing elements* can become a material, by virtue of its network connections. It is possible to imagine schools of networked robots functioning as this sort of material. Wireless networking between separate computing elements in a single computing object, can also help reduce bulky wiring materials, and make materials more shapeable and practical.

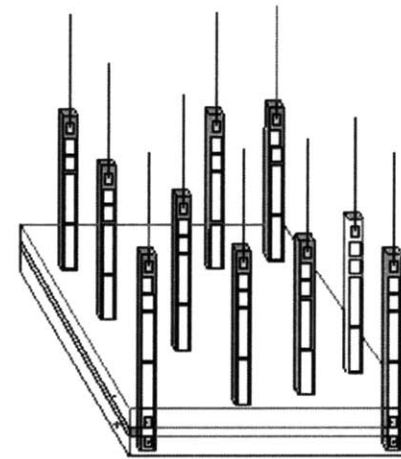


Figure 6.4 Sussman's *Pinless Processor*, 1999.

Amorphous Computing, Jay Sussman

Jay Sussman's *Amorphous Computing*³ and his *Pinless Processor* represent a far-reaching vision of networked computing materials. Sussman has proposed many ways to create a material made of thousands of wirelessly connected tiny pinless processors that can compute. While his work has focused primarily on software for these interconnected processors, it has also explored some possible hardware solutions. These solutions include creating a substrate of layered power and ground to plug the *Pinless Processors* into. Wireless connections between the processors would provide communication. But *none* of these hardware solutions creates materials that are actually physically and mechanically paintable, amorphous, or skin-like. That is because, while Sussman's focus has not been on the mechanical properties suggested by the name of his research, but on the software model. Thus, when he claims that the hardware problem is trivial,⁴ it is based on the fact that truly achieving the physical and mechanical material properties that he uses to describe his research, is not really his goal. But if this research were to emphasize enabling the physical and mechanical properties of paintable computing, it would find a wealth of additional applications. Creating computing materials that are *truly* physically, paintable and amorphous will have tremendous ramifications and use for artists and designers working in computation.

³ H. Abelson, D. Allen, D.I Coore, C. Hanson, G. Homsy, T. F. Knight, Jr., R. Nagpal, E. Rauch, J. Sussman, R. Weiss, *Amorphous Computing*, Communications of the ACM, 43, 5, (2000).

⁴ Ibid.

The Potential of Structured Computing Materials

There is tremendous potential for the development of structured or composite computing materials. I imagine these materials as a sort of computing wood, or more advanced computing textiles. Like silicon, these materials might have the potential to be transformed through different processes into various electronic components or precursor elements, like screens or displays. These materials might come in sheets that could be cut, bent and sewn or glued together. The sewing and gluing would both electrically and mechanically fasten them together. The materials might then be "treated" or coated to turn part of them into a display of sensor or a speaker. This could allow for a much more direct building and design process.

How My Portfolio of Projects Fits In

The projects presented in this thesis only begin to suggest the possibilities of sculptural and active computing materials. This thesis develops electrically active textiles as smart or multi-functional, and active, sculptural, computing materials. These smart textiles function as the physical housing or design material, power distribution materials, wires, sensors, antennas and - in the case of the *Firefly Dress* - a display substrate. Design projects in this thesis that use smart textiles include: the *Firefly Dress and Necklace*, the *Ball Gown*, *Serial Suit*, *Piecework Fabric Keypad*, *Musical Jacket*, *Electronic Tablecloths*, and *Embroidered Musical*

Instruments. This thesis presents the *Triangles* as an example of networked sculptural computing materials.

While some of the projects presented in this thesis are stand-alone, many rely on off-board computing and speakers to keep the computing objects as light and textile-like as possible. In this way, objects like the embroidered musical balls are *smart material systems*⁵ that consist of smart fabric balls connected to an external PC and speakers. As a smart material system, these materials take advantage of off-board computers, to do much of the computation and media output. However, by replacing quite a few separate parts of computing objects, these smart textile objects demonstrate the artistic impact that more fully developed smart and active computing materials will make when they actually arrive.

⁵ Ball, Phillip, *Made to Measure: New Materials for the 21st Century*, Princeton, University of Princeton Press, (1997) pp.103-110.

Chapter 7.

Introduction to the Design Portfolio

The following sculpted computational objects chronicle the design and artistic work of this thesis. These projects include the *Triangles*, *Electronic Fashions*, and *Embroidered Musical Instruments*. They are presented as support for the main design and artistic premise of this thesis: that a meaningful expressive language for physical computing cannot be fully developed without new, sculptural and active computing materials. Because I believe that the story of my work has developed over time, I have chosen to present the portfolio works generally, in the order in which they occurred, rather than in an order related to the most significant contributions. I have also chosen to group some projects, which are related both in time and content, together in chapters. I have done this to best communicate my story, not as a reflection of the importance of any single project.

While the portfolio of projects focuses on design and artistic issues, these cannot be truly separated from the technical constraints and advances related to the

creation of these objects. Without my technical development of smart textiles, I simply could not have made the design and artistic advances and experiments that this portfolio presents. Moreover, the many of the technical contributions of this thesis were driven by the needs of creating these objects. Consequently, technical developments that are essential to and directly influence the design and artistic story are included in this section. More detailed technical information can be seen in Chapters 13-16.

Motivating Design Work in Tod Machover's Brian Opera, 1996*

My interest in computing technology as a three-dimensional artistic medium began while designing and building many of the physical interfaces of the interactive musical instruments in Tod Machover's *Brain Opera* (1996).¹ I firmly believe that the artistic and technical questions I am asking today, are motivated by the artistic experiences I had while working on this project. Before this project, computers seemed abstract and isolated to me. Designing new physical interfaces and environments for the *Brain Opera* intrigued me because I began to see how and why computers could emerge from their boring beige,

* I designed the *sensor objects and hand-held interfaces* in the Brian Opera, and collaborated closely with project architect, Ray Kinoshita, on the larger objects that hold them. This was all done with the input of visual design director, Sharon Daniel.

¹ Orth, M., *Interface to Architecture: Integrating Technology into the Environment of the Brain Opera*, The Proceedings of Design of Interactive Systems, (DIS 1997), Amsterdam, ACM Press, (1997).

plastic boxes. Moreover, the direct and hands-on material struggle I faced during this early design work, led directly to the work created for this thesis.

My motivation to use new materials and physical forms in the *Brain Opera* was multiple. Practically, the sensing needs of these musical instruments demanded new materials and manufacturing processes. The fact that these instruments would become part of a traveling public show meant that they had to be robust. Artistically, I wanted to create computers that were both tactilely and visually, unique and unexpected. My design goals included using unique textures to encourage audience members to touch and interact with the instruments, and creating a physical space that encouraged a different type of exploration than computer keyboards and mice. I wanted people to see and experience the expressive and creative potential of computers, not just their practical abilities. To do this, I felt I had to create a new tactile, material, and visual identity for computers. The resulting objects are physically and visually antithetical to what was then the standard look and feel of technology at the time. They are transparent, organic, soft and rubbery.

Most of my design work in the *Brain Opera* involved simply re-housing commercial sensors and display devices into novel physical forms made from unusual plastic and rubbery materials. Commercial screens, earphones and microphones were wrapped in silicon. Commercial sensors were cast into rubber casings. The bulk of the computer and audio equipment, (PC's, synthesizers, etc.), were placed on a grid up top, away from the equipment with which people had to directly

interact or touch, like speakers and headphones. This allowed the physical interfaces to be light and transparent. While the re-housing of commercial devices and sensors (like headphones and LCD screens), inside rubbery, transparent and light materials was successful on many artistic levels, it was not enough to truly achieve my goals, either practically or artistically. Soon deeper artistic questions emerged, questions that ultimately led me to this thesis. These included how to create better physical computing design materials and how to realize the expressive potential of physical form, networking and computation.

Talking Trees*

Perhaps the best examples of the re-housing of commercial electronic devices in the *Brian Opera* are the *Singing*² and *Talking Trees*.³ These interactive stations integrate an LCD screen, a microphone, headphones and a re-housed commercial mouse, in a sculptural, silicone rubber and polypropylene pod. The bending of the rubbery and transparent silicon sheet material into an organic shape gives these interactive stations an entirely unexpected feeling. Soft and rubbery materials helped encourage people to touch these interactive stations, and become physically

* Physical design in collaboration with Ray Kinoshita.

² Oliver, W., Yu, J., Metois, E., *The Singing Tree, Design of an Interactive Musical Interface*, The Proceedings of Design of Interactive Systems, (DIS 1997), Amsterdam, ACM Press, (1997) pp. 261.

³ Orth, M., *Interface to Architecture: Integrating Technology into the Environment of the Brain Opera*, The Proceedings of Design of Interactive Systems, (DIS 1997), Amsterdam, ACM Press, (1997).

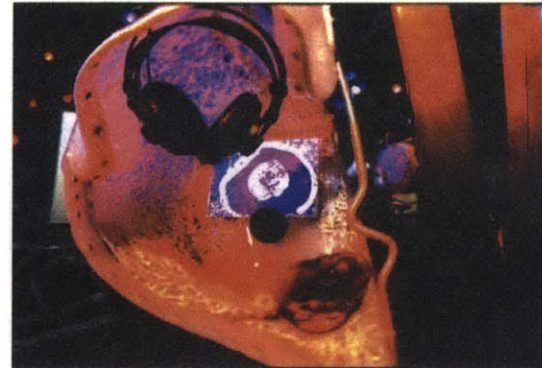


Figure 7.1 Maggie Orth, Ray Kinoshita, *Talking Trees*, from Tod Machover's *Brain Opera*, 1996.

intimate with them, placing their heads inside. But despite the success of this transformation, I was ultimately disappointed in its superficiality for two reasons: 1) The *Talking Tree's* software was functionally no different than that written for a computer with a standard monitor and mouse. 2) I had to accept the square and rigid mechanical properties of all the electronic devices built into the organic pods, especially the LCD screen. Ultimately, I felt that the silicon hoods were only putting a new face on existing forms, not fully exploring or changing their fundamental meaning and function.

Rhythm Tree Pads

While many of the objects in the *Brain Opera* remained in the category of re-housed, commercial electronic devices, the *Rhythm Tree*⁴ and its organic, rubbery drum pads began to suggest the artistic potential of computational objects to me. The *Rhythm Tree* was a digital musical drum machine consisting of three hundred networked drum pads. Each drum pad had a unique ID, a piezoelectric sensor, an LED and a connection to a central computer. Artistically, I wanted to incorporate each of these elements into a rubbery, organic, and extremely tactile housing. Practically, this housing needed to trigger the piezoelectric sensor, hold and protect the electronics, and be made from a transparent material, to display the lighting of an LED when the pad was hit. To achieve this, the electronics were cast directly into a rubbery urethane form molded

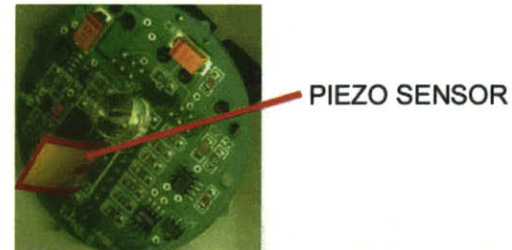


Figure 7.2 *Rhythm Tree* Circuit (Joe Paradiso), *Rhythm Tree* Pad Housings, (Maggie Orth), *Rhythm Tree* in Brain Opera, (Ray Kinoshita and Maggie Orth), 1996.

⁴ Paradiso, J., *The Brain Opera Technology: New Instruments and Gestural Sensors for Musical Interaction and Performance*, Journal of New Music, Research, Vol. 28, No. 2, (1999) pp. 130-149.

from a hand-made original. Originally, I varied the shapes of the drum pads and made them highly textured to create visual variety and encourage people to touch them. Unexpectedly, the different shapes of the drum pads also allowed players to play them differently. Pads with different sizes and shapes caused different vibrations in the sensors and ultimately created different music in the computer. In addition, players could use different textures to play the pads differently. For instance, the pointy pads can be plucked, creating numerous quick sounds, as opposed to the smoother pads which create one sound per hit.

The interaction between the physical form of the pads and the behavior inside the computer excited me and suggested new possible interactions between physical form and computation. The *Rhythm Tree* also made me raised the question, “What does it mean *expressively* to have three hundred networked objects that can communicate, know each other’s identity and state?” These two issues, how can the form of an object be meaningful in computation, and how can an artist use networked objects expressively, became the fuel for my later research.

Digital Baton*

Designing and manufacturing the physical housing for Teresa Marrin’s *Digital Baton* ^{5,6,7} truly crystallized the

* In collaboration with Teresa Marrin and Joe Paradiso.

⁵ Marrin, Teresa, *Possibilities for the Digital Baton as a General-Purpose Gestural Interface*, Extended Abstracts of the Conference on Human Factors in Computing Systems, (CHI 97), Atlanta, ACM Press, (1997) pp. 311-312.

material challenges involved in creating computational objects. My design goal was to integrate five commercial pressure sensors, an accelerometer, an infrared LED (for pointing in a 2-D space), and central electronics, into a small, squishy form that fit in the palm of your hand and was easy to play. My basic design involved creating a hard plastic central core to hold the electronics, covering it with pressure sensors, and then imbedding it all in a rubbery goo. The central core had to be fairly large, to hold all the electronics. This meant that the rubbery material covering it had to be thin. Consequently, the squishy feeling of the baton was literally only skin deep. The commercial pressure sensors were glued to the surface of the core. These sensors were big, square and extremely fragile. To preserve their electrical abilities, they had to lie flat on a rigid substrate. Integrating these bulky sensors under a rubbery skin, and over a sculptural three-dimensional form was nearly impossible. The electronics in the core also had to be awkwardly connected to the sensors with bulky, rigid and fragile wires, two per sensor. All of these factors limited the shape and size of the baton, and eventually the sensors failed electrically.

After trying to imbed the commercial sensors into a sculptural rubbery object, I longed for sensor materials

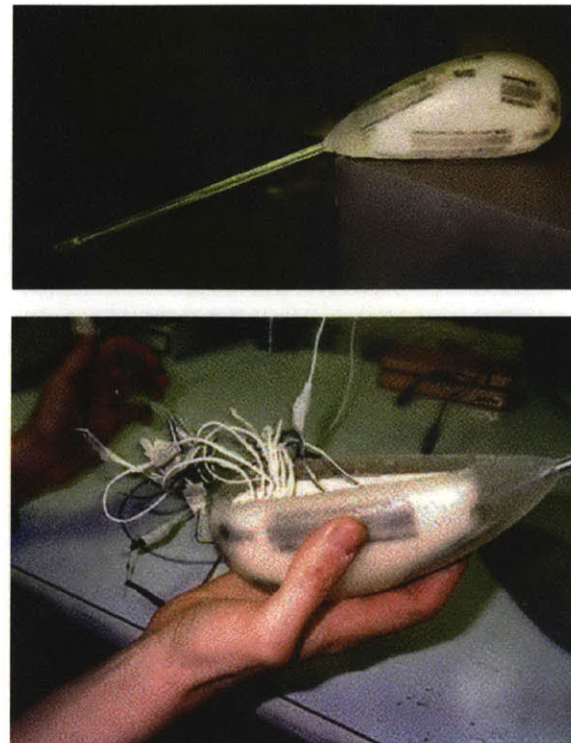


Figure 7.3 Teresa Marrin's *Digital Baton*, 1996, with commercial pressure sensors under clear squishy skin.

⁶ Marrin, Teresa, Paradiso, J., *The Digital Baton: a Versatile Performance Instrument*, Proceedings of the International Computer Music Conference, Thessaloniki Greece, (1997) pp. 313-316.

⁷ Teresa Marrin, Joseph Paradiso, Tod Machover, Christopher Verplaetse, and Margaret Orth, Apparatus for Controlling Continuous Behavior Through Hand and Arm Gestures, United States Patent # US5875257, (1999).

that would allow me to create small and intricate instruments, with both ease and an economy of steps. I wanted materials that could be both the sensors and housing, that I could bend, cut and mold into any shape I wanted. I wanted a sculptural sensor skin to create multi-channel musical instruments.

Chapter 8.

***Triangles** as a Networked, Computing Material**

Overview of the *Triangles*

In many ways, the *Triangles*, (1997-1999)^{1,2} may seem disconnected from the smart textile projects developed in this thesis. They are not soft, and do really rely on smart textiles, accept as part of their patented, flexible

* In collaboration with Matt Gorbet.

¹ Much of the description in this chapter refers to: Gorbet, M., Orth, M. and Ishii, H., *Triangles: Tangible Interface for Manipulation and Exploration of Digital Information Topography*, *Proceedings of Conference on Human Factors in Computing Systems*, (CHI 1998), Los Angeles, ACM Press, (1998) pp. 49-56.

² Gorbet, M., and Orth, M., *Triangles: Design of a Physical/Digital Construction Kit*, *Proceedings of Designing Interactive Systems*, (DIS '97), ACM Press, Amsterdam, (1997) pp. 125-128.

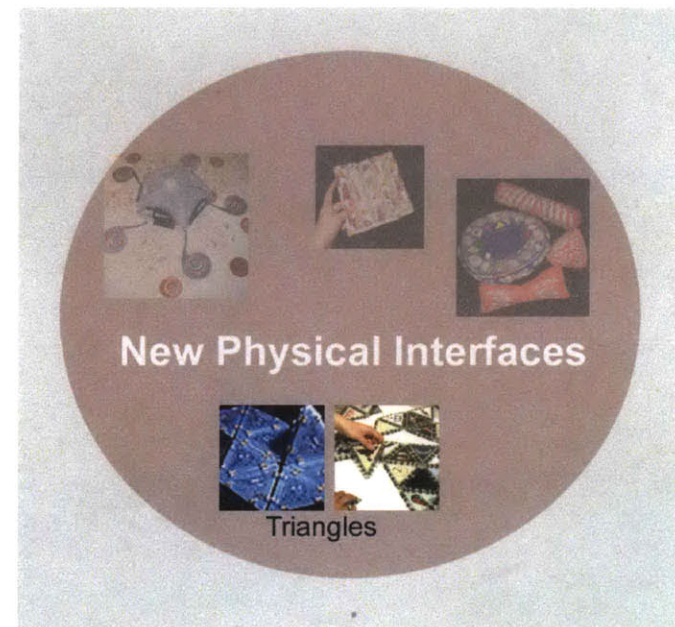


Figure 8.1 *Triangles* in relation to the Tree of Projects.

connector³. However, it is essential to this thesis that the *Triangles* themselves be seen as a large-scaled, networked, sculptural and active computing material. With the *Triangles* shapes and forms can be built and made, as with clay. The *Triangles* were originally created to explore the expressive possibilities of a large group of networked computational objects. Moreover, their triangular shape was always meant as a departure from the square and pictorial world of rectangular computers.

How They Work

Each *Triangle* contains a microprocessor programmed with a unique ID, and a patented hinge-like connector that allows the *Triangles* to simultaneously mechanically and electrically connect to one another. When the *Triangles* are physically connected together, they communicate their identities to one other across that physical/electrical connector, and then relay that connection information back to a master computer. This master computer keeps track of the physical configuration of the *Triangles*. Information from the *Triangles* about which side of which *Triangle* is connected to which side of another, allows the PC to infer the exact shape and relationship of a connected mass of *Triangles*. The computer can then use this information to control applications that range from HTML storybooks, to audio landscapes.

³ Orth, Margaret, Gorbet, Matt, Digital Communication, Programmable Functioning and Data Transfer Using Modular, Hinged Processor Elements, US Patent # US5941714, (1999).

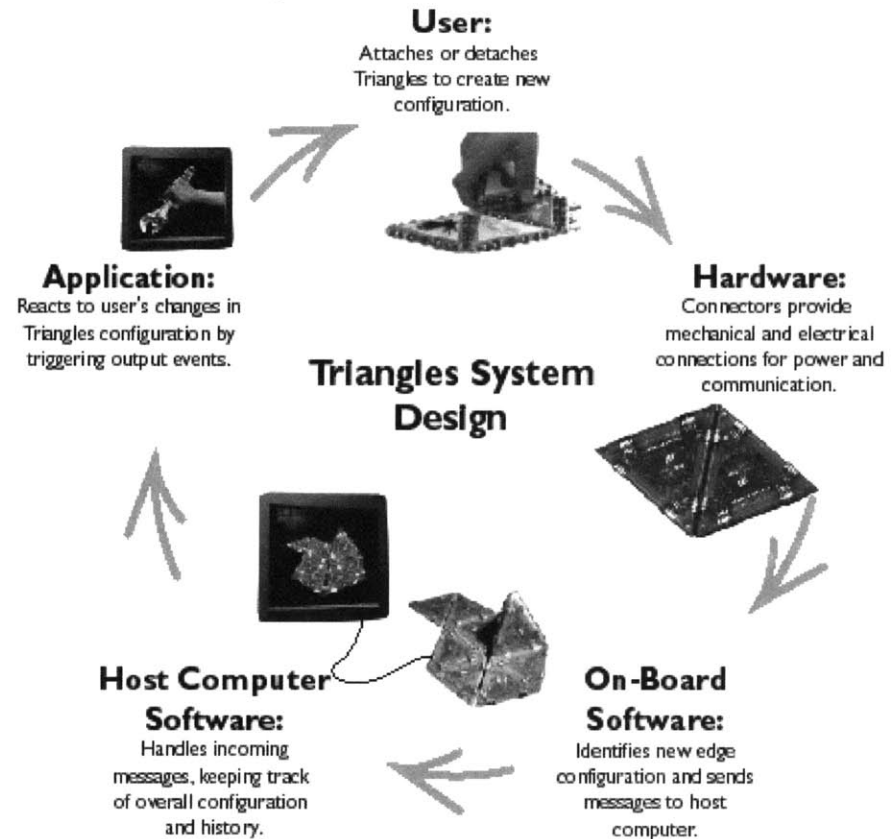


Figure 8.2 Overview of *Triangles* System, image from: Gorbet, M., Orth, M. and Ishii, H., *Triangles: Tangible Interface for Manipulation and Exploration of Digital Information Topography*, Proceedings of Conference on Human Factors in Computing Systems, (CHI 1998), Los Angeles, ACM Press, (1998) pp. 49-5.

Why Three Sides?

The three-sided triangular shape of these pieces is both an aesthetic departure from square circuit boards, and a reflection of the non-linear, complex and branching structure of digital information. Three sides means that a *Triangle* can have two inputs and one output, or two outputs and one input. Three sides (vs. four) is also the least number of sides that are required to create a physical object that is non-linear. This keeps the physical complexity of the system as small as possible; two, three sided objects have nine unique combinations, and two, four sided objects have sixteen. In fact, the possible unique combinations of any number of *Triangles* is factorial. If each side of each *Triangle* has unique ID, the possible number of unique combinations is described by $x \geq 3^n(n+1)!/6$, where $n = \#$ of triangles and $x = \#$ of configurations. If the *Triangles* were four sided, this would both increase the complexity of the system, and also require more complex images, (possibly four, with one referring to each side), on the surface of each *Triangle*.

As A Macroscopic Material

As a group of networked *prefabricated* individuals, the *Triangles* are a networked computing material that allows people to create shapes and objects, which can influence events in software. While each *Triangle* cannot itself be broken apart, a group of twelve *Triangles* can be broken into two smaller groups of six, each group with properties similar to the larger group. Because the connectors are flexible and immediate, the *Triangles* can quickly create both two and three-dimensional objects whose exact shape is known to the

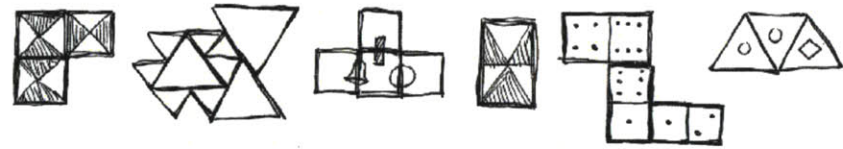


Figure 8.3 Early sketches for alternative shapes of pieces.

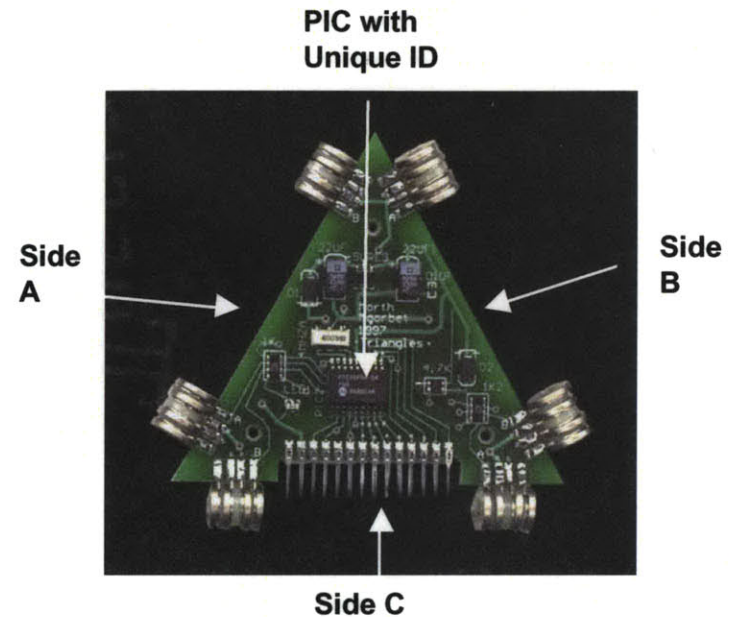


Figure 8.4 *Triangle* circuit board, hardware version 1, with early, sliding magnetic connectors.

computer. In this way, the *Triangles* suggest a sort of macroscopic, computational clay. If they were to shrink to microscopic scale, they would become a truly claylike input device that could play music or paint pictures. If they were to have display elements built into them they could suggest a way to shape a personalized visual display. In summary, what makes the *Triangles* truly material-like is both the repetitive nature of the individual elements, (i.e. they are all identical *Triangles*), and the flexible and immediate connections between them.

Integrated Connector Design

The unique connectors of the *Triangles* demonstrate how artists can use new materials to create an appropriate and integrated form for what is normally a bulky, prefabricated precursor element, (like an electrical connector), that is usually hodgepodge into an object. The final version of these connectors uses a combination of magnets and conductive female Velcro to create an instantaneous and flexible mechanical and electrical connection between two *Triangles*. This new connector allows power, ground, and both local and serial data to be transmitted between the *Triangles*, while guaranteeing a quick and immediate connection. Imagine if the *Triangles* had connected together with a standard serial or DB9 connector. Not only would the *Triangles* have been ugly; the process of physically interacting with them would have been awkward and time consuming, and the effect of the physical object as a means for immediately controlling information far less convincing.



Figure 8.5 Three *Triangles* acting as a material, shaped and/or connected to form a pyramid

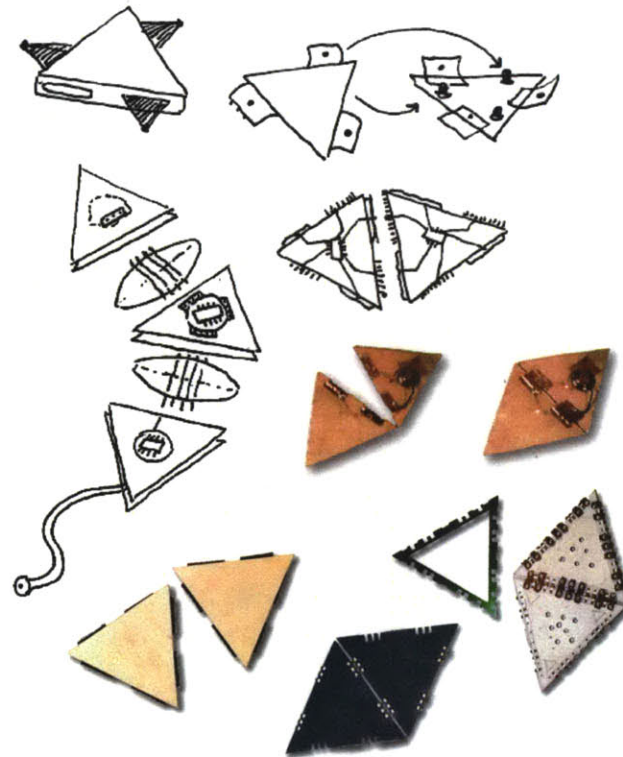


Figure 8.6 Early sketches and prototypes for various integrated connector designs.

First Generation *Triangles*

The first generation of *Triangles* used sliding magnets to create a mechanically stable multi-pin connection. Because magnets are fired, they have low physical tolerances. Consequently, the sliding mechanism was not as consistent as required, and the communication and electrical connection between *Triangles* would sometimes fail.

This generation of *Triangles* also used a unique *Triangle-to-Triangle* routing scheme to pass messages back to the host computer. "The message-passing algorithm was based on a 'gradient-descent' algorithm, through which messages were passed along a gradient, established between the host computer and each of the triangles. A good analogy for this is that of altitude: if one thinks of the connection to the host computer as being at the lowest altitude, then our gradient is established by slightly augmenting the 'height' of each new tile as it is added. This ability of the *Triangles* network to 'self-organize'⁴ ensures a sloping, direct path from every tile back to the host connection. When any *Triangle* generates or receives a message, it simply seeks its *next lowest* neighbor, and passes the message along in the 'downward-sloping' direction. This system guarantees that each message will eventually reach the host computer, and requires each tile to store very little topographical information. It also avoids redundant and unnecessary passing of messages."

⁴ Smith, J.R., *Distributing Identity*, IEEE Robotics and Automation Magazine, Vol.6, No.1, (March, 1999).

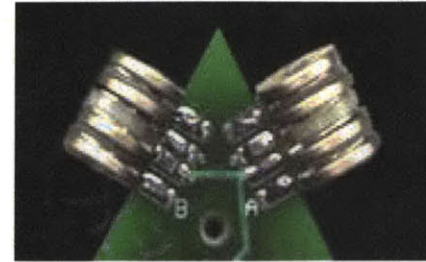


Figure 8.7 *Triangles*, first generation hardware, detail of connectors with sliding magnets, and image of *Triangles* connected.



Figure 8.8 Illustration of gradient algorithm used for communication in the first generation *Triangles*.

“This method for acquiring and relaying topographical information minimizes demands on each microprocessor in terms of memory and functionality. Each PIC chip only has to store five items of information: its unique ID, the most recent IDs of its three neighbors, and its ‘height’ value. Functionally, each chip needs to be able to perform the following functions: set its height value, poll its neighbors (detecting changes in IDs and heights), and generate and pass messages. The circuitry required for this system is also fairly simple in that each *Triangle* needs only a direct local connection to each of its neighbors, plus power and ground”⁵

Second Generation *Triangles*

The second generation of *Triangles* overcame the unreliability of the first generation by using a new, and more mechanically stable connector. A combination of conducting female Velcro and magnets created a reliable and immediate multi-pin connector on each side of the *Triangles*. In this connector, The Velcro was used to overcome the low physical tolerances of the magnets, by making each pin “hairy” and guaranteeing that it would electrically connect to its mate on the other side. The polarity of the magnets was used to ensure that the connectors lined up correctly every time two *Triangles* were connected. .

⁵ Gorbet, M., and Orth, M., *Triangles: Design of a Physical/Digital Construction Kit*, Proceedings of Designing Interactive Systems, (DIS '97), ACM Press, Amsterdam, (1997) pp. 125-128.

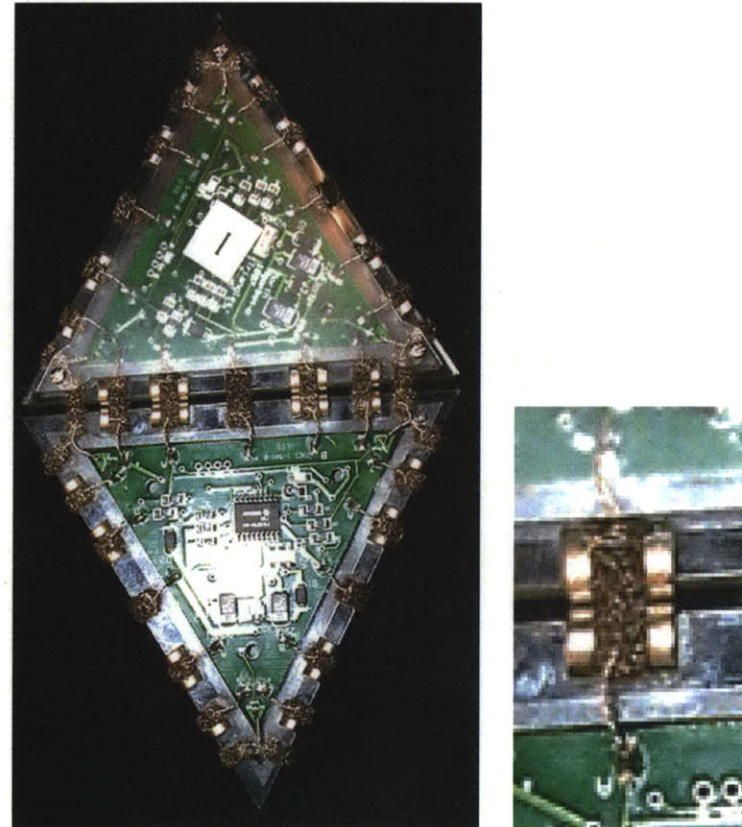


Figure 8.9 Second generation with magnetic and conductive female VELCRO connectors.

The second generation of *Triangles* registered connections much faster by using a speedy serial bus to pass messages back to the host computer. In the first generation, each *Triangle* acted like a router, passing the message along and looking for new connections simultaneously. This required a lot of time. Adding an isolated serial bus, meant that the *Triangles* could communicate much quicker with the host computer. It also required an additional pin. Each *Triangle* now needed a pin for power, ground, *Triangle*-to-*Triangle* communication, (to determine who on what side was connected to whom), and serial communication. Because equilateral triangles are radially symmetrical, the connectors also needed to be arranged so that 'male' would always meet 'female' and vice-versa. To guarantee that each transmit pin meets a receive pin, and that shared pins, such as power and ground, would always find the correct mate when two *Triangles* are connected, there had to be redundant pins.⁶ Practically, this meant that each side of a Second Generation *Triangle*, needed at least seven pins.

Triangles Applications

As a physical interface that relies on a desktop computer for output, the *Triangles* are an excellent example of the positives and negatives of creating controllers. Because the *Triangles* are physically free

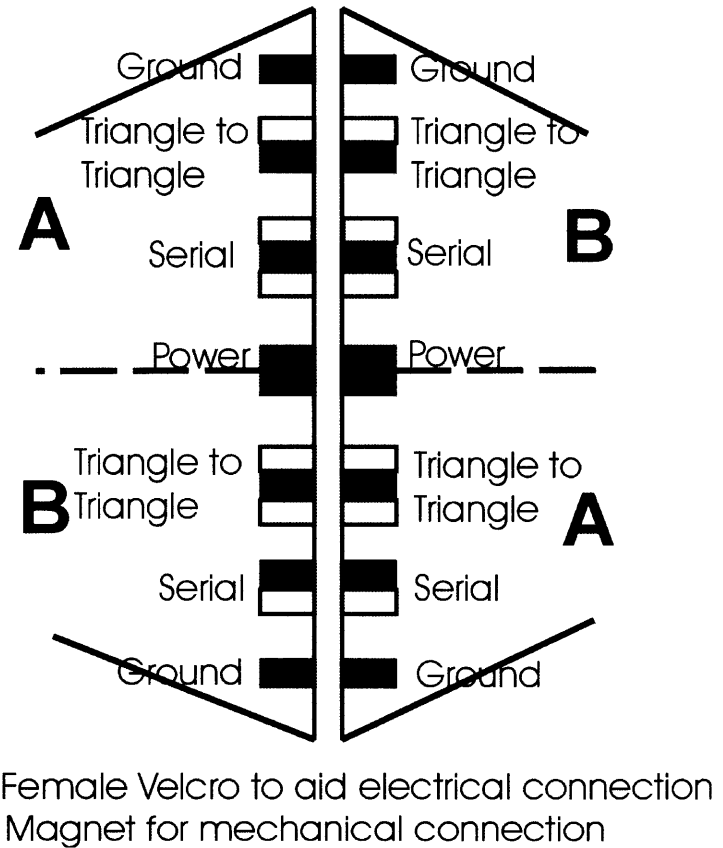


Figure 8.10 Diagram of second generation connectors. Symmetry means that connector half A must meet half B, so redundancy of pins is required. Seven total pins are used.

⁶Gorbet, M., Orth, M. and Ishii, H., *Triangles: Tangible Interface for Manipulation and Exploration of Digital Information Topography*, Proceedings of Conference on Human Factors in Computing Systems, (CHI 1998), Los Angeles, ACM Press, (1998) pp. 49-56.

from any visual or audio display device, they are light and have little power requirements. Relying on a PC to create content also allows for experimentation with applications and their relationship to the physical form to the *Triangles*. But being physically separated from their output media also presents many drawbacks when designing applications for the *Triangles*. In general, these drawbacks revolve around the split between the physical objects themselves and their output media, especially screen-based images.

Triangles software includes both a C++ API* and content applications that were written on top of this API. The API is documented and available on the *Triangles* CD. The higher-level content applications were written in Visual Basic, HTML and C++. The applications I created for the *Triangles* include *Galapagos** (a simple non-linear, web-based, children's story, *Cinderella 2000*, (a feminist retelling of Cinderella), *Toy Search*, and the *Digital Veil* for Ars Electronica*.

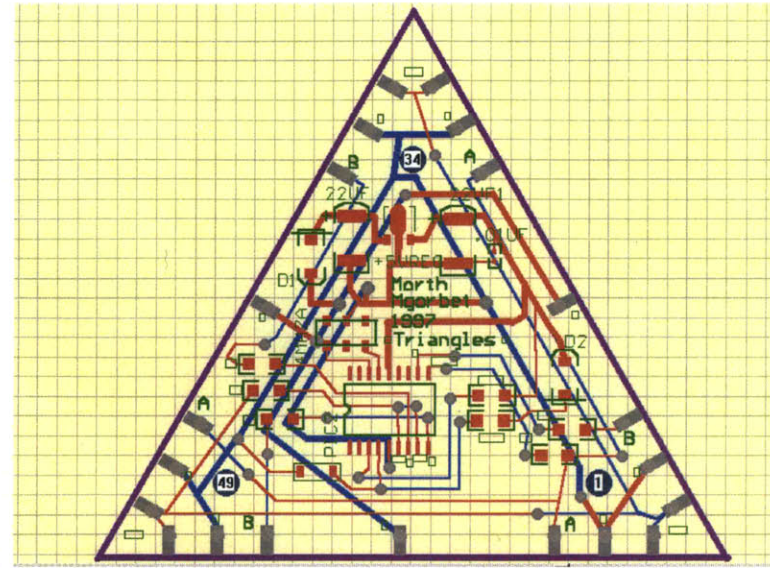


Figure 8.11 Circuit diagram of generation 1.

* Matt Gorbet.

* In collaboration with Matt Gorbet.

* In collaboration with Matt Gorbet.

Galapagos: An Interactive Web-based Narrative*

Galapagos (1997) was an interactive web-based, storytelling program that let players connect two halves of characters (like the turtles and blue-footed boobies), or places (like beaches and rocks), to guide a story. When two halves of a character or place were connected, web pages containing the appropriate animated content of the story appeared on the computer screen. The result was a non-linear narrative told partially by a puzzle-like arrangement of physical tiles, and partially by animated images and text on a computer screen. The design of the characters on the *Triangles* reflected this simple branching story. The first *Triangle* was always a turtle half. Once the other half was connected, the player then had two choices; go to the beach or the sea. After choosing either the beach or the sea, the player then had another set of choices: meet a booby or another turtle. If the player met another turtle, they would eventually have eggs and babies. In this application, the design of the images on the *Triangles* made only certain connections valid (for instance egg to egg is valid, but not egg to turtle), limiting the possible valid connections and therefore the content that had to be created. In other, words, nothing happened if you connected an egg to a turtle half, so we did not need to create a story page for it.

A major problem with *Galapagos* was the separation of its media or dynamic output, which was in the form of the animated images on the computer screen, from the

* In collaboration with Matt Gorbet.

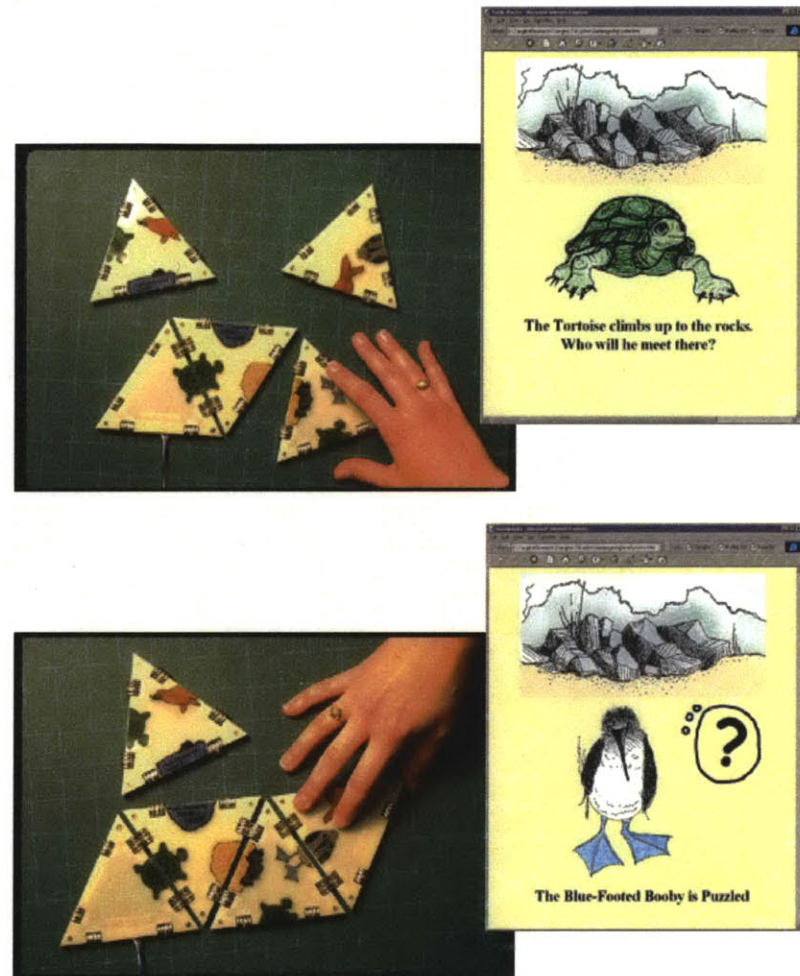


Figure 8.12 Connections of *Triangles* and the websites they called in *Galapagos*. This sequence starts by connecting the turtle, and then the beach, taking the turtle to the beach. Finally, the player chose to meet a bobby rather than another turtle, by connecting the two-halves of the booby. Drawings by Maggie Orth.

physical *Triangles* themselves. Because the storytelling output was entirely visual, the player was *required* to split his or her visual focus between looking up at the images and text on the computer screen, or down at the *Triangles* on the table. Children who played with the application were so busy looking at the *Triangles* in their hands, that they often did not look up to see what happened on the screen when the *Triangles* were connected. This issue was addressed in the next storytelling application that was created, the purely audio comic book, *Cinderella 2000*.



Figure 8.13 *Galapagos* characters and places. Connecting two halves of a character or place would call a new website in the story. (Note: these images are not in the order of the final application.)

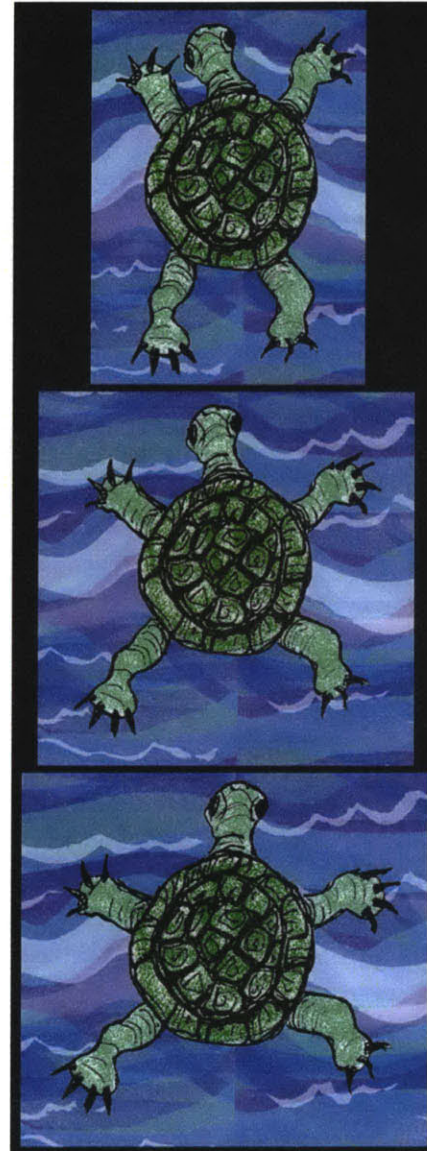
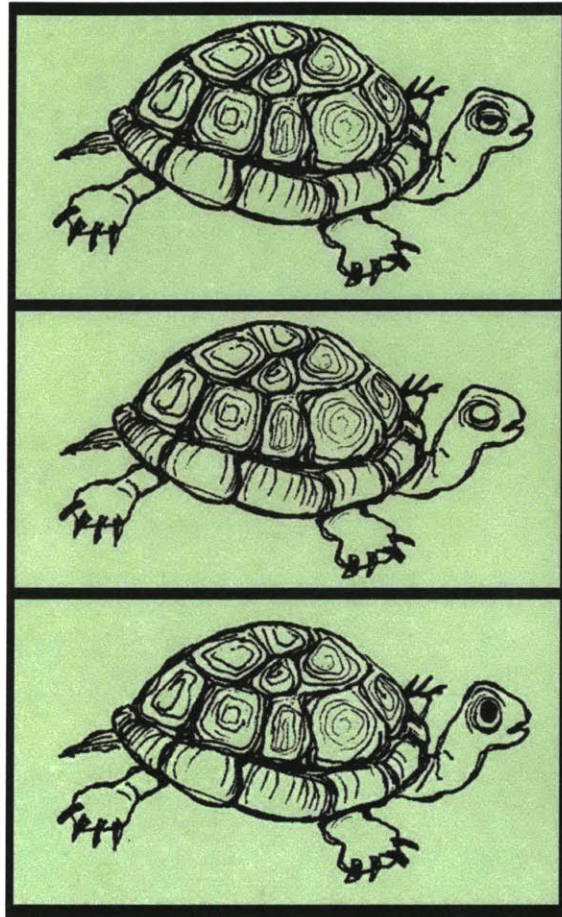


Figure 8.14 Two typical animation sequences from *Galapagos*. Drawings and animations by Maggie Orth.

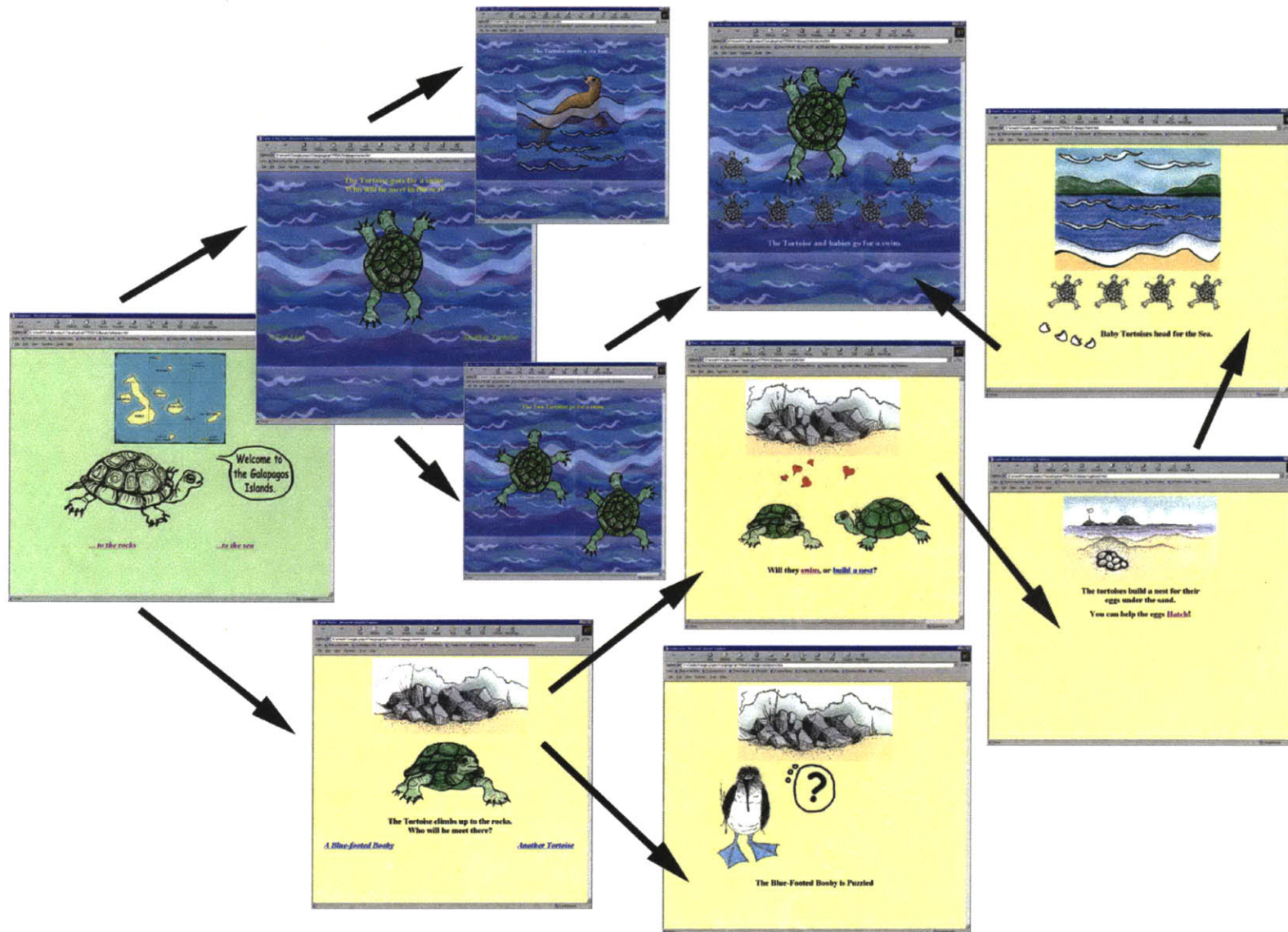


Figure 8.15 Animated websites and narrative structure from *Galapagos*. Drawings, animations and story by Maggie Orth.

Cinderella 2000: An Audio Comic Book

Cinderella 2000 (1998) is an audio comic book that presents a modern version of the Cinderella fairy tale. In this version, players use the *Triangles* to reveal a feminist subtext behind the typical Cinderella story. At first Cinderella appears to be a sweet, hardworking and exploited girl. But exploration with *Triangles* reveals that she is a shallow young woman who has become obsessed with her own personal beauty and is using it to avoid her responsibilities, schooling, and chores. Her stepmother is at first, stereotypically, presented as a tyrant, but further exploration reveals her as just another working mom, trying hard to hold it all together. Other characters in the story include the stepsisters and the house in which they all live.

By arranging the comic book-like images of *Cinderella 2000*, players trigger audio samples stored on a desktop computer, and create a medley of sound effects, narration and dialogue between the characters. Using audio for the output of the *Triangles* avoided the split-focus experienced with *Galapagos* because players could both look at the *Triangles* and hear immediate reactions to any connection of *Triangles* that they might make. In this audio application, players were comfortable with the physical separation of the *Triangles* from the sound source.

One constant issue that came up in discussions about the *Triangles* was the fact that there were no dynamic displays on the *Triangles* themselves. This application was designed to demonstrate how to visually tell an

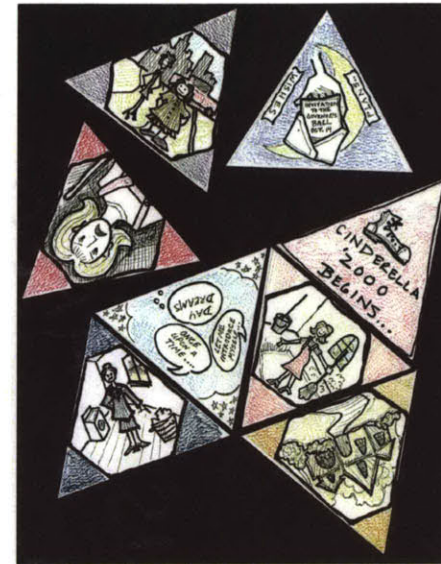


Figure 8.16 Cinderella 2000's triangular comic pieces. Drawings, story and software by Maggie Orth.



Figure 8.17 Linear comic strip sketches, by Maggie Orth.

interactive and dynamic story with a progression of static images. For reference material, I turned the world of narrative painting, hieroglyphics and comic books.¹ After all, these traditions have been telling stories through a progression static images, for hundreds of years. Specifically, the images used in *Cinderella 2000* rely on the techniques and visual language of comics, including framing, action close-ups, text bubbles and scene setting devices.

In *Cinderella 2000*, *Triangles* can have different degrees of resolution within the computer. For instance, some *Triangles* are **Whole Triangles** and some are **Three-sided Triangles**. When using a **Whole Triangles** it does not matter what side is connected; for instance, the software simply sees the Sweeping Cinderella *Triangle* as Sweeping Cinderella, no matter what side she is connected on. When using a **Three-sided Triangle**, the specific side that is connected makes a difference. For instance the *Text Bubble Triangle* has a different text box on each side. Depending on which text box is attached, the characters say different things. *Cinderella 2000* also has three types of *Triangles*: **Character Triangles**, **Event Triangles**, and **Information Triangles**, or *Text Bubble Triangles*. Each type of *Triangle* has a different function in the telling of the story.

Character Triangles

Typically, each **Character Triangle** was a **Whole Triangle** that had both a general background sound,

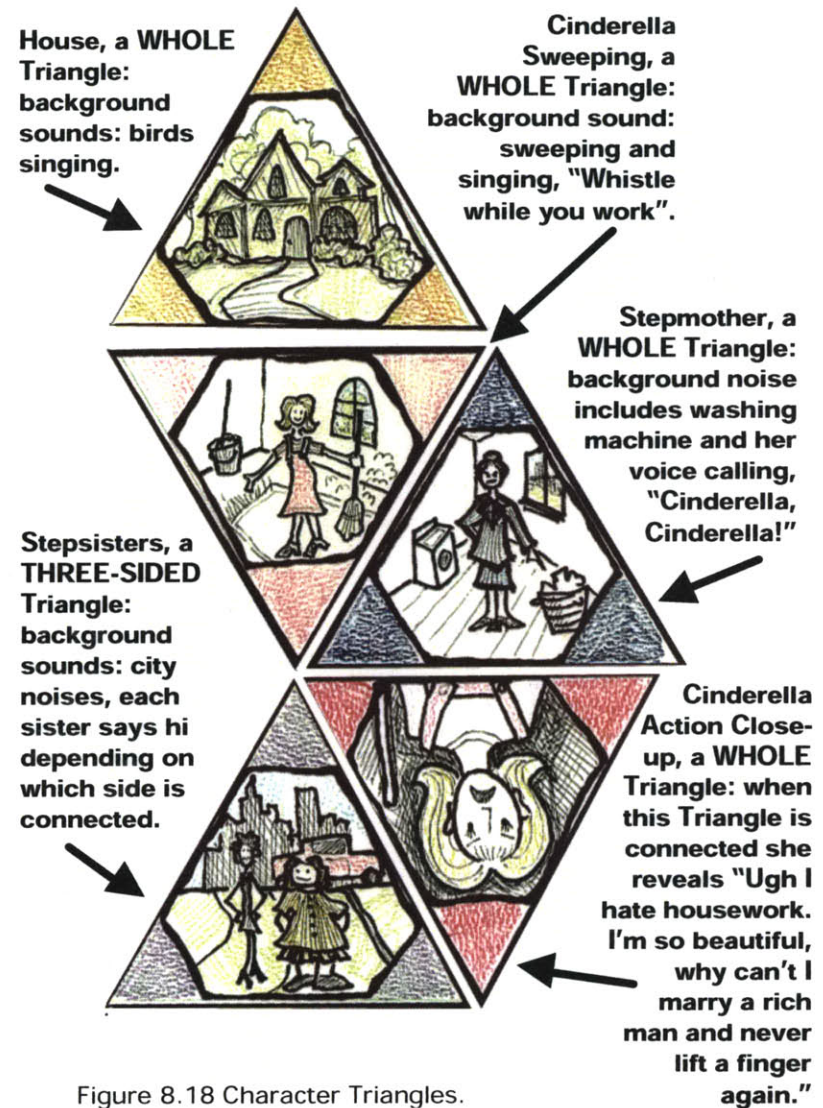


Figure 8.18 Character Triangles.

¹ McCloud, Scott, *Understanding Comics*, Kitchen Sink Press, (1994).

which was always played while it was connected (letting the player know it was attached), and specific sounds that it made in relation to specific connections. For instance, when the House was connected, a whistling, bird-like sound played. When Sweeping Cinderella was connected the sound of a broom could be heard in the background. In addition to these background sounds, there were sounds and dialogue for specific connections. If the stepmother was connected before Cinderella, she would call for Cinderella over and over: "Cinderella, Cinderella". When Cinderella was then connected, the stepmother would say, Cinderella, there you are. I want you to do this laundry!"

Text Bubble or **Information** Triangles

The **Information Triangle** is a **Three-sided Triangle** that allowed characters to convey hidden or secret information, revealing the subtext of the story. The three text bubbles on this *Triangle* said: "Once upon a time", "Let me introduce myself", and "Day Dreams". If the "Once upon a time" side of the **Text Bubble Triangle** was connected to a character, you would hear the some sort of history told from that character's point of view. If the "Let me introduce myself" side of the **Text Bubble Triangle** was attached, you would hear the character introduce themselves "publicly", conveying information they would *want* you to know. The "Day Dreams" side revealed each character's deepest and darkest secrets, what they truly wished for and hoped for, and what they might not want you to know. In this way, the **Text Bubble Triangle** was an

Information or Text Bubble Triangle
Each Character Triangle had a
different reaction when connected to
each side.

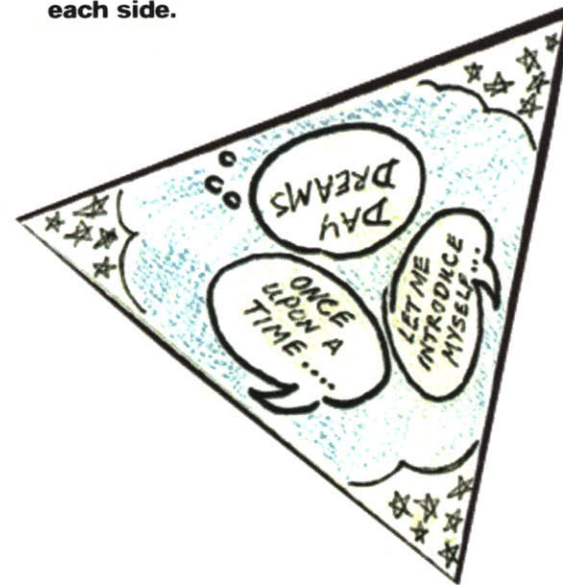


Figure 8.19 Text Bubble or Information Triangle.

interesting mechanism for exploring point of view in the story.

Event Triangles

Event Triangles were used to symbolize specific events in the story, for example the arrival of the invitation to the ball. Once an **Event Triangle** was connected, the behavior of the characters in the story would advance. This enabled connections between characters to have different behaviors at different points in the story. For instance, once the invitation for the ball arrived, the characters stopped their introductory behavior and began to prepare for the ball. Each character now had a whole new set of character-to-character interactions and of course daydreams and introductions to make, etc. **Event Triangles** were very important because they gave players room for exploration in the initial phase. If each connection of a *Triangle* had been time related, or automatically advanced the story, it would have been possible for a player to miss a lot of information about characters. **Event Triangles** allowed the connections to always mean the same thing in the first round of the story, leaving players were free to explore the characters and their secret thoughts before advancing the story.

Narrative Conclusions

The implementation of *Galapagos* and *Cinderella 2000* made it clear that creating unique content for the astonishing number of configurations possible with the *Triangles* was a daunting task. *Galapagos* and *Cinderella 2000* applications used no more than seven *Triangles*. Because the possible number of unique

Event Triangles advance the story. Once an Event Triangle is attached, each character takes on a new set of behaviors and reactions.



Figure 8.20 Event Triangle.

combinations of *Triangles* is factorial, the seven *Triangles* in *Cinderella 2000* were capable of creating millions of unique combinations. Unlike music, storytelling could not dynamically create new content for every possible combination of *Triangles*. To avoid the daunting task of hard-coding a unique response for every possible combination of *Triangles*, the images on the *Triangles* were designed to either limit the number of 'appropriate' connections that could be made, or reduce each *Triangle* to a **Whole Triangle** rather than a **Three-sided** one. In *Galapagos*, the halved characters suggested which connections would be appropriate: one half of the frog should connect to the other. If a frog was connected to an egg nothing happened. Still, interaction issues arose around what would happen if 'incorrect' connections were made. Connecting half of a turtle to half of a bird might seem reasonable in a fantasy story about mythical animals. In *Cinderella 2000*, only a few of the *Triangles* are **Three-sided**, reducing the possible number of combinations. For instance the *Triangle* with the Cinderella character meant the same thing no matter how she was attached. But creating a new piece of dialogue for every connection in this story was daunting, and some connections just repeated old information.

The next two applications use other means to create the huge amount of content required for numerous *Triangles*. One application relies on the web to create content, through a web search engine. The other application lets audience members record their own messages into unique combinations of *Triangles*.

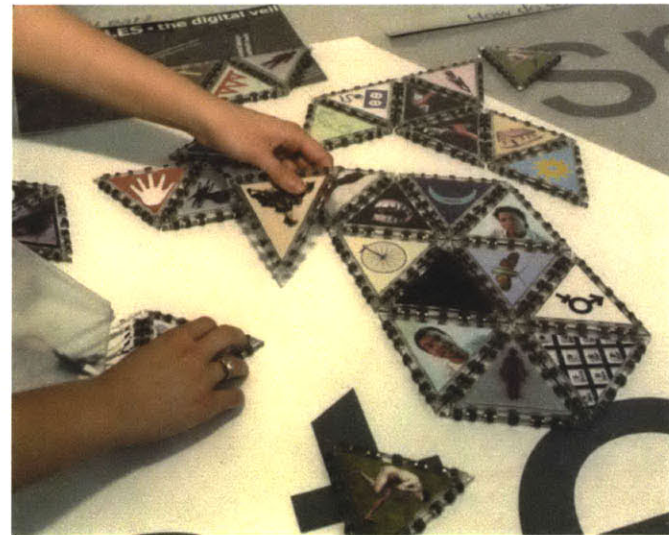
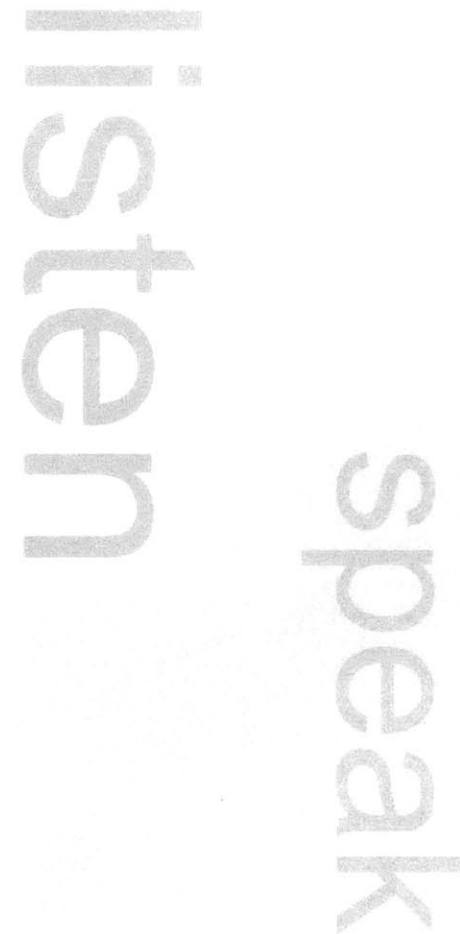


Figure 8.21 *Digital Veil* at Ars Electronica, 1997.

each individual *Triangle* that they add, triggers a pre-programmed audio sample, building an aural texture to accompany the configuration. If the player arranges any of the tiles to form one of the 'phrases' that had been recorded by a previous participant, that audio recording is also played back. In this way, the piece grows and changes over the course of its presentation, keeping a memory of the meanings and associations that players have created. One of my favorite combinations was of "a woman, water (image not shown), and the telephone". The player associated this group with Laurie Anderson's famous line, "Hello, its your mother."

While this piece did solve the problem of creating content for the innumerable combinations of *Triangles* possible, it had a number of limitations. People often had nothing to say, even with the list of questions we provided. The huge audio texture was also often difficult to associate with a specific shape or arrangement of *Triangles*. Moreover, with thirty-five *Triangles*, it was highly unlikely that people would accidentally find the combinations that other players had recorded into. (We had to discard side information early on, and only work with whole *Triangle* information. Eventually, we also went from having people pick three *Triangles* to just two.) Surprisingly, the *Triangles* became a great place to hide secret messages. People would record a message and then tell their friends what *Triangles* to put together to hear the message.



listen
speak

Figure 8.23 Design of tabletop graphics for *Digital Veil*. Graphics by Maggie Orth.

Working Notes on Images, Sounds and Associations

Male Expression	Word reaction: Yippie, Mumble Sound effect: Notes: This is like a close up where people express things, reactions, words, etc. However, using a verbal response may the frame the meaning or emotion too much.
Female Expression	Word Reaction: Sound Effects: Notes: Sadness concern, upset are her emotions. Obviously we have a male/female thing here, which is continued in the next few triangles. I would like to explore this binary division, by giving symbols that people may to associate with that are obviously opposites. However, in this case it may that a man might associate with Tara's emotion, more than Ben's. Maybe we could have Ben sound like a woman and Tara like a man. I don't want to limit these two pictures with something to literal.
Painted Woman	Words: Falling, spinning, turning, to rest. Sound effects: Bite an apple, crunch- crunch, a body falling in heap. Notes: I put all the people images together so you could compare them. Obviously there is a scale change and a vocabulary change. The close ups are kind of like close ups in a comic book, where you focus on a character and they speak or tell you a secret or reveal something While these figures are more archetypal. To me these are a little about our desire for paradise, for a utopia, for a time before.
Painted Man	Words: falling, looking, searching, thinking, dreaming, disorder, Sound effects: sound of person falling, wail, keening, yelling timber, tree falling, lumbering sounds, laying railroad tracks, axe. Notes: Obviously we have a male female thing here, but that might not be the focus. See the notes for painted woman but think masculinity or difference in pose
Lenticular Male Symbol/Tech Image	Words: Male, Man, Masculine, Scan, Heat, Sound effects: sound of a scanner, and MRI machine, an Ultrasound, like a hollow submarine sound, sounds from inside the body, blood flowing. Notes: Again, a male female thing here, but that might not be the focus.
Lenticular Female Symbol and Tech Image	Words: Female, Woman, Feminine, white, heat, penetrate Sound effects: sound of a scanner, and MRI machine, an Ultrasound, like a hollow submarine sound, sounds from inside the body, blood flowing. Notes: Remember, the symbol emphasizes difference, and the Tech/heat image emphasizes similarity. Sounds might do the same.
Androgyny	Words: Male, Female, Neuter, No simple opposites here... Sound Effects: People having sex? Notes: Ambiguity, no clear sex role.
Eye Blinks, Lenticular	Words: Perception, vision, sight seeing, dust, Short time, finite, Sound Effects: something startling, something fast and tinkly... Notes: This is the eye symbol, but animated, moving, awareness, knowing,
Castle	Words: Castle, fort, dream house, journey, trek, servitude, aspiration, desire, construction, protection, defense, isolation, royalty Sound effects: Dumb Renaissance music, armor clang, (these may be too literal) Bricks being laid Some and mortar being laid, the echo in a well or basement or hollow space Notes: Ed liked music for this Triangle. i think if we use music it should be very rarely. This will give it a tremendous power in the piece. I think I would like this to be more abstract. This is about dreams places, hopes for something higher for protection, for a place in this world that is fantastic and uplifted, but also about a nostalgia for a past world for fantasy spaces.
House	Words: Shelter, home, day-to-day, daily life, roof. Sound Effects: Vacuum, Wind, tornadoes, door slam, lots of clammering feet running to a door slam. Notes: This is just your daily abode, not a fantasy space.

Figure 8.24 Working notes on images, sounds and associations for the pieces in the *Digital Veil*.

Plane	Words: Glide, coast, sail, fly, flight, leaving, rising, sailing, gliding, soaring. Sound Effects: Flapping engine? Not sure on this one. Notes: A Fantastic plane for one person to fly away.
Rocket	Words: Escape, new world, voyage, blast, trip, dream, journey, adventure. Sound Effects: Take off... Rattle Notes: This is obviously less earth bound than plane. Could be many people, traveling to many places. I think it is a very fantastic ship and associate it with the search for the beyond. Just as there were spirits and mediums in the 19th century, today there are spaceships and aliens.
Wheel	Words: pedal, pushing, turning, spinning, locomotion, self-powered. Sound Effects: Old creaky bike, bike bell, chains, gears, bring. Notes: This is about one person traveling on the ground from place to place by his/her own power. It is about self-movement, and the work and pleasure it takes. It is a little nostalgic.
Car/Automobile	Words: Cruising, coasting, Driving, moving. Sound effects: Door, engine, engine start, horn, beep-beep, crash, vrmmmmm... Notes: This depends on direction of the entire work. In this case something literal might be ok if there are more abstract things elsewhere.
Hand with Tool	Words: Build, turn, transform, work, remake, manipulate. Sound effects: turning banging any hand tool noise.... Notes: This is about the manipulation of non living materials, about our ability to build and create and work.
Hand with Fish	Words: Husbandry, farming, catching, eating. Sound effects: Flapping of a fish, eating. Notes: I particularly like this triangle because I think it is about our relationship with living things and our constant use of them as resources, food and materials. It also is about our trade in them. I think of Moby Dick and how the whalers transformed whales into heating oil, buildings with their bones, peg legs, meat, clothing, just about everything you could conceive of. This is also about our domination of nature.
False Teeth	Words: Teeth, artificial, augmented, prosthetic, plastic, man-made. Sound effects: Chattering, chewing. Notes: This triangle is about man-made additions to our bodies. About things we put in our bodies that become part of ourselves. So while the tool Triangle is about extending ourselves externally with things we can choose to use, this is about permanent, internal changes that technology or the artificial can make!
Keypad	Words: Type, add, phone, call, contact, communicate, reach. Sound effects: button presses, clackity-clack. Notes: This one is supposed to be more than just a phone pad. It is an adding machine, computer, etc., any thing digital. It is about today's technology, our ability to communicate over long distances and get data, etc.
Keys	Words: Security, fear, lock, protection, privacy, control. Sound effects: Key jangle. Lock turning. Notes: The keys are a tool for control safety fear, protection and privacy. Maybe something literal is ok for these.
Lenticular Water	Words: Water, river, sea, pond lake, contemplate, blur, stare. Sound Effects: Water. Notes: This is an animated version of a standard water symbol... It should stand for all images of water.

Moth	Words: Moth, fly, dark, stealth, invader. Sound Effects: a soft flapping, a bug zapper, If we use a bug zapper it may be about destruction Notes: This is a little about things we cannot control so easily, things that are small and capable of disturbing us, refocussing our attention
Torn	Words: Rip, tear, not, no, negative, rend. Sound Effects: Rip, break, crack. Notes: This is supposed to be our negative Triangle. This means "is not", or "is separate from", or "does not equal".
Open Hand	Words: hello, stop, greetings, give, aid, help, Sound Effects: clap, the sound of one hand clapping, punch. Notes: We wanted this symbol to be able to represent the many gestures people make with their hands.
Shelter/Arrow	Words: Shelter, direction, place, way, path, arrive. Sound Effects: roofers, walking on a path. Notes: We hope that this can function as an abstract shelter and an arrow. I think it is more likely to be a shelter. It is a little like the drawn house, but more symbolic, able to span more places and times.
Electricity	Words: Power, electric power, energy, light. Sound Effects: Electric crackle, buzz, radio noise? Notes: This is about modern power, not hand power or human power, and using external energy, light.
Moon, crescent	Words: Moon, crescent, mountain, hill, bridge. Sound Effects: Perhaps a song? Maybe a few pieces could have a piece of music attached. The symbols seem most appropriate for this. Notes: This one is much more about nature or elemnts of nature than most other images.
Sun/Saw	Words: Circular saw, gear, sun. Sound Effects: Gears, saw, grinding, kind of that slow mechanical/insect buzz that a blinding hot day can have. Notes: This is another on that is purposely ambiguous. I think i would like to try and capture that in the sound.
Tap/Plumbing	Words: Circular saw, gear, sun. Sound Effects: Gears, saw, grinding, kind of that slow mechanical/insect buzz that a blinding hot day can have. Notes: This is another one that is purposely ambiguous. I think I would like to try and capture that in the sound.
Bulls Eye	Words: Target, Bulls eye, aim, breast, eye, Oh, goal. Sound Effects: Thunk, an arrow hitting a target, OHHHH, Notes: This one is a goal, something practiced, something seen, something squinted at something examined,
Tree/Tooth	Words: Wooded Area, forest trees, mountains, Teepees, Teeth, Sharp, Danger, cut, bite, cold front, weather, clouds. Sound Effects: Nashing, Thrashing, Mountains? Notes: We particularly liked the multiple meanings in this one. We have a few images of the lanscape that are varying degrees of abstractness.
Hand through ice, Lenticular	Words: Hazard, warning, alert, caution, drowning, help. Sound Effects: crack, very fast water, alarm, siren, warning. Notes: This symbol means caution warning, error, help, alert, falling. I don't think we want to define it too much, though the alarm like sound is appealing
Fur	Words: Animal, warmth, creature. Sound Effects: purr, growl. Notes: A fur Triangle, I don't want to limit this one because the fur is great for everything from being unshaven to a warm coat, it is very evocative of many meanings.
Miniature Landscape	Words: Park, Garden, Land, forest, fields, outdoors, space. Sound Effects: wind, rustle of leaves. Notes: I little model of a landscape built on a Triangle, very magical, with a path or river running through it.

ultimately they only began to suggest ways that a sort of computational clay might interact with software. One major reason for this is that it is simply still unclear what to do artistically with ALL the information that this kind of system provides. In fact, many of the *Triangles* applications did not make use of information about which side was connected to which, or about the shape of the overall system. There is still much room left for experimentation with physical system like the *Triangles*.

Chapter 9.

Early Smart Textiles Projects: Electronic Fashions

Why Textiles?

My interest in smart textiles as a sculptural and active computing material was fueled by two very different fields of research: Wearables and Tod Machover's Hyperinstruments. After my early work in the *Brain Opera*, I desperately wanted a sensor skin that could be wrapped around a sculptural object to create a multi-channel, pressure-sensitive, musical instrument. At the same time, the Wearable Fashion Show (October, 1997) was happening at the Media Lab. While I was not particularly interested in the existing paradigm of strapping a PC to your body, I was fascinated by the idea of making clothes compute. Smart and electrically active textiles presented themselves as a solution to both problems. I was already interested in using textiles because of their

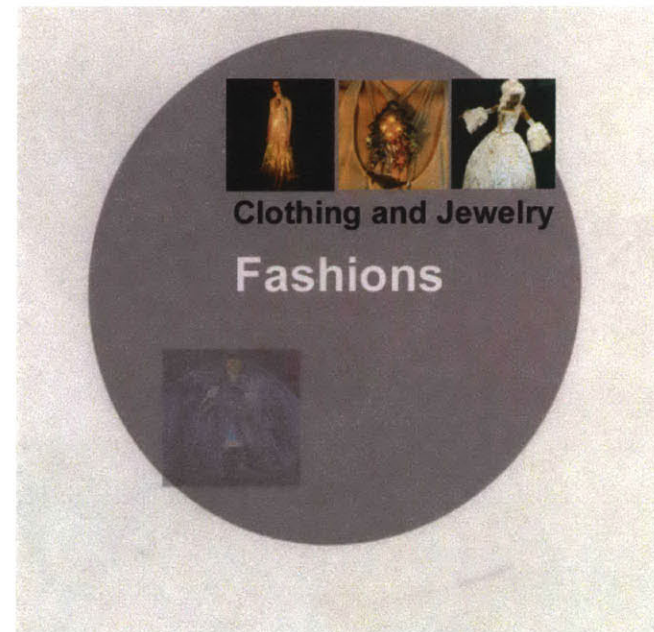


Figure 9.1 Early fashion projects in the Tree of Projects.

excellent design properties. Fabric is highly sculptable and immediate. It can be easily cut, shaped and sewn into many shapes. It can be dyed or printed on, and comes in many colors, textures and weights. Its woven structure makes it extremely flexible and strong when bent or stretched. Finally, textiles are the exact opposite of most computing materials: they are soft, flexible and intimate, and encourage people to touch them. As the material antithesis of most computers, textiles provided a direct way to radically change the meaning of computers through their tactile and materials properties. I also hoped that smart and electrically active textiles would provide a way to change and explore an active relationship between physical form and computation.

The smart textile projects presented in this thesis also represent a journey from the making of labor intensive, one-of-a-kind items, to limited series, mass production. The first smart textile projects, like the *Firefly Dress*, were labor intensive, one-of-a-kind items. Later projects, like the *Musical Jacket*, attempted to use manufacturing processes and designs that could be easily reproduced with a minimum of handwork, and that were easily implemented by textile labor untrained in electronics. Reproduction meant that these projects had to dummy proof, able to be made using the standard processes for manufacturing any stuffed item, like a teddy bear. Because textiles are an excellent material for creating a limited-series of multiple items, they made an enormous amount of sense for both demo-making and interactive projects. Replicating textile items does not require the cost of an expensive tool, as the injection molding of plastic does. And

provided that the design of a textile object is done with the manufacturing process in mind, that object can be relatively easily replicated with a pattern. This is an ideal process for creating a limited number of multiple objects, in the 10-100 range. Mechanically, textiles are highly durable, perfect for the touching necessary for interactive installations, and the ability to easily reproduce textile objects also means that broken parts can be easily replaced.

Because the smart textile works presented in this thesis were motivated by different research agendas, they span a range of functions, from musical instruments, to electronic tablecloths, to purely visual fashions. And while they may seem to be functionally unrelated, artistically they are not. All the smart textile projects presented in this thesis are explorations of how sculptural and electrically active computing materials can truly change the aesthetic experience of computers and enable artists and designers to better communicate. They also all represent an investigation into *functional ornament*¹. In all of these works, the smart fabrics are used both as functional circuit elements and as ornament. Early projects show a limited relationship between the design and sensing/electrical properties of the ornament. In later projects, that relationship becomes intimately intertwined. The design of the embroidered pressure sensors in the *Embroidered Musical Instruments* is both the result of aesthetic choices and their sensing and electrical needs.

¹ A further investigation of *functional ornament* can be seen in Chapter 2.

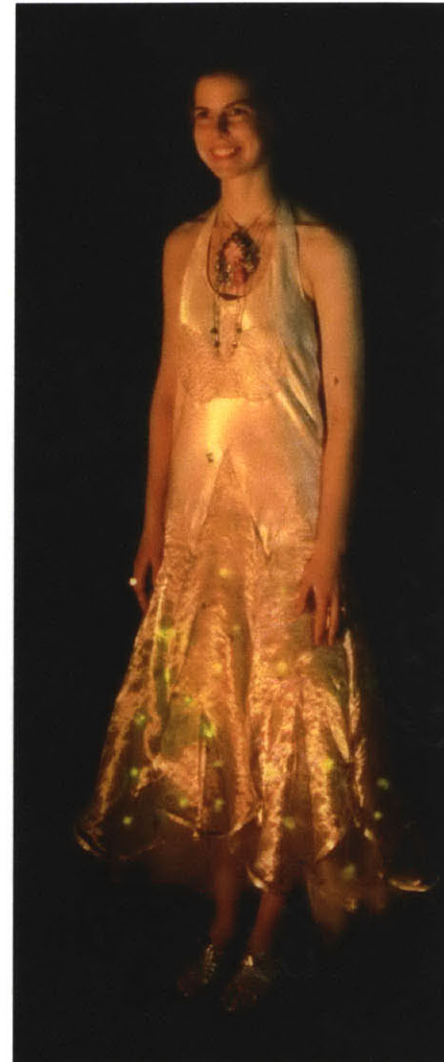


Figure 9.2 Emily Cooper, wearing the *Firefly Dress and Necklace*.

The Electronic Fashions

These electronic fashions² were created exclusively for the MIT Media Lab's 1997, Wearable Fashion Show, in collaboration with designers from different fashion academies around the world.

I began to think about using conductive fabric or computing fabric when Thad Starner presented me with Wearable Computers. They were so hard, and their cables so bulky and fragile, that I thought that there had to be a better way to do it. My first demonstration of an electrically active textile was a sample of fabric from my wedding dress (metallic silk organza³), with a flashing LED magically suspended in it. I tested the conductivity of this fabric on a lark, and found that it was highly conductive. It was also anisotropically conductive (conductive in one direction). In metallic silk organza, conductive threads or yarns run only in one direction, on the weft of the fabric. They are also well spaced, so that each yarn can be individually addressed, like a single wire in a ribbon cable. This meant that it was possible to have both ground and power, or a circuit in a single piece of fabric. The idea of having a circuit in a single piece of fabric fueled much of the smart and electrically active textile works to follow.

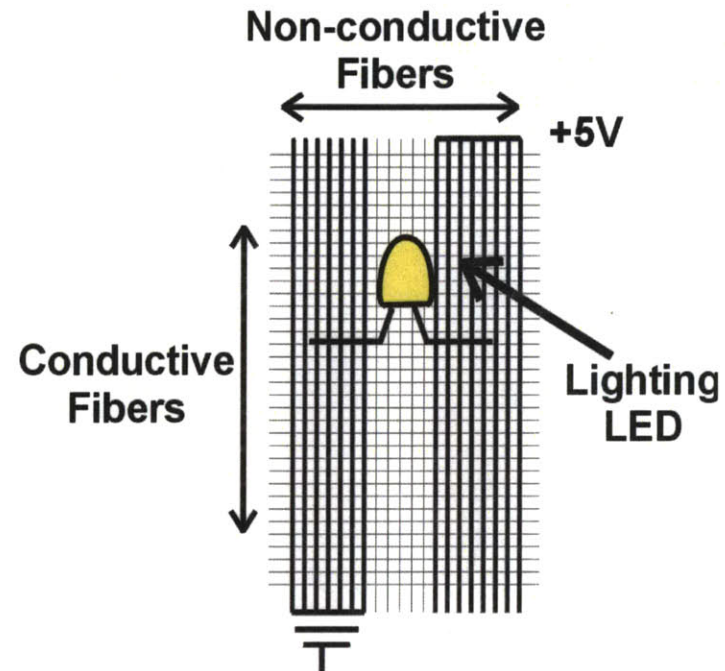


Figure 9.3 Diagram of my first demo of a fabric circuit, with a lighting LED suspended in anisotropically conducting metallic silk organza, 1997.

² Descriptions of projects in this chapter refer to: Orth, M., Post, R., and Cooper, E. B., *Fabric Computing Interfaces*, (short paper), *Proceedings of Conference on Human Factors in Computing Systems*, (CHI '98), Los Angeles, ACM Press, (1998).

³ See the Chapter 15, the Materials Index.

The threads that make metallic silk organza conductive, are silk fibers wrapped with a metal foil, or what is called a gimped yarn. All of the fashions featured in this chapter use either the metallic silk organza, or the gimped yarn from which it is made, as electrically active elements. These metal wrapped yarns are centuries old and have been couched (tacked down), or woven into many decorative fabrics, like saris, in many cultures, for centuries. The fashions in this chapter turn these electrically active textiles into *smart* materials by using them for housing or design materials, (the fabric of the clothes), sensors, resistors, capacitors, antennae, and wires. These fashions also contain carefully disguised central circuitry or power supplies. Careful placement and design of these necessary “hard” parts, helped keep these fashions soft and flexible. Because all of these fashions display dynamic feedback visually, they must incorporate visual displays or lights, which are usually tactilely hard. Unfortunately, these hard and fragile display elements ultimately limited the flowing and soft quality of these fashions, as well as their practicality.

Firefly Dress and Necklace*

The *Firefly Dress and Necklace* combines lights, simple on/off switch sensing, and sewn circuits into a dress with a level of detail and romance rarely associated with computing technology. While neither the necklace nor the dress *compute*, they still provide an exploration of the design advantages of making smart textiles function as a sensor, display substrate,

* In collaboration with Emily Cooper and Derek Lockwood.

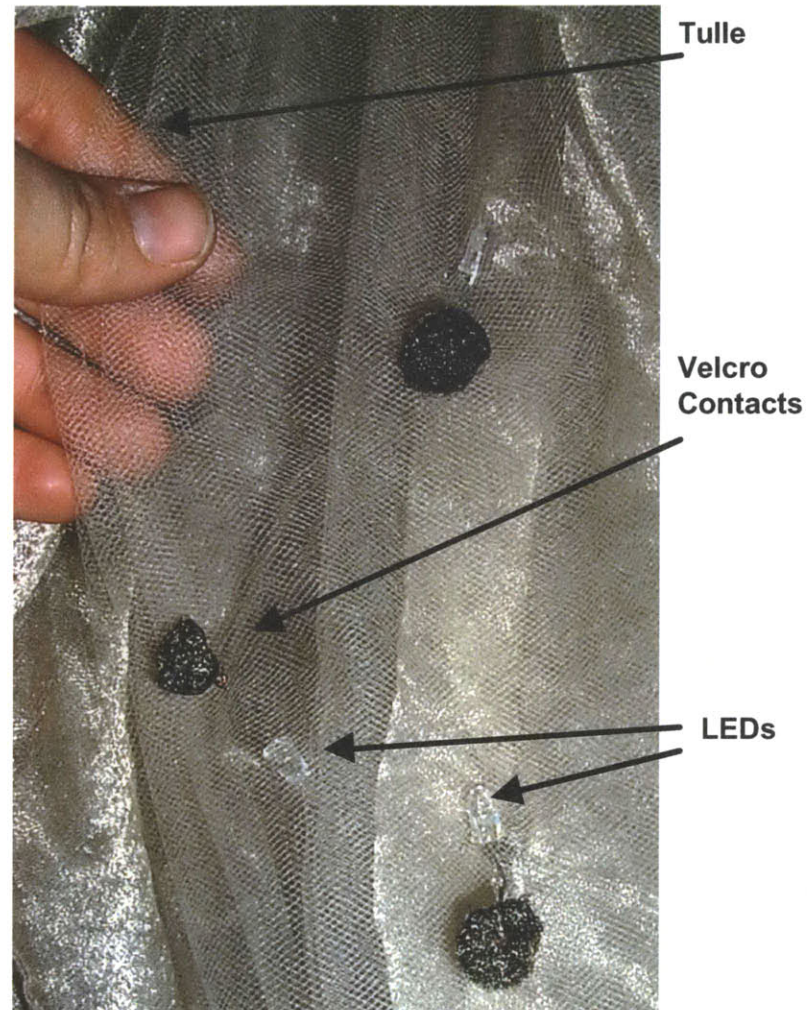


Figure 9.4 Detail of *Firefly Dress* skirt, with LED's suspended on tulle, and conductive, female Velcro brushes on their ends.

and design or housing material. The *Firefly Dress and Necklace* are also an exploration of how an electronic object can simply, visually, and expressively reflect the motion or state of its wearer. Both are a surprisingly beautiful reflection of its wearer's motion.

In the piecework *Firefly Dress*, the conductive metallic silk organza acts as a sensor, a display medium, a medium for electrical transport, and the physical material of the dress itself. Fabric traces sewn from the metallic silk organza distribute power and ground from a battery pack hidden under the dress to the outer skirt and bodice of the dress. The skirt is built from two layers of conductive fabric that form a power and ground plane, which are separated by a layer of insulating tulle. Suspended on the tulle between the fabric power and ground planes are LED's whose ends are attached to fuzzy brushes made from conductive, female Velcro. As the wearer moves, the fuzzy conductive ends of the LEDs brush against the fabric power and ground layers. This intermittent contact with the fabric power and ground plane completes the circuit, and causes the LEDs to light, simply reflecting the wearer's movement.

The *Firefly Necklace* uses multi-colored LED's to convey the motion of its wearer. The necklace has no power supply of its own. It is connected to the ground with a snap at the back of the neck, and connects to power when its conductive tassels brush against a fabric power panel sewn on the front of the dress. The flexible conductive tassels are made from metallic wrapped thread and conductive beads. As different tassels brush against the power plane, they feed

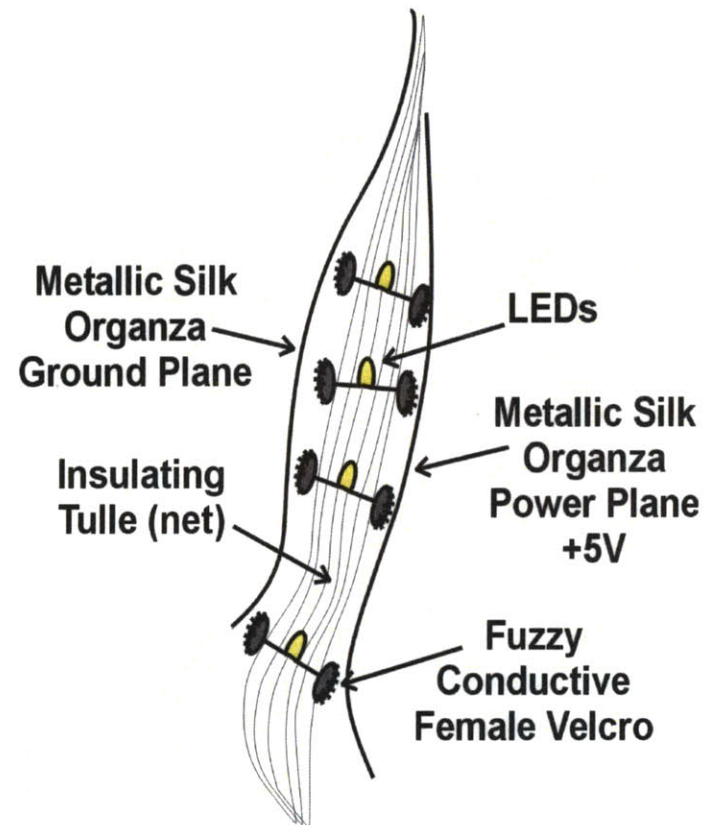


Figure 9.5 Electrical diagram of the skirt in the *Firefly Dress*.

current into different resistors and then into multicolored LED's. Because each tassel controls the current contribution necessary to create a specific color in the LED, the brushing of different tassels against the power plane causes the LEDs to rapidly change color.

This dress represents hours of labor on the part of many people. Creating durable fabric circuits, avoiding short circuits, and integrating fragile LED's into the dress was painstaking beyond belief. And while the resulting dress is very beautiful, it is not practical. You simply cannot sit down it, because the LEDs are hard and break. In this sense this dress is really a piece of haut couture, a one of a kind item that cannot be reproduced, and is not practical to wear.

material references: conductive Velcro, metallic silk organza and metallic wrapped thread.



- Connection to ground at back of neck**
- Multicolored LEDs**
- Conductive tassels send current to LEDs**
- Fabric power plane**



Figure 9.6a, b *Firefly Necklace*, the blue tassel contributed the amount of current that made the LEDs flash blue. The red tassel did the same for red in the LED's and the green tassel did the same for green in the LEDs, creating color mixing in the multicolored LEDs.



Figure 9.7 Fashion illustration/circuit diagram of *Firefly Dress and Necklace*, Maggie Orth, 1998.

Electronic New Year's Eve Ball Gown*

Patterned after a 17th century French gown, the *Electronic New Year's Eve Ball Gown* is covered with floral hand embroidery made from the gold wrapped or gimped metallic thread. The floral embroidery acted as capacitive switches and wires to connect LEDs on the skirt to PIC microprocessors sewn into the hem of the dress. In this dress, the embroidery allowed the skirt of the dress to light up, but remain free from wires and other hard materials. By touching different metallic, embroidered, capacitive sensors sewn onto the dress, the wearer of the dress could trigger and control different light effects on the skirt. The PICs both capacitively sensed the embroidered electrodes, and controlled how the lights flashed. Each PIC circuit was individually powered with its own battery. Because the sensing was capacitive, the wearer was grounded to the circuit using an internal, fabric, power plane sewn into the waist of the dress. This demonstrated that placing a piece of metallic organza next to person skin was an excellent way to ground them for different capacitive sensing methods.

Like the *Firefly Dress* this dress was the result of the hand labor of many people. The gimped or wrapped thread used to create this dress stripped easily and had to be hand sewn with great care. Avoiding short circuits and creating electrical continuity in the dress was a painstaking process. Simply tying a not between the different threads did not create continuity. Folds in the skirt caused short circuits.

* In collaboration with Emily Cooper and the students of Bunka Institute.



Figure 9.8 *Electronic New Year's Eve Ball Gown* with electronic embroidery, LEDs and PICs in the hem of the skirt.

Like the *Firefly Dress and Necklace*, the *Ball Gown* is a relatively impractical, one of kind piece of haut couture. Unlike the *Firefly Dress and Necklace*, the *Ball Gown* uses *computation* to control and interpret the information from the sensors, making for an interesting comparison. While the *Ball Gown* allowed the user to actually turn off its lights, control the rate of flashing, and parts that flashed, it also required a lot more attention from the wearer. The *Firefly Dress* was ultimately far more visually compelling and easily “interactive” despite its lack of computation.

material references: metallic wrapped thread.

technical references: Complex Impedance Sensing.

The *Serial Suit**

The *Serial Suit* allowed its wearer to use a simple touch to send enigmatic messages on an LCD display pinned to the lapel of the suit. The serial messages were sent from processors located in the pants to a serial pin located in the jacket, through circuitry sewn from metallic silk organza. Conductive fabric sewn into the waist of both the jacket and pants made the ground connection between the two when the wearer closed the jacket. The message was transmitted from the pants to the jacket when the wearer touched a conductive button on their sleeve, to a conductive fabric panel on the pants. This allowed the wearer to choose when to pass the message on to the display. However, the wearer could not choose which message

LED suspended in electronic hand embroidery,

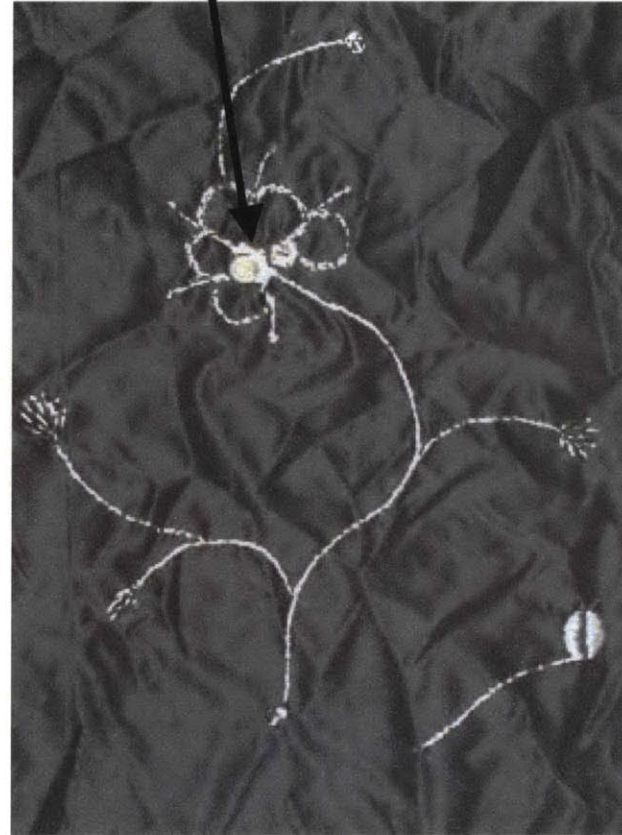


Figure 9.9 An early example of the conductive, floral embroidery, used in the *Electronic New Year's Eve Ball Gown*.

* In collaboration with Emily Cooper and Derek Lockwood.

was sent, as the processor randomly rotated through a series of messages.

This suit demonstrated the potential for distributing information around the body without hard wires and fixed electrical connections. The combination of the wearer choosing when to display a message and the computation choosing what message to display was humorous and encouraged conversation.

material references: metallic silk organza.

Fabric covered buttons to send messages from pants.

Conductive fabric in waistband grounds the jacket to the pants.

Serial pin/display



Figure 9.10 *Serial Suit* jacket.

Chapter 10.

Projects in Fabric Sensing:

Spanning Fashions, Musical Instruments and New Physical Interfaces

The ultimate goal of my early work in fabric sensing was to create a multi-channel sensor skin that I could shape into a musical instrument. These early projects, including the first row and column, *Piecework Fabric Keypad* (1997), the *Musical Jacket*, (1997) and the *Electronic Tablecloth* (1998)^{1,2}, do use fabric for multi-channel sensing on a single surface, but only allow for the sensing of “on and off”. Two different methods for

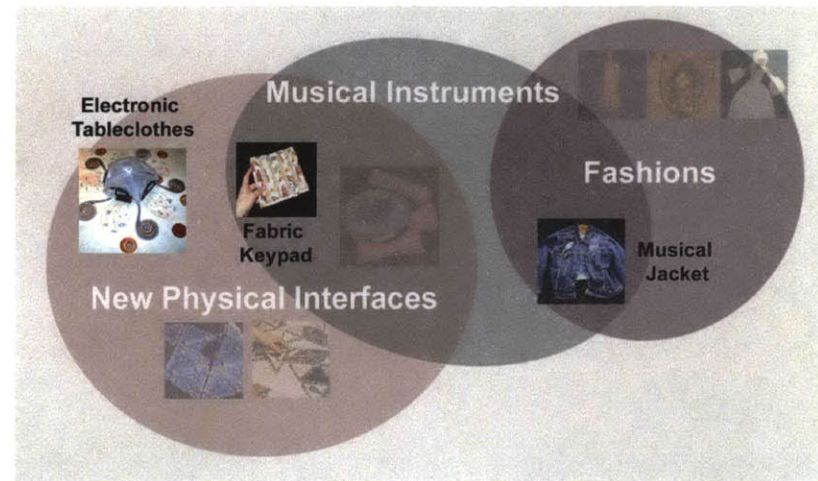


Figure 10.1 Fabric sensing projects within the Tree of Projects.

¹ Post, E.R., Orth, M., *Smart Fabric, or Washable Computing*, the Digest First IEEE International Symposium on Wearable Computers, Cambridge, MA, (1998) pp. 167-8

² Post, E.R., Orth, M., Russo, P.R., Gershenfeld, N., *E-broidery: Design and Fabrication of Textile-based Computing*, *IBM Systems Journal*, Vol. 39, Nos 3&4, Armonk, NY, IBM Corporation, (2000).

sensing on and off are used. The fabric keypad was a hand-made piecework structure that used mechanical fabric switches to sense on/off. The embroidered keypad relied on the complex impedance sensing³ of high impedance machine embroidered electrodes, which were designed in a commercial CAD environment. This manufacturing process allowed for more flexibility in the design and shape of sensors and the fabric objects that contained them. Like patchwork quilts, objects sewn with piecework usually have square edges and can only get so small. Machine embroidery allowed the sensors to be almost any shape or size, and to be sewn on a single layer. It also allowed us to easily make multiples. And though CAD-based, it was a relatively direct and immediate process. Through the CAD system, I could quickly make a design and IMMEDIATELY print it on the embroidery machine to see what it looked like and how it behaved electronically.

Ultimately, the machine embroidery system gave me the freedom to truly control the shape of sensors and electrodes. This led from more simple keypad designs, like that of in the *Musical Jacket*, to truly expressive and decorative designs like those in the *Electronic Tablecloths*. In many ways, the *Electronic Tablecloth* represents my first chance to REALLY shape electronics that to expressed both my ideas and aesthetic goals. It also represents a more advanced foray into *functional ornament*.

³ See Chapter 13, Complex Impedance Sensing.

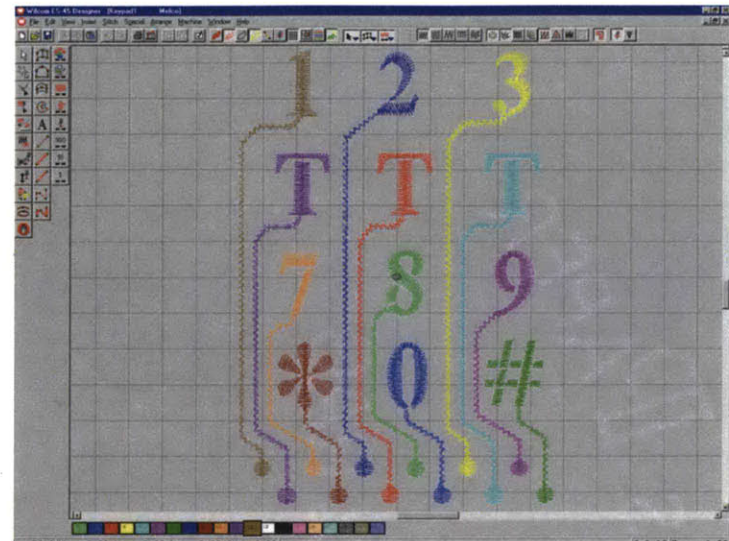


Figure 10.2 Image of *Musical Jacket* keypad in commercial embroidery CAD environment from Wilcom software.

Piecework Fabric Keypad*

This was the first addressable, multi-keyed, fabric keypad. This keypad was a row and column switch matrix made from conductive metallic organza and non-conductive cotton. This piecework keypad had sixteen switches, and was incredibly soft, flexible and durable. It could be rolled up and wadded into a ball, or just gently stroked. Each key was mapped to different note through MIDI. When squeezed or rubbed, the keypad created a simple medley of notes from a MIDI device. The physical softness, and gestural immediacy of the music made by this prototype instrument, suggested that fabric instruments had real potential for expressive and higher level musical exploration. The keypad also suggested a way to make a soft sensor skin or musical instrument.

The top and bottom layers of the keypad were sewn from alternating rows of conducting metallic organza and non-conducting cotton. The two layers were then sandwiched around a central layer of tulle or netting, which acted as the insulation and mechanical "spring" between rows and columns. When the keypad was pressed the two conductive rows and columns squeezed together and the tulle compressed. The holes in the netting let the two make electrical contact and the switch triggered. The keypad used snaps to attach to circuitry and wires.

As a layered, piecework structure this keypad was tedious to manufacture. Using piecework also required



Figure 10.3 *Piecework Fabric Keypad*, 1997 rolled up and wadded into a ball.

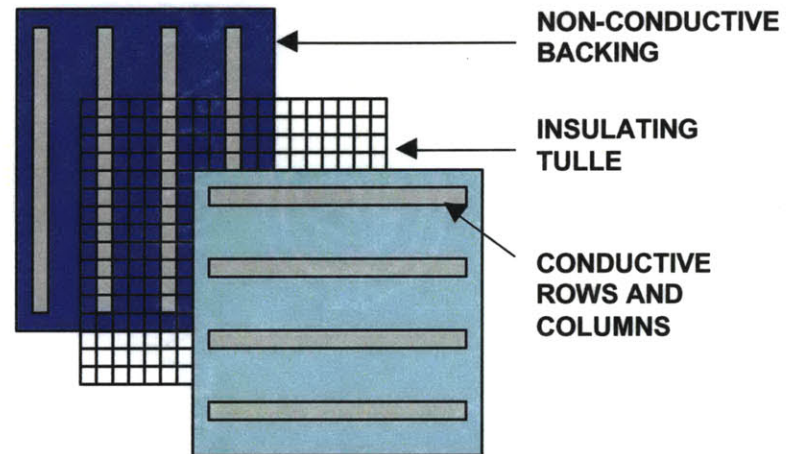


Figure 10.4 Diagram of *Piecework Fabric Keypad*.

* In collaboration with Emily Cooper.

working with linear fairly large pieces, and limiting the size and shape of the rows and columns. (This was limiting because most switch matrixes are not made with simply straight rows and columns, but with a complex geometric pattern.) Finally, because there are no non-linear fabric components (i.e. transistors or diodes), to place at the switch points, the keypad registered false positives. We were anxious to create a less labor-intensive fabrication method that allowed us to control the shape and size of the circuit elements precisely, that used a single layer to sense, and that eliminated false positives.

material references: metallic silk organza.

Musical Jacket*

The *Musical Jacket* incorporates an embroidered fabric keypad, a conductive fabric bus, a battery pack, a pair of commercial speakers, and a miniature MIDI synthesizer* into a stand-alone, wearable, musical instrument. My specific contribution to the *Musical Jacket* includes guiding the overall physical design and concept for the jacket, collaborating with Rehmi Post on the design and sewing process for the *Embroidered Keypad*, and the design and creation of the fabric busses. I also directed (if not executed) the manufacture of the fifty *Jackets*. The *Embroidered Keypad* used in the *Jacket* is sewn from a composite stainless steel thread, (the first thread we could get

* In collaboration with Rehmi Post, Emily Cooper, Josh Smith and Josh Strickon.

* MIDI synthesizer by Josh Smith and Josh Strickon.

through the needle of a sewing machine)⁴, and senses on/off through a complex impedance method. When the wearer touches any key on the keypad, a note is played or rhythm triggered. The *Embroidered Keypad* communicates through the fabric bus to the MIDI synthesizer, which generates notes. The synthesizer also sends audio to the speakers over the fabric bus. Power from the batteries is distributed over the fabric bus as well. The *Embroidered Keypad* and fabric bus eliminated the need for most of the wires, connectors and plastic inserts that would make the jacket stiff, heavy and uncomfortable. The electrically active textiles and electronic embroidery used in the *Jacket* are multifunctional and smart materials. They act as sensors, wire, electrical contact pad and the physical substrate or design material of the object.

In many ways, I think of the *Musical Jacket* as the ultimate demo. It truly captured peoples' imaginations in a way I had not envisioned, and demonstrated how computing technology could completely transform an ordinary everyday jean jacket into a fun and creative experience. People loved wearing this *Jacket*. They would put it on, play it, and laugh. The musical application developed by Josh Strickon was essential to this success. This application let wearers create music with both note-by-note control and the generation of higher-level rhythms. In its initial mode it allowed users to touch a key and play a single note. This let people experience how well the keypad worked and gave them a sense of music control. In its advanced mode, it let them initiate a computer

⁴ See Chapter 14 on sewability.

generated rhythm, speed it up, slow it down, add voices or individual notes. Because playing the *Jacket* is ultimately a public performance, having higher-level, quantized, and pre-composed rhythms accessible to the player is essential. No wants to walk around in public with a musical jacket and sound bad.

The design and placement of the *Embroidered Keypad* used in the *Musical Jacket* demonstrates how creating a demo requires making very different design choices than one might make when designing a product. The *Embroidered Keypad* is placed on the lapel of the *Musical Jacket Jacket*. This was driven not by ergonomics, but by the need to communicate a story about the potential of sewn circuitry and smart textiles. The *Embroidered Keypad* was designed to look like a circuit and standard keypad, making people imagine sewn circuits in many fabrics and also implying that this technology could become a calculator or a cell phone. The *Keypad* was placed on the lapel of the jacket for visibility, not ease of use. (Many people have asked me why it is not on the sleeve.) This location makes a great photo. You can see the *Embroidered Keypad* and the player's hand touching it. This location also unexpectedly let people play each other while looking at each other.

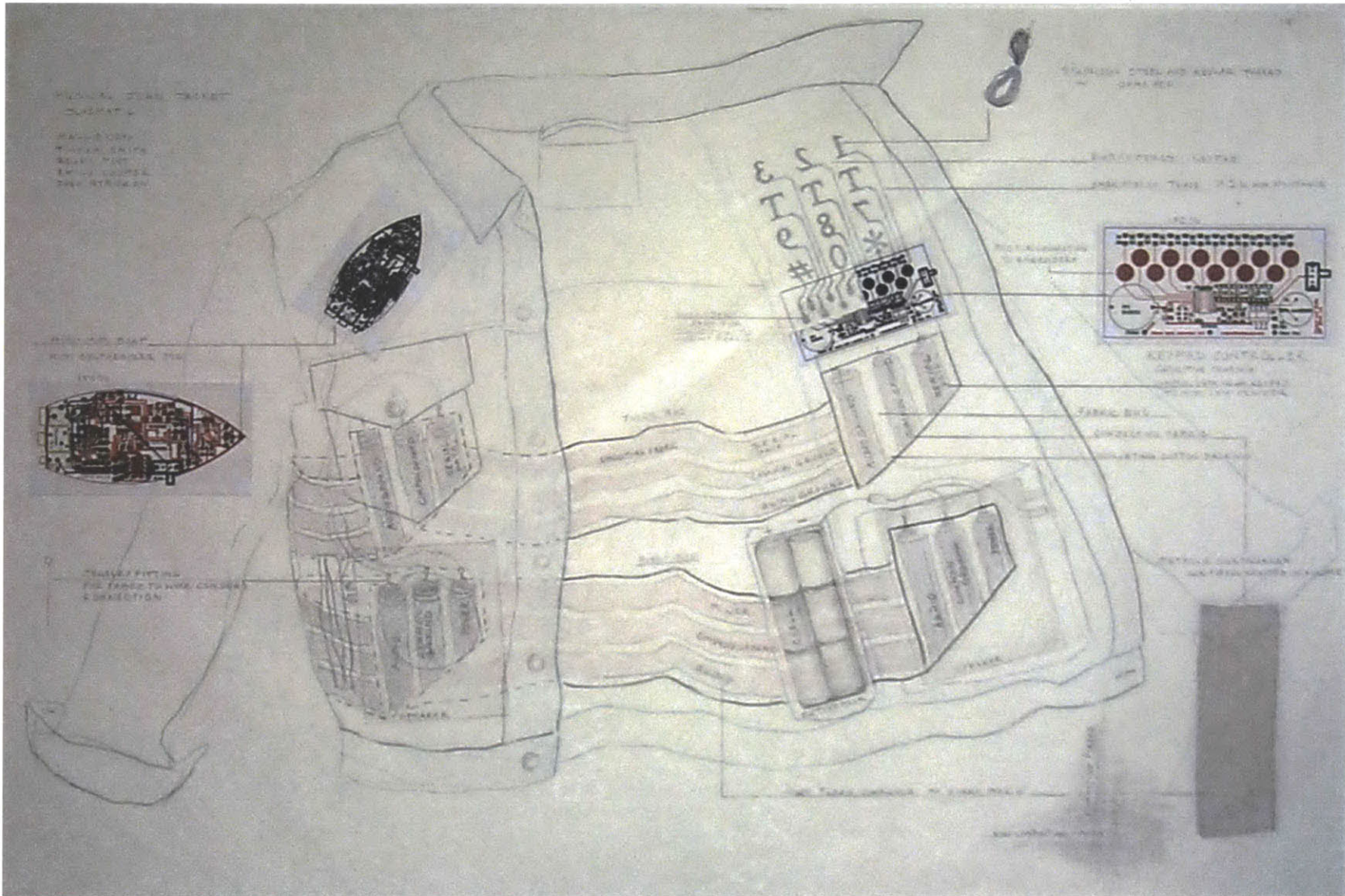


Figure 10.6 Fashion illustration/circuit diagram of the *Musical Jacket*, Maggie Orth, 1998.

Embroidered Keypad

In the *Embroidered Keypad*, each embroidered key was a high impedance electrode whose change in capacitance/complex impedance, when touched, was sensed by a microprocessor in the time domain. The embroidery process used to create the keypad overcame many of the limitations of the *Piecework Fabric Keypad*. The keypad was sewn on a single layer, designed in a CAD environment that allowed precise control of the size and shape of the electrodes, and sewn on a commercial embroidery machine with a composite polyester and stainless steel thread. Until we found this thread, we simply were unable to machine sew any conductive thread. Wrapped or gimped threads (like those used in the metallic silk organza and the fashions in Chapter 9) always stripped under the mechanical stresses of sewing. 100% stainless steel threads bunched and jammed the machine. With this high resistance, flexible, composite thread we were able to machine sew a conductive trace, or stitch, for the first time. This thread was commercially available, and had in the past been used for static control in carpets. Using capacitive/complex impedance sensing to sense every electrode individually also overcame the problems of false positives in the row and column keypad. The embroidery also allowed us to stitch electrical paths and contact pads to reach the circuitry. This avoided the mechanical complications of using wires to connect the fabric keys to the sensing electronics.

While the *Embroidered Keypad* made many technical and process advances over the *Piecework Fabric*

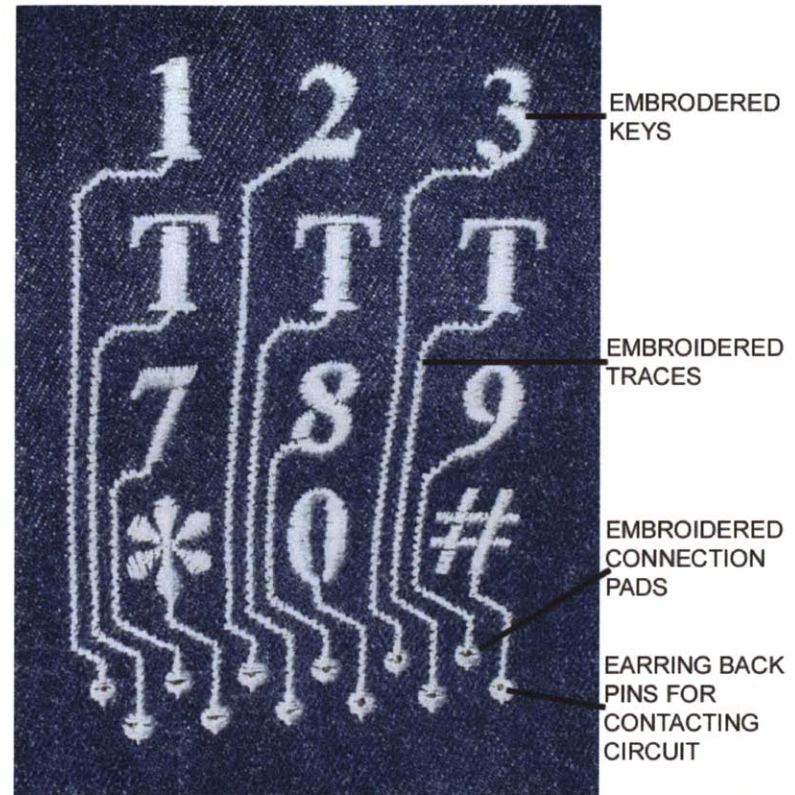


Figure 10.7 *Embroidered Keypad*, 1997, from the *Musical Jacket*.

Keypad, it still had many drawbacks for musical applications. The sensing method did not provide a means for sensing continuous information, or pressure, which is very important for expressive input in musical instruments. In addition, because the composite stainless steel thread was so high in impedance (in the mega ohms), we had to design our electrodes practically stitch-by-stitch. Any needle punch through a previously sewn trace caused a dramatic decrease in conductance. This was incredibly painstaking and time consuming. It also limited the types of stitches and designs that were usable. Finally, the *Embroidered Keypad* was still attached to the sensing electronics in a manner that made half of the keypad rigid. We had yet to find a flexible means for attaching the fabric electrodes to the electronics.

material references: stainless steel and polyester composite thread (BK 50/2), and metallic silk organza.

technical references: Complex Impedance Sensing.



Figure 10.8 The back of the *Embroidered Keypad* attached to sensing electronics.

Electronic Tablecloth*

The *Electronic Tablecloth* was designed to encourage guests at a cocktail party to mingle by playing a personalized game of Jeopardy on a beautiful, interactive tablecloth. Each *Tablecloth* contained five interaction stations, which enabled people to play a game together as they gathered around the table. Each of the five stations had a *unique* embroidered keypad (each station had different symbols), an embroidered electrostatic, RF ID tag reader electrode, and a text-based display in the centerpiece (which was connected to central PC). Each player received an embroidered coaster that contained a commercial, capacitive ID tag, linked to the player's identity. The player threw his or her coaster onto the embroidered tag reader and touched it to start playing. Once logged in he or she could use the keypad to pick categories, or answer personalized questions, which were displayed on the screen in the centerpiece. The centerpiece also contained sensing circuitry and links to a computer.

In the *Electronic Tablecloth*, the embroidered keypad and tag reader were truly physically transformed. Each embroidered key on the keypad was shaped to convey a specific meaning. The "yes, no, a, b, c, and d" keys let players choose their answer to questions. The image shaped keys (the Mona Lisa or the car), let players choose a category like art or cars. In this way, the embroidery on the tablecloth was shaped as an

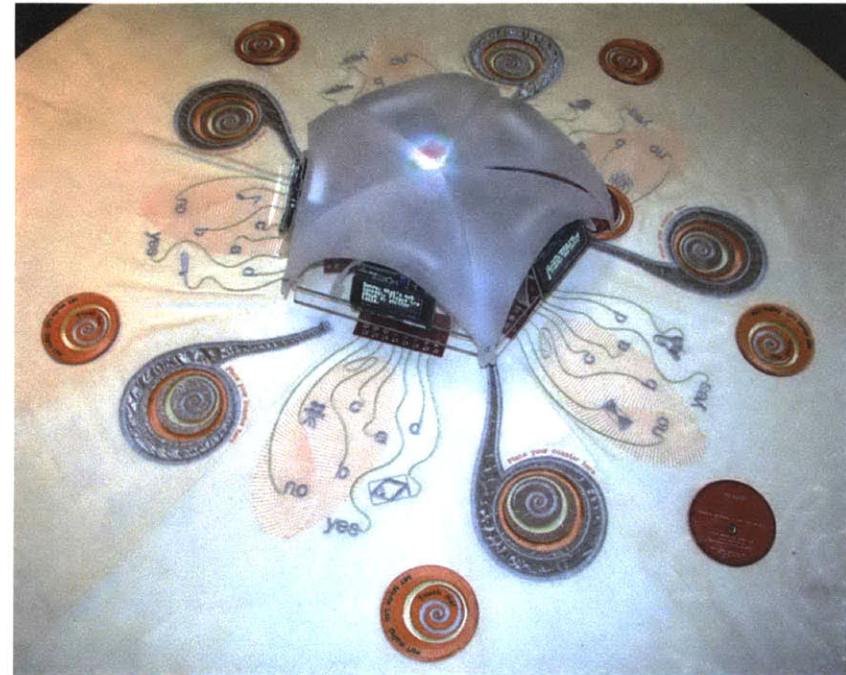


Figure 10.9 *Electronic Tablecloth*, 1998.

* In collaboration with Andy Lippman, Rehmi Post, Peter Russo and Pam Mukerji.

icon, an image or a word, just as the pixels on a screen can be shaped in a GUI. Directions to players, like place your coaster here, were also embroidered directly on the *Electronic Tablecloth*. With the embroidery design process I was also able to simultaneously shape and control the artistic content, (the shape and aesthetics of the letters and icons), and the electrical properties of the sensors.

The aesthetic transformation of the keypad and tag reader into a beautiful fluid pattern gave players a very different relationship to the game than they would have to plastic keyboards and tag readers arranged on a table similarly. Guests at the party found the technology emerging out of what they normally expect at a party, a beautiful table setting, and like the partygoers, the technology was dressed up for an elegant occasion. They were excited to see the coaster ID tags and tablecloth. If the *Tablecloth* were at a child's party the images on it could be designed appropriately to communicate to children.

The *Electronic Tablecloth* is an excellent example of the design potential of smart textiles as sculptural and active computing material. In many ways, this project was the first time I got to truly have some fun with the design of electronic fabric. I used various art nouveau patterns as a starting point for this piece. Because I had found a process where I could simultaneously and directly design both electronics and ornament, this was also the first project in which functional ornament started to become more advanced. Many of the decorative elements, like the gray keys and big gray swirl were electronically functional. Yet, I still did not

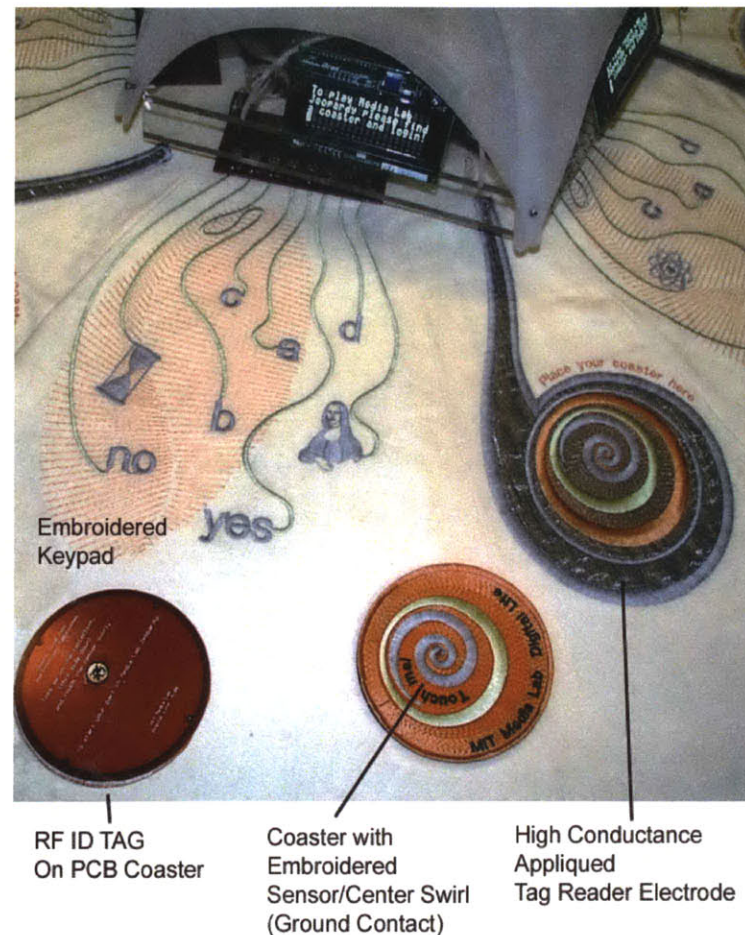


Figure 10.10 Details of *Electronic Tablecloth*, keys represent information in images and words.

feel that there was a meaningful design relationship between the ornament and the electronic needs. Even though the design of the conductive embroidery was incredibly painstaking, involving stitch-by-stitch control to insure the best electrical continuity and highest level of conductance, this did not have a tremendous effect on the visual design. Certainly, there were some very definite stitch patterns that led to highly conductive embroidery. Satin stitches were undeniably the best.⁵ One continuous thread was also necessary. But these factors limited, rather than expanded, what I could do as a designer. There was still room for more variety in the visual style of embroidery I used, and a more intimate link between the images and conductivity or electrical properties of the electrodes.

The *Electronic Tablecloth* had many problems that were related to its integration into a larger game system that, unfortunately, was never completed. Consequently, speaking about the interaction of guests with the *Tablecloth* in depth is difficult. All of the tag-reader and keypad technology worked, so guests did get to log in and use the keyboard. However, they never got to play the larger game where they interacted with other guests. Moreover, the centerpieces of the *Electronic Tablecloth* demonstrated the sculptural problems that still exist when integrating prefabricated display materials into computational objects. The shape and physical properties of these displays were fixed. The best transformation of these materials that could be achieved was incorporate these displays into



Figure 10.11 Close-up of stitched Mona Lisa.

⁵ See Chapter 16, Sewing Process Timeline.

a fancy housing. This housing was not offensive, but of very different style than the cloth itself.

material references: stainless steel and polyester composite thread (BK 50/2) and metallic silk organza.

technical references: Complex Impedance Sensing.

Chapter 11.

Early, Embroidered Musical Instruments

Introduction to *Embroidered Musical Instruments*

The development of *Embroidered Musical Instruments* fulfilled my desire to create a multi-channel, pressure sensitive¹ skin that I could wrap around any sculptural object. In addition to my early work in the *Brain Opera*, I was inspired to create these instruments by Gili Weinberg, who was writing interactive music software for the *Squeezable Cluster*², an instrument made from soft foam balls glued around a central core of

¹ See Chapter 13, Complex Impedance Sensing, for an explanation of what is actually being sensed in the balls.

² Gan, Seum Lim, *Squeezables, Tactile and Expressive Interfaces for Children of All Ages*, Thesis for the Degree of Masters of Science of Media Arts and Sciences at the Massachusetts Institute of Technology, Cambridge, MA, September, (1998).

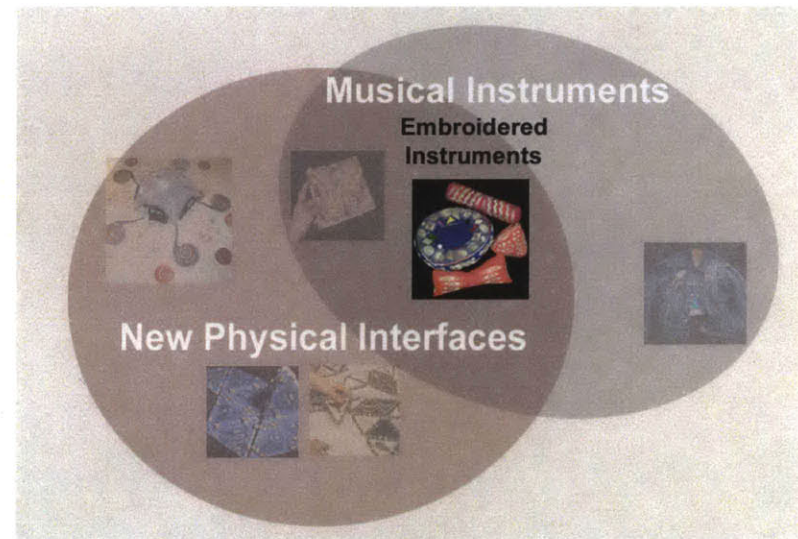


Figure 11.1 The *Embroidered Musical Instruments* within the Tree of Projects.

electronics and commercial pressure sensors.³ These sensors often failed and were bulky. I believed I could make a softer and more mechanically reliable version in textiles.

Physical Interdependency in the *Embroidered Musical Instruments*

Weinberg's first foam *Squeezable Cluster* was created to explore interdependency between sensors and its musical ramifications. Weinberg defines what he calls "internal interdependency"⁴, or interdependency within a single instrument as using digital technology to map a single gesture or sensor input to various musical parameters.

"...players of most traditional instruments expect full control over precise musical parameters for every action they perform (from generating notes to articulation and expression marks). This autonomous control can be digitally enhanced by mapping one gesture to several, sometimes partly contradicting, musical parameters as well as by mapping different gestures to the same musical parameter. Individual interdependent musical connections allow gestures, which are being simultaneously controlled by other gestures or musical parameters, to control other musical parameters, or gestures."⁵



Figure 11.2 Gili Weinberg and Seum-lin Gan, *Squeezable Cluster*, 1998.

³ Descriptions from this chapter refer to: Weinberg, G., Orth M., and Russo P., *The Embroidered Musical Ball: A Squeezable Instrument for Expressive Performance*, *Proceedings of Conference on Human Factors in Computing Systems*, (CHI 2000), The Hague, ACM Press, (2000).

⁴ Weinberg, G., *Expressive Digital Musical Instruments For Children*, Thesis for the Degree of Masters of Science of Media Arts and Sciences at the Massachusetts Institute of Technology, Cambridge, MA, (1999).

⁵ *Ibid.*

Weinberg also points out the difference between interdependency created in software and interdependency caused by hardware design. In the first foam *Squeezable Cluster*, the placement of sensors inside the ball meant that a player had to trigger more than one sensor simultaneously.

"Another factor that contributes to the complexity of the interdependent connection is the *Squeezable Cluster* hardware design. Since the instrument is held in both hands, it is relatively difficult to squeeze only one isolated sensor and to manipulate only one isolated arpeggio parameter. It is impossible to have a "non-squeezing" hand since each hand must provide contra force in order to allow for the other hand to squeeze in the desired axis. This contra force unavoidably exerts pressure on at least one additional sensor that manipulates at least one additional parameter. The placement of the sensors among the balls also contributes to the internal interdependency. The different angles at which the sensors are mounted make it difficult for the user not to trigger a cluster of neighboring sensors. Due to these factors, it is almost impossible to fully explore the *Arpeggiator's* parameters and to control them separately."

These ideas led me to believe that I could make a variety of instruments whose physical design had a direct affect on what happened in music software, and that explored interdependency by looking at how different physical designs, shapes, sizes and sensor arrangements might create different types of forced, *physical interdependency*. In this thesis, I will refer to interdependency between musical parameters caused by physical design as *physical interdependency*.

**From the Generic to the Specific:
Timeline of the Embroidered Musical Instruments**

My first of group of *Embroidered Musical Instruments* was a series of technical and design experiments, which led to both the stabilization of the electronic embroidery for use as continuous, fabric sensors, and to the development of the *Generic Musical Ball*, my first neutral, design, control object. This stable, design control object became the starting point for the specifically *Shaped Embroidered Instruments*, which were designed to *physically* create different musical and sensing effects in software. In this second series of instruments, different sensor designs and shapes were explored extensively, and a clear relationship between the physical design and the musical software it controlled was established.

My first *Embroidered Musical Ball*, *Squiggle Ball 1*, (1998) was an effort to jump right into an exploration of physical form and its relation to software. Consequently, I started with a ball whose organically shaped sensors were highly varied in size and shape. But this was simply too confusing, both because the sensing and fabric electrodes were not robust, and because the design was so amorphous that one could not understand what was happening in software. In order to simply verify that the sensing was working clearly, the balls had to use a more simply designed ring of sensors, as in the *Circle Balls* and the *Generic Ball*. But that simple design was so neutral that it was not musical. Because of the size of the sensors, and their layout, the *Generic Ball* was only was good for

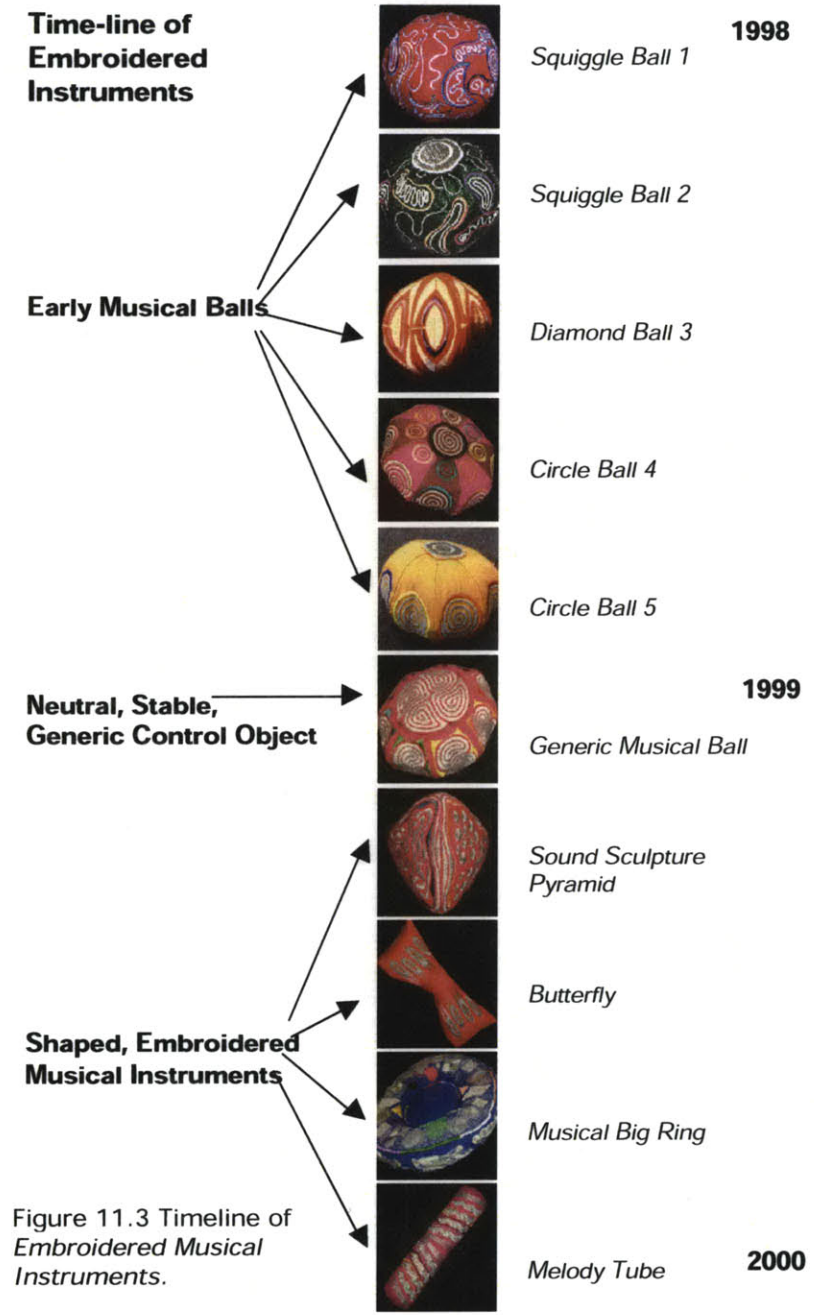


Figure 11.3 Timeline of Embroidered Musical Instruments.

trying each sensor individually. Its layout constrained players from using multiple sensors in different ways. However, it was stable and neutral enough that we could use it as a jumping off point for the *Shaped, Embroidered Musical Instruments*. Each of these instruments was *physically* designed to let players control its sensors in different ways. These differences in designs ultimately made each instruments more appropriate for a different type of musical software.

It is essential to emphasize that the design of the final *Shaped Embroidered Instruments* is not based on pre-planned ideas about how they would interact with specific software. During the design process there was a lot of experimentation with different shapes and different software. In some cases, this led to a change in the instruments physical design, and in some cases it led to new ideas for software. This is not scenario driven design. With sculptable and direct materials we could sketch, experiment, find, and develop actual relationships between software and physical objects that were not merely imagined, and far richer than what could have been imagined without such an iterative and hands-on design process.

Embroidered Musical Instruments as a Smart Material System

Each *Embroidered Musical Instrument* contains eight embroidered pressure sensors, two ground electrodes, a central sensing circuit, (a PIC microprocessor and a few resistors on a circuit board), and a wired, serial connection to an off-board PC or Mac. Because the central processors, speakers, and synthesizers are

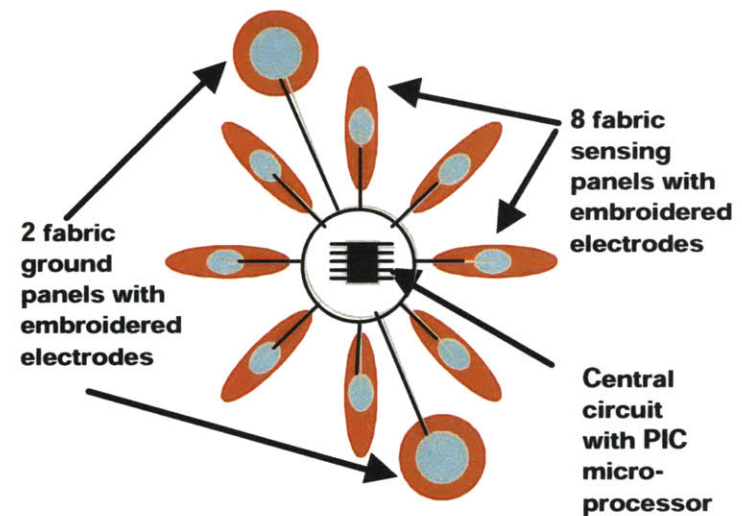


Figure 11.4 Diagram of a typical fabric pieces attached to central circuit.

located away from the fabric instruments, they remain very light, soft, and flexible. The textiles in the *Embroidered Instruments* were *smart or multifunctional* in that they were able to take over *most* of the remaining functionality required by the instrument. They function as pressure sensors, wires, connectors, and a soft, flexible, and durable physical housing. By connecting to central circuitry and off-board computers and audio gear, these smart textiles are part of a smart materials system.

The sensing in the *Embroidered Musical Instruments* is a significant advance over that done on the keypad in the *Jacket*. While the jacket could only sense on/off, these new *Embroidered Instruments* have continuous sensing, allowing players to experiment with a range of pressure, from soft to hard. Normally, continuous sensing in electronic instruments is accomplished with a number of bulky sliders, buttons, knobs, or bend sensors that are impossible to put into a single hand-held object. The fabric brought together all these bulky items, and their wire connectors into a single, integrated housing and sensing material.

For the fabric to sense continuous information (or what at this time was described as pressure) with embroidered electrodes, both the sensing and sewing technique had to be perfected. Accurate complex impedance pressure sensing on embroidered pressure sensors was achieved with new and improved circuitry, better microprocessor software, and the use of better conductive threads and sewing methods that made the sensing electrodes far more conductive, durable and consistent. These new sewing methods allowed for a

MULTIMEDIA COMPUTER

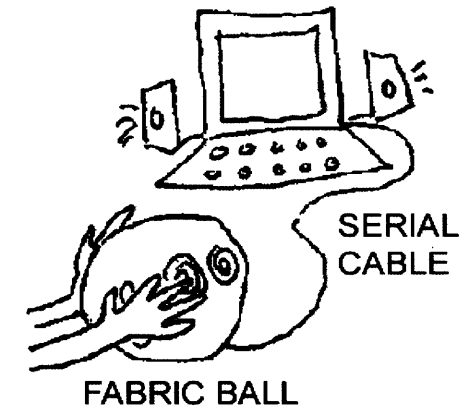


Figure 11.5 *Embroidered Musical Ball* attached to multi-media computer.

more direct relationship between the visual and tactile design of the sensors and their electrical properties.

The later *Embroidered Musical Instruments* also used a new, mechanically knottable and highly conductive braid to literally tie the electrodes electrically and mechanically to the sensing circuitry. This is a significant advance over the keypad in the *Musical Jacket* and *Tablecloth*, which were directly connected to the sensing circuit board, leaving only the top part of the keypad truly flexible. Moreover, this thread allowed a means for a quick and reliable mechanical and electrical connection between the fabric and circuit. This material was essential for easy iteration and experimentation on different musical instruments.

Early *Embroidered Instruments*

This chapter presents five early *Embroidered Instruments* (1998-1999) that lead up to the sixth and final instrument presented in this chapter, the neutral, *Generic Musical Ball*. These instruments represent a design journey from the chaotic and amorphous *Squiggle Balls*, to the regulated and cognitively clear, *Generic Musical Ball*. That journey was necessary for two reasons. Without clear sensor design it was not possible to test and stabilize the continuous sensing technique and electrode design. A clear design was also necessary to understand how the sensor design behaved in musical software.

Through direct observation, I learned that to improve the continuous sensing in the *Embroidered Musical*

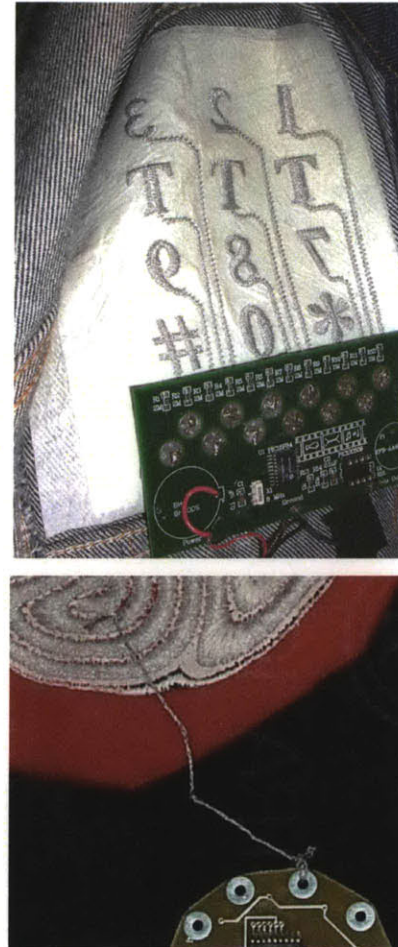


Figure 11.6a, b Back of *Musical Jacket* keypad with circuit board directly connected to the fabric, by a mechanical/electrical connection made by a knotted yarn.

Instruments, far more conductive electrodes had to be sewn than of the *Electronic Tablecloth* or *Musical Jacket*. Finding a highly conductive, machine sewable thread was difficult. Gimped, or foil wrapped threads, stripped in the sewing machine. Threads with higher percentages of stainless steel jammed the machine. Eventually, highly conductive threads were tried the bobbin. This was significant because the bobbin puts far less mechanical stress on threads, allowing us to sew far less flexible threads.

The *Embroidered Instruments* in this chapter represent simultaneous experiments in electrode design, bobbin threads, panel design, and overall shape and form. At this point the design of the ground electrode also began to play a significant role. In the *Musical Jacket*, the player was grounded relative to the circuit through either the fabric bus, which ran across the back of the *Jacket*, or a ground plane ironed into the back of the jacket. In the *Embroidered Musical Instruments*, the player's hands has to be directly in contact with a ground electrode as well as the sensing electrode. Consequently, strategies for properly placing the ground electrode and avoiding a short circuit with the sensing electrode became very important when designing the *Embroidered Musical Instruments* with continuous sensing.

Squiggle Ball 1* with Composite Thread

This was the first fabric instrument that used embroidered pressure sensors. These sensors were

* In collaboration with Peter Russo.

high impedance electrodes (in the kilo-ohms), embroidered from composite stainless steel and polyester thread that was run through both the bobbin and needle of a commercial embroidery machine. The organic electrodes were shaped in an intertwining pattern in an attempt to create forced, *physical interdependency*. Their size was varied to explore how making one sensor bigger, and therefore more likely to be touched, would affect the music. The randomness of the pattern was an attempt to physically create a more intuitive and less one-to-one experience for the player, and *physical interdependency* between the sensors. The goal was to not to allow the player to immediately realize which sensor he or she was controlling, but instead to give him/her an immersive musical experience *immediately*. The design was also meant to allow an investigation of what happened when sensors were different sizes and shapes and had different physical relations to one another. Some sensors were closer together and even wrapped around each other.

The sensing in this instrument failed because of high electrode impedance. We knew that the high impedance electrodes were causing the problem because when Peter Russo and I originally tested the sensing microprocessor code and circuitry, we did so with perfectly conductive copper electrodes. As soon as we attached the circuitry to embroidered electrodes, we had numerous problems. The highly resistive sewn electrodes did not provide as consistent sensing results as the highly conductive copper ones. This led me to attempt to increase the conductivity of the embroidered electrodes to improve the sensing.

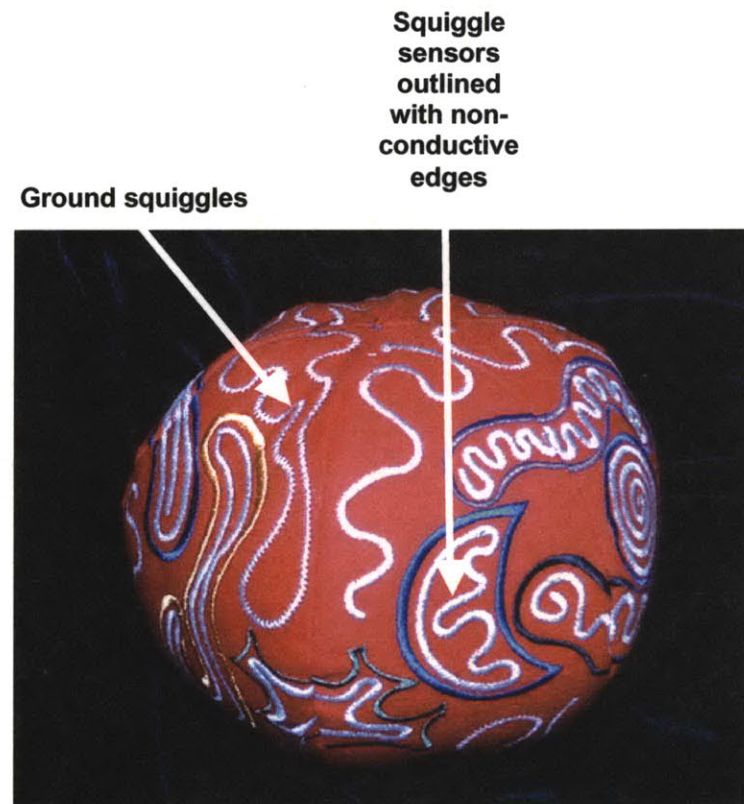


Figure 11.7 *Squiggle Ball 1*.

materials notes: BK(50/2).

Squiggle Ball 2* with 100% Non-Continuous Stainless Steel Thread in Bobbin

The new sewing technique used in this instrument represented a major breakthrough in creating conductive electrodes. Until now, experiments in making highly conductive electrodes had focused on getting thread with higher conductivity through the needle. This was because the complex impedance sensing technique required players to come into DC contact with, (physically touch), the conductive surface of the embroidered electrodes. All of the highly conductive threads that we experimented with simply could *not* be sewn through needle of a sewing machine. They bunched, or their conductive wrapping stripped. During the development of the *Musical Jacket* we learned that using a conductive bobbin in conjunction with a conductive top thread led to far more conductive electrodes. Until now, we had used a highly resistive composite thread in both the bobbin and needle. But by placing a 100%, non-continuous, stainless steel thread in the *bobbin* we were able to mechanically sew a highly conductive thread and create an extremely conductive and stable electrode.

Unfortunately, the non-continuous, 100% stainless steel threads used in the bobbin also presented many problems. Because these non-continuous threads are made from very small pieces of ultra-fine stainless

Appliquéd
ground
electrode



Figure 11.8 *Squiggle Ball 2*.

* In collaboration with Peter Russo.

steel fibers, they were very fuzzy and had a lot of stray fibers. The stray fibers caused skin irritation for the person sewing the ball, and short circuits between the sensing and ground electrodes. On *Squiggle Ball 2*, the squiggly ground electrode, (which must be touched at the same time as sensing electrode), was shorted to the sensing electrodes by the stray fibers. To test the ball we disconnected the ground electrodes and grounded the player with a wrist strap. We could then see that the more highly conductive electrodes were far more responsive and consistent, than their restive counterparts. Eventually, two highly conductive metallic organza electrodes were sewn onto the top and bottom of the ball for grounding. These electrodes were created with an appliqué technique. While they were highly conductive they were also stiff, so I did not see this as a long-term solution to creating more conductive electrodes.

Even after the removal of the ground electrodes, stray fibers still created electrical cross talk between the sensing electrodes. This made it difficult to really see how the physical design and pattern of the sensors was affecting software. In addition, the electrodes on this ball spanned multiple panels, and there was no good way to electrically connect them. Between the inconsistent electrodes, the cross talk, and the amorphous design it was almost impossible to understand what was going on, either in the sensor design or the music.

materials notes: see BK(50/2) and 100 % non-continuous stainless steel.

Diamond Ball 3* with 100% Non-Continuous Stainless Steel Thread in Bobbin

This ball represents my first attempt to create a cognitively clear sensor pattern, and to integrate the ground electrode around the sensing electrode so that the two could be simultaneously touched with ease. Each embroidered internal diamond was a sensor electrode. The diamond-like pattern surrounding it was the ground electrode. All the electrodes were the same size, so that it was easy to observe if the sensing was consistent. The electrodes were also arranged evenly around the ball. Each sensing electrode and the surrounding ground electrode were sewn on a single panel. This helped reduce the possibility of cross talk between electrodes and also reduced the need to electrically connect parts of electrodes sewn on different panels.

I had hoped that by sewing a non-conductive satin stitch between the ground and sensing electrode, I could eliminate short circuits. Unfortunately, this did not work. While I was anxious to design a ground electrode that was more integrated into the final instruments, I realized that as long as I used this hairy thread, every electrode would have to be sewn on a separate panel, with lots of space in between, and lined. This was because a lot of stray fibers were released during the sewing process, so electrodes on the same panel tended to get shorted out.

materials notes: BK(50/2) and 100 % non-continuous stainless steel.

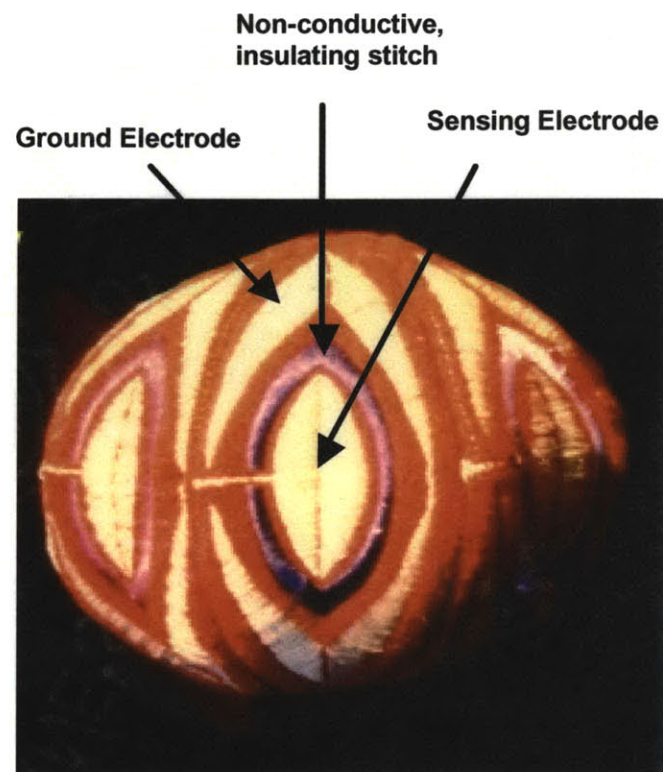


Figure 11.9 *Diamond Ball 3*.

* In collaboration with Peter Russo.

Circle Ball 4* with 100% Non-Continuous Stainless Steel Thread in Bobbin

The goal of this ball was to create stable electrodes for sensing on a single panel, and a clear, legible design to enable an understanding of their musical function and playability. To solve the problem of short circuits between electrodes sewn with 100% non-continuous stainless steel, two steps were taken. Each sensing and ground electrode was sewn on a separate panel, so that any stray fibers that occurred during sewing could not spread between two electrodes. Each panel was also lined with cotton, to prevent stray fibers from *reaching out* and connecting to the fibers on other panels, after the instrument was assembled. To create a cognitively clear design for easy playability, eight identical sensors were evenly arranged in a ring around the outside of the ball.

This ball was technically very successful, but a few drawbacks remained. The hairy thread was difficult to work with because it was painstaking to prevent short circuits by lining, and the fibers still caused skin irritation for the machine operator. At this point, it also became clear that this sensing method required the player be very WELL grounded. This meant that the ground electrode needed to be very conductive, and carefully placed so that the player's hands were always in contact with it. Because the electrodes needed to be sewn on separate panels, it was difficult to place the ground in an easy-to-reach spot. To avoid possible short circuits, every electrode had to be on a separate

GROUND ELECTRODE APPLIQUÉD FROM METALLIC ORGANZA FOR EXTRA CONDUCTIVITY



Figure 11.10 Circle Ball 4.

* In collaboration with Peter Russo.

panel and evenly spaced, so I had little freedom to experiment with shape, size, placement or physical relationship of the sensors. I felt highly constrained as a designer.

materials notes: BK(50/2) and 100 % non-continuous stainless steel.

Circle Ball 5* with Wrapped Thread

This ball used the same electrode design as the previous ball, but replaced the hairy stainless steel bobbin thread with a very neat and highly conductive thread made from nylon wrapped with three strands of continuous stainless steel. While the conductors in this thread stripped and bunched when passed through a needle, they remained intact in the bobbin. The electrodes it created were very conductive and tidy.

Surprisingly, *Circle Ball 5* did not work as consistently as the *Circle Ball 4* with 100% non-continuous stainless in the bobbin. After experiments, it became clear that this was now a reflection of the area of the electrode. The hairy bobbin thread was fat and provided the electrode with a lot of conductive area. The player coupled to that area through the high impedance composite thread on the top of the fabric. While the thin continuous stainless steel fibers in the new nylon thread were highly conductive, they did not provide enough electrode area to couple to. This was particularly significant for the ground electrode, which was replaced by an appliquéd piece of metallic organza.

* In collaboration with Peter Russo, software by Gili Weinberg.

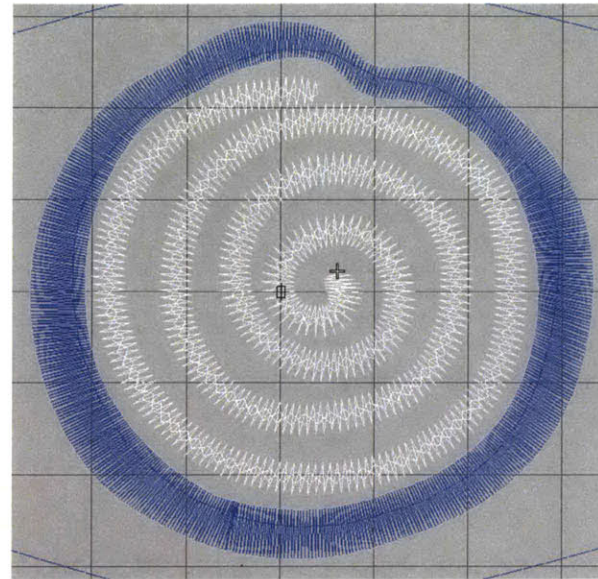


Figure 11.11 Embroidery CAD File of circle sensor.

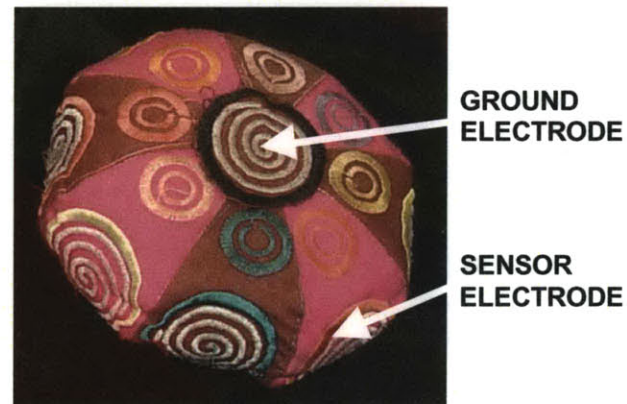


Figure 11.12 *Circle Ball 5*.

materials notes: BK(50/2) and nylon wrapped with continuous stainless steel.

Generic Ball 6*: A Design Control Object

This instrument is the final and stable *Generic Ball* from which later experimentation with physical form and software began. The clarity of the *Generic Ball's* physical design and sensor layout, and the technical success of its sensing, presented a clear jumping-off point for later instruments. The electrode design was both conductive enough, and had ample area to allow consistent sensing. The bugs in sensing circuitry had been perfected. The *Generic Ball's* clear layout of eight sensors around a large top and bottom electrode made it possible to think about the form of the ball in relationship to its musical applications. The sensors and ground electrodes were very large, guaranteeing that the player's hand could easily contact the two simultaneously. Each electrode had a different colored border, by which the player could identify it. Each sensor and ground electrode was sewn on a separate lined panel to prevent short circuits. To increase the area and stability of the conductor in the electrode, the electrodes were sewn in a very dense satin stitch, and as one continuous trace, in layers that build up over one another.

While the physical design of the ball enabled stable sensing through electrode layout and size, it also limited the expressivity and experimentation of the player. Because the sensing technique demands an

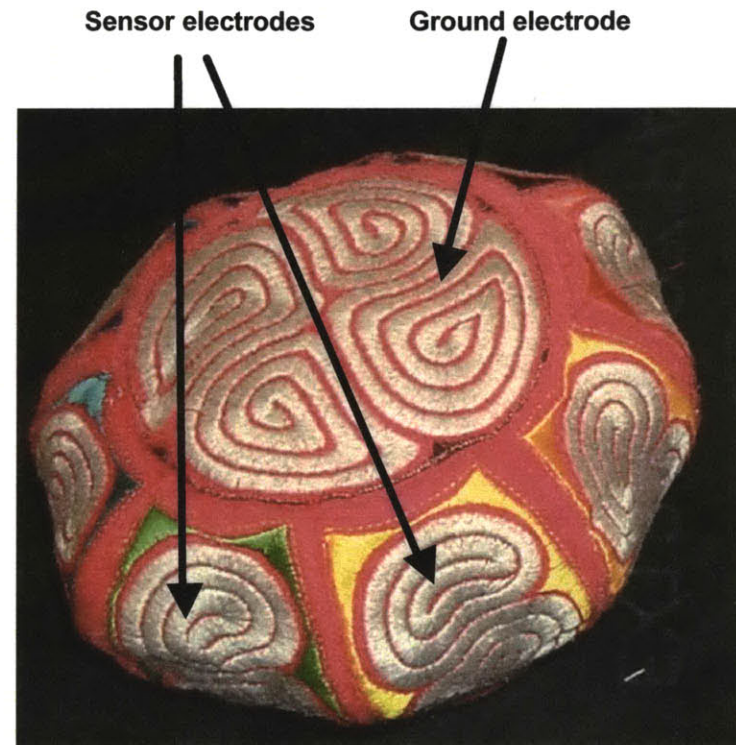


Figure 11.13 *Generic Ball 6*.

* In collaboration with Peter Russo, software by Gili Weinberg.

excellent connection to ground, the placement of the ground electrodes on any ball is essential to how it is played. While the size of the sensor and ground provided a good area for coupling, it also made it difficult to grasp a number of sensors simultaneously. With the *Generic Ball*, players could precisely control only two to four sensors at a time, with each hand touching ground and one or two sensing electrodes, simultaneously. With great effort, a player could play all the sensors on the ball and stay well grounded, but have little control over which one, he or she played, when. New players had to be taught how hold the ball to properly get a contact with ground and the sensing electrode, simultaneously. In this way, the ball did not allow for as much immediacy and exploration of physical interdependency as had been hoped for. And while this new electrode design was very sensitive, they were also unfortunately stiff and dense.

Experimentation with the *Generic Ball* led to the desire to create specific balls for specific musical applications. The application that this ball played was a multi-track piece of pre-composed music by Gili Weinberg. Different sensors controlled the volume and timbre parameters of each track or voice. The ball allowed users to experiment with the mixing of the tracks, for instance bringing in violins, pianos or flutes, each playing different music. The physical form of the *Generic Ball* let players bring in and out one to four of these tracks with ease and control. It also let players bring in many tracks simultaneously with less control. As different applications were experimented with, it became apparent that the generic shape of this instrument, while good for experimentation, was not

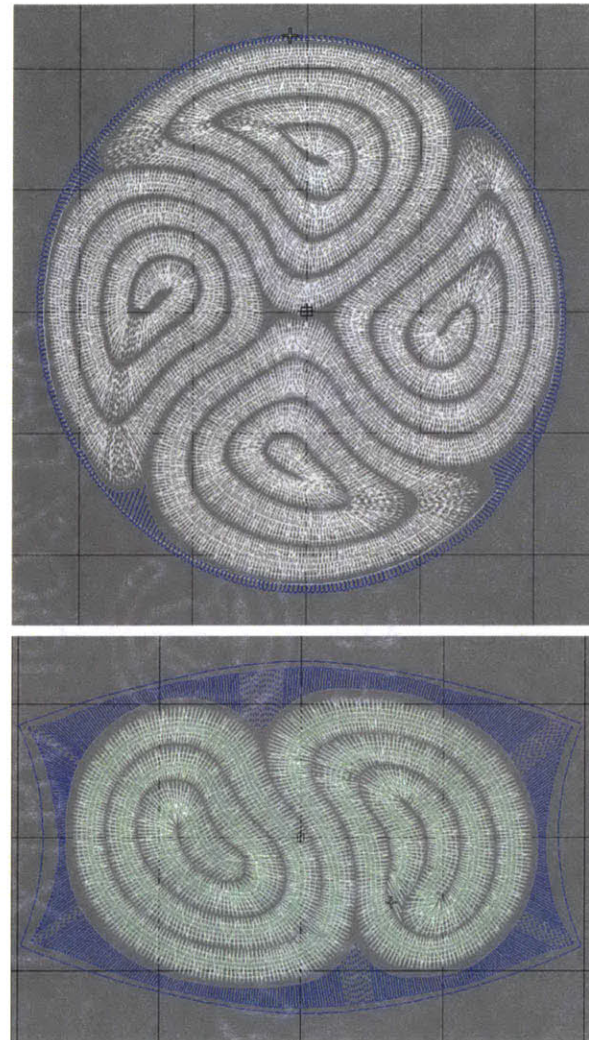


Figure 11.14 CAD file electrode design from *Generic Ball*. Ground Electrode is above and sensor electrode below.

suiting well to any specific musical application. Exploring the relationship of the parameters mapped to the sensors was difficult. Because its form was symmetrical, players could not use shape to orient themselves while playing. The texture and shape of the sensors also did not inform the players in any way.

materials notes: BK(50/2) and nylon wrapped with continuous stainless steel.



Figure 11.15 Embroidered ground electrode from the *Generic Ball*.

Chapter 12.

Shaped, Embroidered Musical Instruments

As Musical Instruments

The final *Shaped Embroidered Musical Instruments* presented in this thesis, demonstrate how multifunctional and smart materials can dramatically improve the design and process of creating computational objects. In these instruments, sensors, wires and housing are all replaced with the single, durable and flexible material, smart textiles. These instruments also demonstrate how physical objects might become less neutral, and how the form and tactile properties of an object might reflect, and directly interact with computation or software. Each instrument has an overall shape and design that is appropriate to its software, and that directly influences its musical output. The careful placement of ground electrodes allows for an immediate playing style that emphasizes



Figure 12.1 *Shaped Embroidered Musical Instruments.*

natural squeezing. This gesture of squeezing is often reflected in the music that the instrument creates. The sensor size and placement relates closely to the musical functionality of the instrument. These instruments also represent a real advance in the development of *functional ornament*. The visual design of each sensor electrode is directly related to its electronic, technical and instrumental needs. Finally, these instruments are physical computing objects and musical instruments that are truly *materially antithetical* to normal musical instruments and computing technology. And these soft and squishy objects use fabric, normally an acoustic and electrical insulator, to conduct electricity and make music.

Music Shapers in Tod Machover's Toy Symphony

All of the *Shaped Embroidered Musical Instruments* are designed to be part of a larger project called the *Toy Symphony*. The goal of this project is to introduce kids to musical creativity in a new way. Music Toys are one of the main tools for this. Ultimately, these instruments/music toys will be used for both music workshops involving kids and mentors, and performances with kids and a symphony orchestra on stage. According to Machover:

"Toy Symphony is a three-year project (1999-2002) to combine children, virtuosic soloists, composers, and symphony orchestras around the world to radically alter how children are introduced to music, as well as to redefine the relationship between professional musicians and young people. A complete set of Music Toys will be distributed to children in each host city (including New York, Boston, Manchester/London, Berlin and Tokyo),

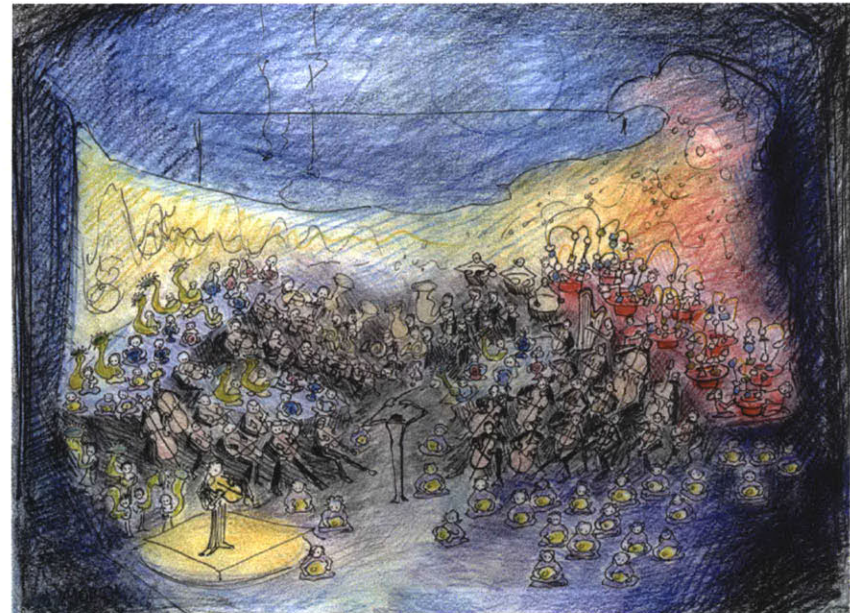


Figure 12.2 Conceptual illustration of kids, soloist and orchestra on stage in the *Toy Symphony*, Maggie Orth, 2000.

where children will be mentored to create their own sounds and compositions for toys and traditional instruments. A pedagogy for using these Music Toys to teach - and instill a love for - musical creativity will also be developed. Final concerts will be presented in each host city including kids' compositions and especially commissioned works by young composers, to be performed by children, soloists, and orchestra, playing Music Toys, Hyperinstruments, and traditional instruments."¹



Figure 12.3 Conceptual sketches of Music Toys, including, *Embroidered Musical Ball*, musical costumes, musical collage, sonic vacuum, and musical clay, *Toy Symphony*, Maggie Orth, 2000.

To accomplish all this, the *Embroidered Musical Instruments* must be durable, reproducible in at least a limited number, and ergonomic (physically able to be picked up, and played relatively easily by kids). So while I may have many abstract artistic and design goals for these instruments, they are also highly practical. They can be manufactured at a normal commercial embroidery house. They are durable. They are also relatively ergonomic, and designed to be playable by the small hands of children.

Within the *Toy Symphony*, these instruments are part of a larger instrument category called *Music Shapers*. These instruments are intended to let kids *shape* existing music at a relatively high level of expressive function, rather than at the level of note-by-note control. For instance, each of these instruments control three different pieces; the *Sound Sculpture Pyramid* allows for the mixing of audio filters and timbral exploration, the *Melody Tube and Butterfly* allow for the distinct control of two melody lines, and the *Big Ring* lets

¹ Machover, T., [Opera of the Future Website](http://www.media.mit.edu/hyperins/projects.html#TOYSYM), <http://www.media.mit.edu/hyperins/projects.html#TOYSYM>, World Wide Web, (2001).

players re-mix only a few lines of music from a large and potentially cacophonous set of pre-composed musical lines.

Squeeziness and Shapability

The squeeziness of the *Embroidered Musical Instruments* is metaphorically linked to the idea of *shaping*. Ideally, we thought of *Music Shapers* as made from a sort of musical clay, like clay on the potter's wheel that the computer could sense. One prototype of such musical clay was Josh Strickon's *Musical Play-doh*.² *Musical Play-doh* used a platform of four electrodes to make pair wise measurements of the resistance in the salty and conductive Play-Doh that sat on top. While this sensing method did provide some clear idea of the movement or mass of the Play-doh on top of the electrodes, it did not provide an image of the clay's shape. I found this to be conceptually misleading. Kids and people would want to shape the clay into animals and houses, but we could not really see that. We could not even see if the shape of the clay was square or round. Moreover, it is totally unclear how to translate such shapes into music. This might not be a problem for an individual work of art, where an artist establishes a "personal" relationship between certain shapes and music, much like we did in the linking sounds to images in the *Digital Veil*. But an instrument needs some greater internal logic that transcends such highly subjective image/musical associations.

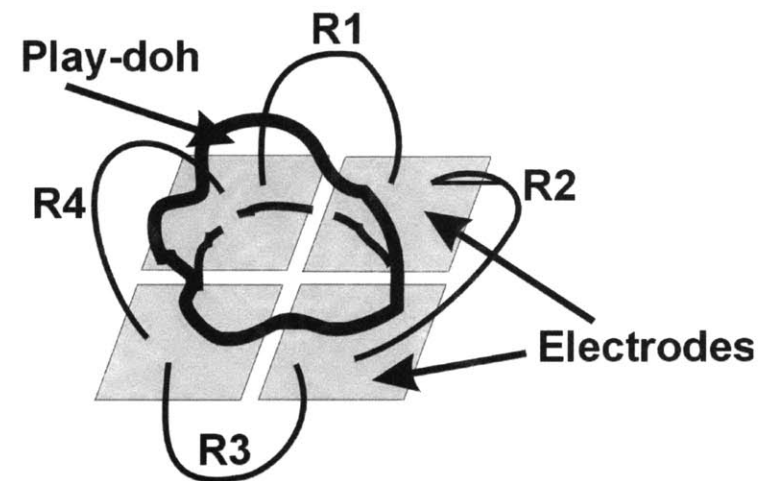


Figure 12.4 Diagram of Josh Strickon's *Musical Play-doh*.

² Toy Symphony Website, <http://www.media.mit.edu/hyperins/toysym/phaseiframes.html>, World Wide Web, (2001).

For both these reasons, (the technical inability to actually "see" the shape of the clay, and the "subjectiveness" of the linking of realistic images to music), I found the idea of relating the literal physical shape of a piece of clay to music highly problematic. The intention of the *Music Shapers* is to let kids shape *music*, not make a sculpture. Consequently, the *Shaped Embroidered Instruments* are not a sculptural medium for creating a shape. In fact, it is important that these shapeable *instruments* are not confused with a *sculptural and shapeable material* as a laid out in the supporting arguments of this thesis. As wholly formed fabric instruments the *Embroidered Instruments* do not set up any expectation that they are a sculptural medium that can be made into a specific shape and then imaged. Instead, their squeeziness lets kids use the *process or act* of shaping, to shape and form music. In this way, the *Embroidered Musical Instruments* are objects whose tactile squeeziness is a metaphor for the actual shaping they do of music.

In many ways, preserving the softness, squeeziness, and metaphorical shapability of these instruments has been my foremost design goal. In fact, my greatest satisfaction is when the music these instruments create, sounds "squeezed". (This happens most often in the *Sound Sculpture Pyramid*.) This is a confession, because emphasizing squeeziness has meant making many design trade-offs, and sometimes musical ones. Except for the small circuit board located in the center of each instrument, I eliminated every other technological material that might interfere with the softness of these instruments. Speakers are off-board, and no hard lights are used for visual feedback. This

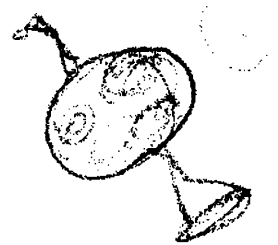


Figure 12.5 Sketch of Ball-horn, in which the speaker is a hard, plastic horn in the center of the embroidered ball, Maggie Orth, 2000.

means the sound does not come from the instrument itself, and that for visual feedback a player must look at a computer screen rather than the instrument itself. Finally, keeping the *Embroidered Musical Instruments* squeezy and soft, has meant that all their sensors are continuous and that these instruments lack any discrete input. When we tested the *Pyramid* running both timbral and melody software with Mattel³, this was a clear problem. Kids wanted to touch something and hear something *immediately*. But in the *Embroidered Musical Instruments*, the sensors start at zero and progress upwards, gradually turning musical parameters on. This meant that even though the sensors might see a touch, kids might not immediately here any music, until the sensing info got high enough to trigger a music event. A one-to-one mapping of some discrete sensor to a musical note might help these instruments immensely.

Quick Demo, Commercial Toy or Practiced Instrument?

One of the challenges of designing these instruments, both in software and hardware, has been balancing ease and immediacy of play, with depth of musical experience. While here in the Media Lab, these instruments had to be a good "demo", i.e., create an immediate and satisfying musical experience for an adult visitor who might only spend 30 seconds playing one. For the *Toy Symphony*, the *Embroidered Musical Instruments* had to be physically and musically far easier to learn and use than a violin, able to be



Figure 12. 6 Still of video from Mattel toy testing with nine year old girls, September 30, 2000.

³ Cambridge, MA, boys and girls ages 6-11, (September 30, 2000).

practiced and learned in short, (1 week) workshops, and also provide the player with a real sense of control and meaningful musical experience. For an event like the Mattel Toy testing, (in which Mattel was trying to determine if music toys could become commercial products), the kids had to be able to pick one up and get a cool musical response, and then feel that they would play with the instrument over and over again. Trying to create an instrument that is easy to play, repeatable, provides an immediate and satisfying musical response, is commercially viable, musically meaningful or sophisticated, and provides the player with the ability to learn and improve is no easy task, in either software or hardware.

In software, high-level musical control of pre-composed music or higher-level parameters, like volume and melody shape, can provide immediate musical success and allow for the exploration of expressiveness and creativity in children. But balancing immediate musical satisfaction with something that has musical depth is difficult. According to Weinberg:

"My challenge as a designer of such digital musical instruments for children will be to balance between these two opposite approaches by providing a rich and expressive musical experience that can also allow for low-level manipulation. The instruments that I design should allow for players to smoothly transit between these two ends, taking into consideration that extreme high-level control might not allow for

precise exploration, while extreme low-level control might impair expressive and fun aspects.”⁴

(Gili Weinberg gives such an eloquent description of this problem that rather than paraphrase it, I have included in Figure 12.7)

The physical design of digital musical instruments presents a similar challenge and Weinberg eludes to it in his thesis. Traditional instruments like a cello can take years to master *physically*. This can be overcome with software mapping, or with physical design. Software can compensate for an incorrectly timed or played note. But it cannot compensate for needed to learn how to hold the violin or the bow. It is possible to design physical instruments that can be immediately picked up with no instruction, and played with everyday gestures, (like squeezing), and that can take no time to practice or learn. This requires making the sensors highly sensitive and the first thing your hand touches. In the case of the *Shaped Instruments*, this meant making sure that anytime a player held an instrument, his or her hand was in contact with ground and a sensor. For kids, it meant calibrating the sensors to be very reactive to their small bodies and hands. But making instruments physically immediate can have high trade-offs. Recalibrating sensors led to far less degrees of control on the sensor. The physical design, that lets players use natural squeezing gestures to play music, also means that players have less precise one to one

“One of the premises for the new digital musical instruments’ design is that there are intermediate levels of involvement on the axis whose ends are playing the cello and pushing the Play button. By combining discursive low-level controllers with presentational higher-level ones, new musical experiences, which are based on an interaction between these complementary levels of representation, can emerge. These interactions can offer expressive and creative musical experiences without requiring an exhausting learning process, virtuosi performance skills or an extensive body of musical theory knowledge.

They can also bridge the gap between different symbolic systems and address bricoleurs as well as planners, figurarlists as well as formalists. Performance skills and music theory proficiency are usually required in order to master the control of low-level musical building blocks, from single notes to melodies, harmony to articulation. In a traditional music learning process, however, these low-level musical aspects often block the vision of expressiveness, creativity and fun that fortunate professional musicians can experience after a long perfection process. The digital musical instruments’ design suggests the use of additional, higher-level, musical controllers as intuitive and expressive intermediate involvement tools. These controllers can be helpful for a more immediate introduction of young potential musicians to the fun aspects of playing music, while still allowing for a rich and meaningful musical interaction. An example for such high-level musical control would be the manipulation of musical “stability” [Dibben 1999].

Digital musical instruments can allow children to interact with such a high-level concept by providing an algorithm that controls interval range, rhythmical consistency, fluctuations in timbre, etc. Another, more generic, intra-cultural example would be the manipulation of melody contour. Psycho-acoustic studies show that two melodies in different scales which share the same articulation, tempo and contour (but not the same pitches) can be perceived as very similar to each other [Schmuckler 1999].

Some experiments show that subjects found such pairs of melodies even more similar to each other than the very same melody played twice with different articulation or tempo. This phenomenon suggests that melody contour can serve as an intuitive high-level control, where users are not generating specific notes, but continuously controlling the abstract “height” of the melody line, based on a pre-programmed scale. It is important to remember, however, that a deep musical experience should also provide low-level delicate control and accurate manipulation of lower-level musical building blocks. Without these features, the high-level musical experience might lead to vagueness and confusion, which can impede further exploration. A comprehensive control of fundamental musical components (such as accurate pitch, velocity and timing) can motivate players to meticulously construct higher-level musical structures. Being provided with only vague high-level control might discourage such players who prefer delicate, precise and controllable manipulation.”

⁴ Weinberg, G., Expressive Digital Musical Instruments For Children, Thesis for the Degree of Masters of Science of Media Arts and Sciences at the Massachusetts Institute of Technology, Cambridge, MA, (1999).

Figure 12.7 Weinberg, G., Expressive Digital Musical Instruments For Children, Thesis for the Degree of Masters of Science of Media Arts and Sciences at the Massachusetts Institute of Technology, Cambridge, MA, (1999).

control over specific sensors. Moreover, the sensing technique used in these instruments (complex/impedance sensing or "intimacy sensing), proved far more technically appropriate for instruments designed for immediate and expressive response vs. one-to-one control.

A Natural Squeezing Style and Intimacy Sensing

The sensing method used in the *Embroidered Instruments* is essentially a measurement of skin impedance,⁵ or what I came to call *intimacy sensing*. This technique has very particular physical design requirements and is also extremely sensitive to external factors that change a player's skin impedance, like hand washing and even temperature. Over time it became clear that because of the physical design constraints and artifacts of skin impedance, this sensing technique was most successful when instrument design emphasized a *natural squeezing style* that used the whole hand to control multiple sensors, rather than *finger-by-finger* control of individual sensors.

During the development of the *Early Embroidered Musical Instruments*, I had empirically observed many factors about the sensing technique that led me to artistically describe this sensing method as *intimacy sensing*.⁶ I observed that the more physically intimate, i.e. the closer, and longer a person's hands were in contact with the sensor and ground electrodes, the

⁵ See Chapter 14, Complex Impedance Sensing.

⁶ See Chapter 13, Complex Impedance Sensing.

more reliable and reactive the sensing was. Consequently, while pressure from squeezing contributed to the reaction rate of the sensor, it was not the only factor. How long a person was holding the ball also made the sensors more reactive. The area of a player's hand on the electrode made them more reactive. How well the person was grounded also made them more reactive. These observations had specific design ramifications. In general, electrode design needed to emphasize high conductivity, a wide area and significant density of conductors on the surface for direct contact with the skin. The placement of electrodes had to allow players to easily grab the ball, squeeze it and get a good contact with both sensor and ground electrodes. All these technical requirements are strongly reflected in the design of the final instruments.

A natural squeezing style works far better than finger-by-finger control. Squeezing with the whole hand gives players simultaneously a good contact to both ground and sensor electrodes. It also lets players use various parts of their hands. This is important because the skin impedance of the player's hands contributes to their ability to control the sensors, and different parts of the hands have different levels of impedance. Consequently, it would not be unusual for one player's pinky to work well and another's to work badly. In addition, I have noticed that using individual fingers to control specific sensors requires a light touch. Thus, the palm, (if finger-by-finger control is used, this is the musically inactive part of the hand), which must touch the ground electrode, may not have enough "opposing" force to be very good electrical contact with it. The most successful instrument designs let people trigger

sensors by using natural squeezing gesture and create opposing forces in either a single hand or between two hands.

It is important to note that while the natural squeezing style emphasized by the physical design of these instruments does reflect the musical goal of using everyday gestures for musical expressivity, it also relates to the fundamental limitations of the sensing technique. The *Embroidered Musical Instruments* do not always provide an ideal level of precise control. Gili Weinberg must be credited with doing a marvelous job of creating software that was very forgiving of the artifacts and limitations of skin impedance sensing.

As Sculpted Computational Objects

A Relationship Between Physical Form and Music Software

The specific design of the *Shaped Embroidered Instruments* clearly transcends neutral physical computing objects, like music controllers that can be mapped to any piece of music software, or neutral computer mice. This is because the shape and sensor design of each instrument is *necessary* and specific to the composition and type of music it performs. For this reason, I have come to think of these instruments as being *physically composed*. I first heard the expression

"composed instrument" in a talk by Dan Truman.⁷ He referred to his built instruments, like the BOSSA⁸, as *composed* because the software he wrote determined what music he could play, and was *part* of the piece he was performing. The idea of performing composed music is, in fact, something that the Hyperinstruments group has been doing for years. After his talk, I realized that my physical instruments were in fact, *physically* composed. Rather than being neutral, or good for playing many different pieces of music, these instruments are physically designed to facilitate very particular types of music or musical compositions. They do this by physically setting up very specific relationships between sensors, the players hands, and consequently the musical parameters they explore.

If we think of pre-composed music software running inside an instrument as determining or limiting some of the choices that a performer can make, we can also think of the physical relationship of sensors as determining or limiting choices. Thus, instruments like the *Pyramid* that force physical sensor interdependency, or make players touch multiple sensors at one time, are not suited towards a musical application that needs one-to-one control. These instruments are however, ideal for applications where the point is to combine parameters, or where no sound is made if only one parameter is played. (For instance a sensor mapped only to volume, might create no sound

⁷ Truman, D., Reinventing the Violin, Thesis for the Degree of Doctor of Philosophy at Princeton University, Princeton, New Jersey, (2000).

⁸ See Chapter 5, Related Work.

if it is not played with a pitch sensor.) Moreover, the physical placement and relationship of sensors on instruments can both encourage certain combinations of musical parameters and prevent them. In fact, Gili Weinberg managed to turn the ability of these instruments to limit choices into a feature in the *Big Ring*. For this instrument, he wrote a piece that would be cacophonous if the player could trigger all the sensors at once. Thus, by limiting the number of musical lines a player can trigger simultaneously, the physical design of the instrument helps and guides the player in performing the piece.

A Hands-on Design Process

My ability to create a relationship between physical form and music software is ultimately a reflection of the direct process by which these instruments were designed. This process was a hands-on investigation with *real* materials (the final materials of the object, not mock-up materials or models) that led to new ideas and artistic choices that we simply could not have made or imagined without the *actual* experience of the physical instruments, materials and software. Each instrument went through numerous iterations in both physical form and software. Because some instruments were completed before others, this process often included the pairing of instruments with the *wrong* music software, (software that was not conceived originally for that instrument). The pairing of oddball software with instruments led to an iterative design process that allowed us to closely look at how different physical designs interacted with different types of music software. Sometimes the musical application came first,



Figure 12.8 Early mock-ups for the *Pyramid* included a stuffed prototype with drawn sensors, and a variety of sensor and ground electrode designs.

guiding the physical design of the instrument. At other times, the application was actually built around the features or even bugs of the physical design of an instrument. In addition, features of some instruments were added to others based on the playing of different applications with different instruments. In this way, a real back and forth between instrument design and music software emerged.

The ability to directly shape and form the fabric also allowed me to easily experiment and iterate with different physical forms. The smart textiles let me simultaneously experiment with the shape and size of the instruments, refine the electrical, tactile and visual components of the individual sensors, and design the overall placement of the sensors and ground electrodes. The typical process for instrument design involved first conceiving of an appropriate shape, mocking up a stuffed, non-electronic model, trying it for size and general sensor placement, and then changing it until it seemed reasonable to hold and play. These stuffed mock-ups were sewn from non-conducting fabric, and possible sensor and ground electrodes were drawn directly onto them. Once the correct shape and size was approximated, a pattern for the instrument was made. The design for the electrodes was then entered into the embroidery software. Different sensors and electrode designs were experimented with by pinning them onto the mock-up instruments. The panels for each ball were then embroidered and the instrument sewn together and stuffed. It was then tested with different software and usually redesigned.

Ultimately, this was an extremely immediate and direct hands-on process that let me physically experience the overall shape, size and tactile feel of these instruments far early than the CAD design of a plastic shell would allow.

A Few Essential Textile Advances

Creating embroidered sensors that are highly conductive would have been easy if I had not also had musical and design goals. I wanted the sensors to be soft and flexible, close to one another, and to create physical interdependency. I also needed to create ground electrodes that were automatically touched when the player grabbed the instruments. Consequently, new sewing techniques, that went beyond sewing an electrode with dense satin stitch on a single panel of fabric, had to be invented.

During the design of these instruments, a new, layered, and multi-stitch, sewing process was developed. This process allowed for the creation of highly conductive and flexible textile electrodes that used a variety of visual and tactile stitch styles. In the past, we were only able to use a continuous, multi-layered, satin stitch to create the level of conductivity we needed. This involved creating a single, continuous stitch path that went back and forth to build up layers of zigzag understitching and the final satin stitch, which was the only "fill stitch" we were able to get enough conductivity with. We also had to hand-place many stitches to increase continuity. The satin stitch itself had real drawbacks because it could not be very wide, or threads would fray and become loose over time. It also had to be

multi-layered and dense, making it stiff. As a result, creating wide objects had to be done with parallel swirls sewn from dense satin stitch paths, as in the *Generic Musical Ball*. These electrodes were relatively stiff, and using a single, parallel, swirled satin stitch was very limiting when designing the shape of the electrode.

The new, layered sewing process builds on what we already knew: that each electrode must be made from a continuous stitch path. However, it eliminates much of the need for stitch-by-stitch control that was necessary with satin stitches. This new process uses a light contour stitch to create an electrical under plane and then stitches over that plane with a variety of densely sewn, shaped objects. These objects tie the parallel lines of the contour stitch together, thus increasing conductivity. In the new sewing style, these objects may be made from a variety of fill patterns, not just satin stitches. The final, and most significant step in this process, is the addition of a light contour stitch over the top of these objects. Without this over-stitch, many objects stitched from lighter fill stitches, like tatami, are not conductive enough. This over stitching allows me to use different sewing styles and densities for ground and sensor electrodes. I like to use more tactile stitch patterns, like satin and bumpy stitches, for sensor electrodes, and smoother stitch patterns, like tatami, for ground electrodes. This process also creates a layered look that allows for the creation of great visual depth.

The new use of tidy stainless steel and wrapped nylon thread in the bobbin also allowed me to experiment again with sewing multiple electrodes on a single panel. This is very important because it allowed me to place

ground electrodes in better proximity to sensor electrodes, which meant that the player was ultimately better grounded, and did not have to constantly think about touching the ground electrode. It was also important because it allowed me to put sensors closer together and create physical interdependency. Finally, it simplified manufacturing considerably. A four panel instrument is easier to sew than a ten panel one. Unfortunately, each instrument panel still needs to be properly lined to prevent internal short circuits. This does add a small, but annoying, extra step to the sewing process.

Essential to the iterative design process used to create these instruments was a new composite braid that I designed with Bekeart Corporation. This braid let me quickly and easily connect the fabric sensors with the central circuit by tying a single mechanical/electrical knot. This made the testing of electrodes and sensor designs quick and easy, and made the connection between the circuit and the fabric skin, durable and soft.

Shaped Embroidered Musical Instruments

Sound Sculpture Pyramid*

The *Sound Sculpture Pyramid* was designed to be the ultimate in interdependent and intuitive instruments, letting players use a natural squeezing to play and explore different combinations of eight sensors, as opposed to one-to-one, finger-based control over specific sensors. In its final incarnation, this instrument allows players to explore timbre through the different combinations of eight different audio filters. The DSP musical software for this instrument (by Tristan Jehan) lets players explore the interaction of many different audio filters and the different timbres those interactions create. The physical design of the *Pyramid* reflects the need for filter mixing and timbral exploration software by emphasizing both the interdependency of the sensors, and an intuitive playing style that lets players use *natural squeezing* to play all the sensors at once. This design allows players to explore audio software in ways impossible with a mouse or a series of sliders and knobs. Most people can only control two knobs, or few a sliders at once. This instrument lets players control eight continuous sensors at once, and use the geometry of the instrument to navigate different sensor combinations. These combinations are determined not only by the player's choices, but by the geometry and layout of the sensors. Careful placement of the ground

* Music software by Tristan Jehan.

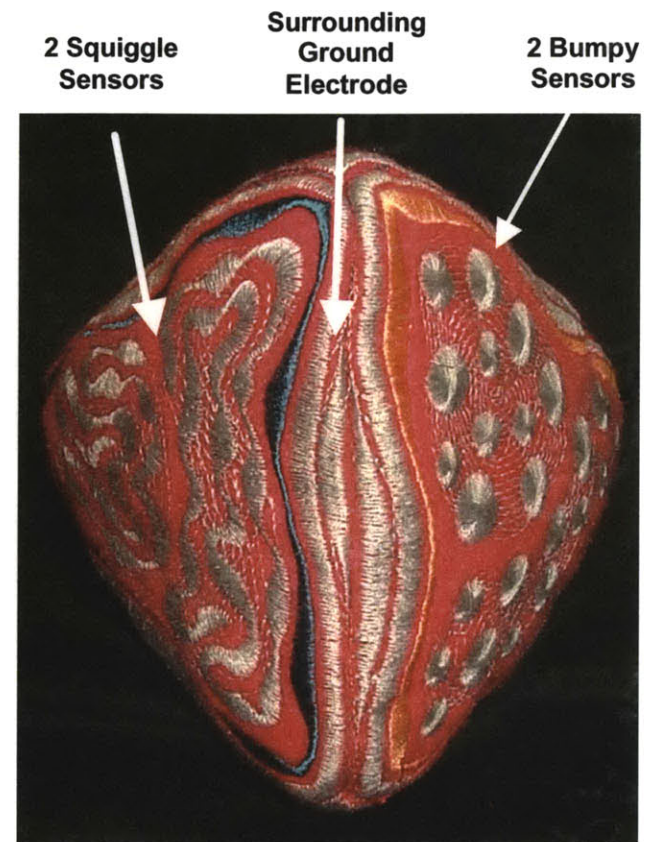


Figure 12. 9 The *Sound Sculpture Pyramid*.

electrode around the edges of the instrument guarantees that the player is immediately well grounded when he or she picks up the instrument. I am particularly satisfied with this instrument and its software because its musical output often seems an aesthetic and sensuous reflection of the gestural, squeezing input. The *Pyramid* is also the first instrument to explore the possibility and importance of tactile variety in the embroidered electrodes.

Physically, the *Pyramid* creates sensor interdependency in many ways. Its design encourages interdependent exploration by allowing players to touch all the sensors simultaneously, and preventing them from playing any one sensor at a time. The instrument is shaped like a four-sided pyramid to reflect the four sides of a person's cupped hands. By cupping his or her hands, a player can touch the entire surface of the instrument, playing eight continuous sensors at once. The *Pyramid* has two sensors per side, for a total of eight sensors. (Originally the *Pyramid* was designed to allow control of sixteen small sensors, but the small size of kids' hands made it important to make the sensors bigger.) The two sensors on each side are designed to visually and tactilely appear as one, making it difficult for the player to isolate them. Consequently, the two parameters controlled by the two sensors on each side are almost always played interdependently. If the ball is cupped in one hand, the player must touch two surfaces of the *Pyramid*, and usually four sensors.

While the shape of the instrument is symmetrical, i.e. with no up or down, the *Pyramid* has other design cues

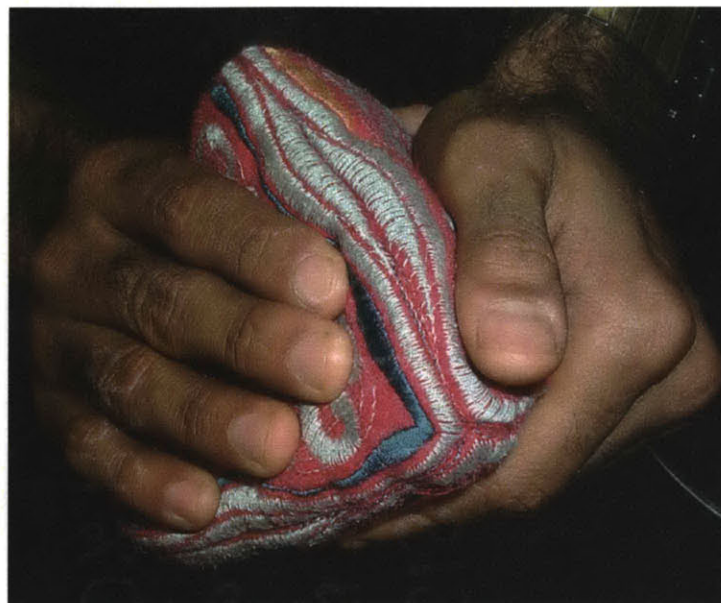


Figure 12.10 The four sides of the *Pyramid* reflect the four sides of cupped hands.

that allow players to use its geometry to navigate and explore different sensor and filter combinations. Each side of the *Pyramid* is marked with a non-conducting embroidered band. There are two blue bands and two yellow bands. The *Pyramid* also has two bumpy sides and two smoother squiggle sides. There is one blue and one yellow bumpy side and one blue and one yellow squiggle side. Players can squeeze the two blue sides, the two yellow sides, the two bumpy sides, or the two squiggles sides. Players can also grab the *Pyramid* by the corners, exploring the relationship of the three sensors that meet there.

An intuitive squeezing or playing style is also emphasized by the physical design of the *Pyramid*. The placement of the ground electrode on the outside edges of the *Pyramid*, and the sewing of it on the same fabric piece as the sensors, guarantees that the player is well grounded as soon as the *Pyramid* is picked up. (This was made possible by the wrapped bobbin thread.) Immediate grounding of the player when the ball is squeezed, makes generating an immediate musical response with simple hand squeezing intuitive and easy. The symmetric shape of the *Pyramid* (no top, bottom, right or left), encourages players to navigate with their ears and explore the timbral relationships, rather than the shape of the instrument.

The *Sound Sculpture Pyramid* was the first instrument to explore the tactility of the embroidered sensors. Before the *Pyramid*, all the electrodes on a single instrument possessed the same tactile qualities. In the *Pyramid*, the tactile differences between different sensors and the ground electrode help the player

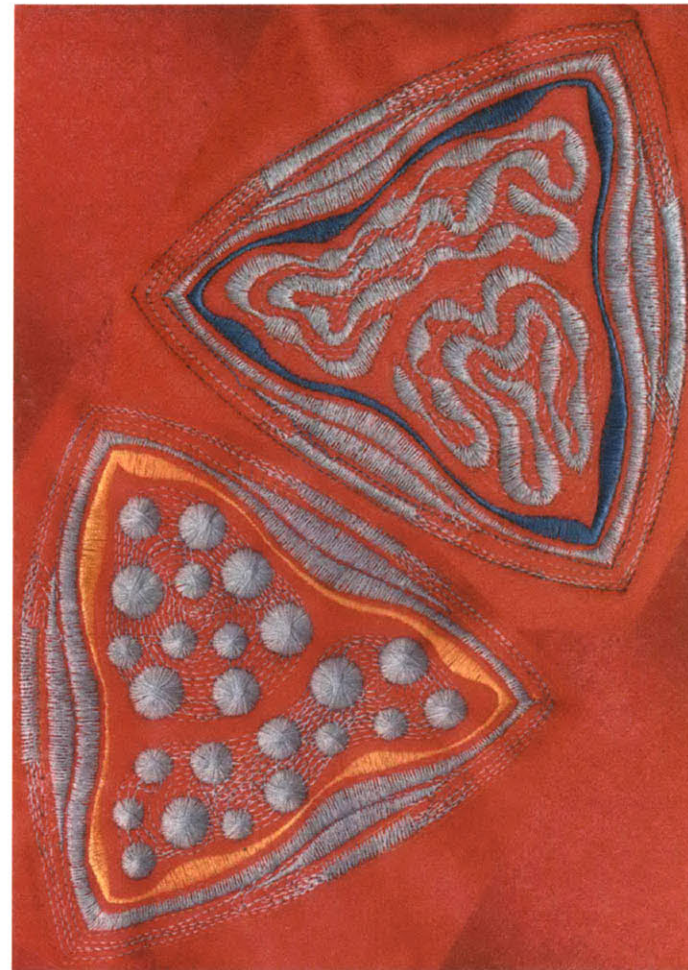


Figure 12.11 Flat design of the *Pyramid* sides, with yellow and blue bands, and bumpy and squiggle sensors.

navigate the instrument. The *Pyramid* has two sides with bumpy sensors, two sides with satin stitched squiggle sensors, and a more evenly stitched satin, ground electrode. The more tactile stitching of the sensor electrodes indicates that these are the places to touch. Players can also use the different textures to navigate the instrument. They can squeeze all the bumpy sides at once, or all the squiggly sides at once.

One major goal for the sensors of the *Pyramid* was to keep their sensitivity, (which, I empirically observed, required both high conductivity and surface area), but at the same time reduce the density and stiffness of the embroidery. For the *Generic Musical Ball*, I had created stable and highly conductive electrodes by densely sewing a continuous satin stitch. While this worked well, it was very stiff. The *Pyramid* used a new sewing method that combines a loose contour under-stitch (to provide a stable electrical plane that was flexible), with denser, well-spaced objects. The contour-stitched under plane created electrical continuity and redundancy; the dense objects on top provided something for the player's hand to electrically couple to, and the spacing of the objects kept the electrode flexible. For instance, in the *Pyramid*, each bumpy sensor is made up of a group of very tactile, stiff bumps sewn over an underlying, loose and soft contour stitch. The contour stitch provides the denser bumps with a soft, single electrical plane to rest on. Using the contour stitch and the wrapped bobbin thread allowed me to create sensors with many different shapes and textures while maintaining their soft qualities. The bumps make these sensors particularly sensitive, because their surface rises above the surface of the fabric to meet

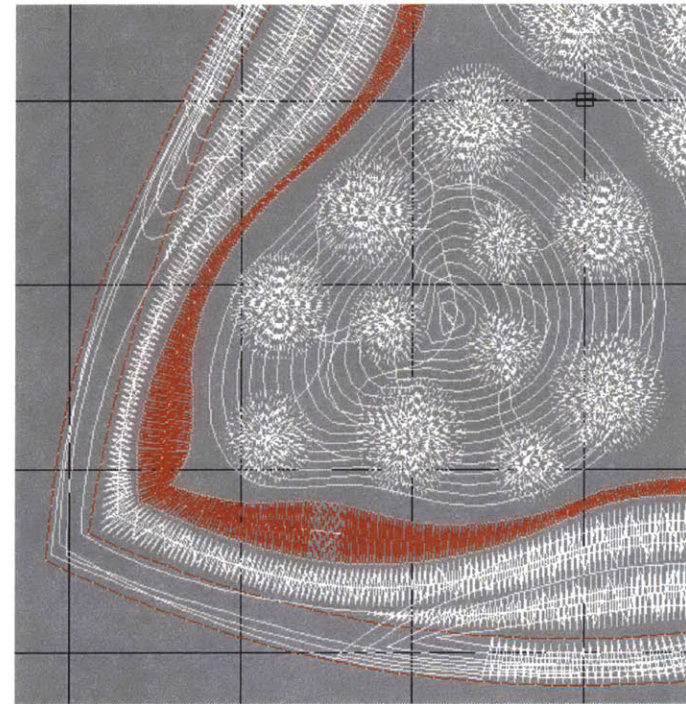


Figure 12.12 CAD file of bumpy sensors sewn over contour under-stitch base.

the surface of the hand, and they give the player something relatively stiff to push against.

The intimate link between the visual design and the electronic/sensing needs of the bumpy sensors is an excellent example of highly developed *functional ornament*. I started out creating many bumps as a way to let players feel the sensors and also as a way to make the two sensors on a single surface tactilely linked and inseparable. I wanted to cover the surface with a series of bumps in a way that prevented the player from distinguishing between one bump and another. These bumps were also essential to making the sensor reactive. The design of the electrical contour plane is both necessary for conductive and visual reasons. In this way, the visual design of the electrode is closely linked to its electrical function.

Using embroidered sensors and textiles allowed me to iterate on this instrument literally dozens of times. Numerous experiments were performed on the sensor design, perfecting both the bumpiness and the electrical properties. Ground design and placement was also experimented with many times. The ground needed to be very conductive, as big as possible and not accidentally short out the sensing electrodes adjacent to it. Ultimately, I wanted the ground electrode to be tactilely different than the sensing electrodes. I experimented with a tatami stitch that creates an even fill that is not particularly bumpy. However, at that point I could not figure out how to make it conductive enough for good grounding.

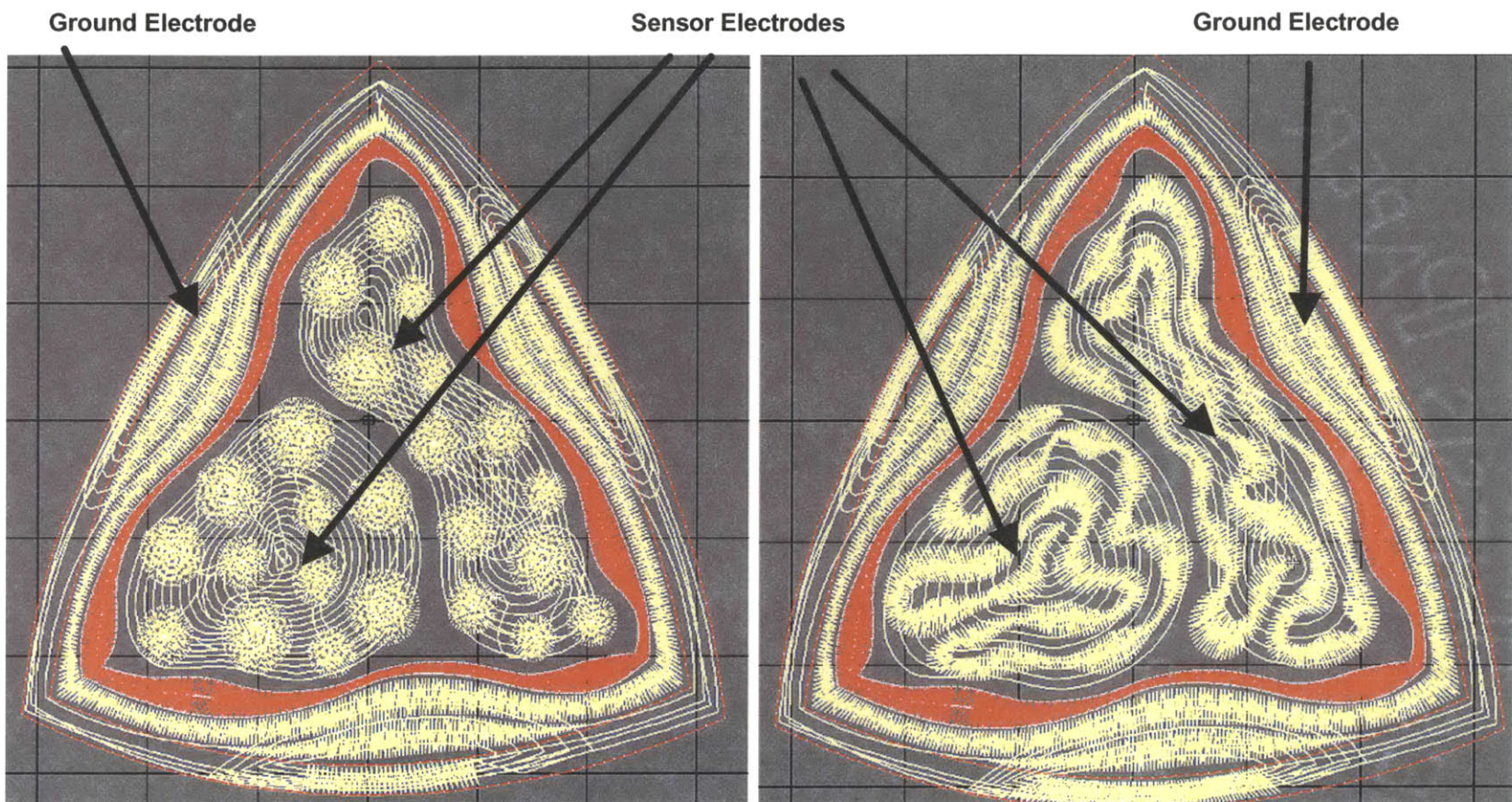


Figure 12.13 CAD files of two separate sides of *Pyramid*.

Melody Butterfly*

This instrument was my first attempt at designing an instrument that would let players create two complementary melody lines. Each melody line is determined by four continuous sensors that are mapped to volume, tempo, pitch/contour and note length. This butterfly-shaped, two-sided instrument was designed to let players control each melody line with a single hand. The four sensors per side were placed so that players could control each sensor with a single finger, like a piano. The instrument was asymmetric so players could orient top and bottom and front and back, being sure of which finger was controlling which musical parameter.

After many sensor designs it became apparent that hand-held, stuffed *Embroidered Musical Instruments* were not meant for one-to-one finger to sensor control. Many problems emerged when I tried to create this type of one-to-one control. It was ergonomically difficult to design an instrument that would fit any size hand and guarantee a good ground connection and finger-by-finger control. An important element of complex impedance sensing is the DC electrical connection between a player's hand and the sensors and ground electrodes. The squeeze balls let players explore, and find out how to best couple their hands to different instruments. The *Butterfly* forced EVERY person to use the tips of their fingers to play the sensors. Because different people have calluses and different skin thicknesses on different parts of their hands, not



Figure 12.14 *Melody Butterfly* designed for piano-like finger-by-finger control.



Figure 12.15 *Melody Butterfly*. Top, the front with four sensors. Bottom, the back with circle ground electrodes.

* Music software by Gili Weinberg.

everyone's fingertips worked equally well. Moreover, getting good contact with ground involves being able to press your hand against the electrode. I found that when players tried to use this sort of finger-by-finger control they tend to lift the rest of their hand away from the instrument, or hold it lightly. This meant that they were poorly grounded. Moreover, getting your hand in good contact with the electrodes involves creating a certain degree of physical pressure. But the fabric is squishy, so it provides no rigid surface to squeeze against (like a piano does). In the *Pyramid*, two hands could push against each other. In the *Butterfly*, each hand needed to be able push against itself to create the necessary pressure to play it well. But the soft touch required by individual finger control prevented the use of opposing force when squeezing the *Butterfly*.

I went through many sensor designs for the *Butterfly* trying to fix this problem. None of them worked. In the mean the time, we started pairing the melody software with highly interdependent *Pyramid* instrument. Our experiments playing the Melody software on the *Pyramid* were surprisingly successful. This is because creating any satisfying musical response with the instrument requires that the tempo and volume parameter of each line must be triggered together. This interdependent *need* of the software was reflected in the physical design of the *Pyramid*, whose design forced them to be played together. In addition, squeezing the *Pyramid* generally triggered enough sensors to create an interesting melody. But the *Pyramid* design still had some drawbacks. Because it was possible to squeeze only four sensors at a time (with one hand), and because there was little clear

orientation about which four you were squeezing, it was possible to squeeze the ball with one hand and get little musical results if you got the wrong combinations of sensors.

Melody Tube

The experimentation with the *Pyramid* and melody software led to a new physical design, the *Melody Tube*. The final *Melody Tube* combines the intuitive squeezing properties and interdependent sensors of the *Pyramid*, with the two-sided nature of the *Butterfly*. The final instrument is a long tube with two halves. Each half has four sensors that control the two melody lines. The sensors are designed diagonally to let players play all four at once with a single hand. The diagonal design of the sensor electrodes forces interdependency by guaranteeing that players cannot trigger the inner sensors, or the unnecessary sensors, without triggering the outer ones. By sliding their hands to the end of the *Tube*, players can trigger only the two sensors necessary to create a musical output. Thus as long one hand is squeezing one half of the tube the player is getting a musical response. The tube-like shape allows players to create opposing hand pressure for good sensor and ground contact. It also lets players explore to see which parts of their hands work better.

In this instrument, I used bumpy sensors, a wide satin stitch, and a contour over-stitch to create the sensing electrodes. The bumpy and satin stitches are highly tactile so the player can easily feel them. Tactility is something I look for when making a sensor electrode. The bumpy dots also give the player's hand something

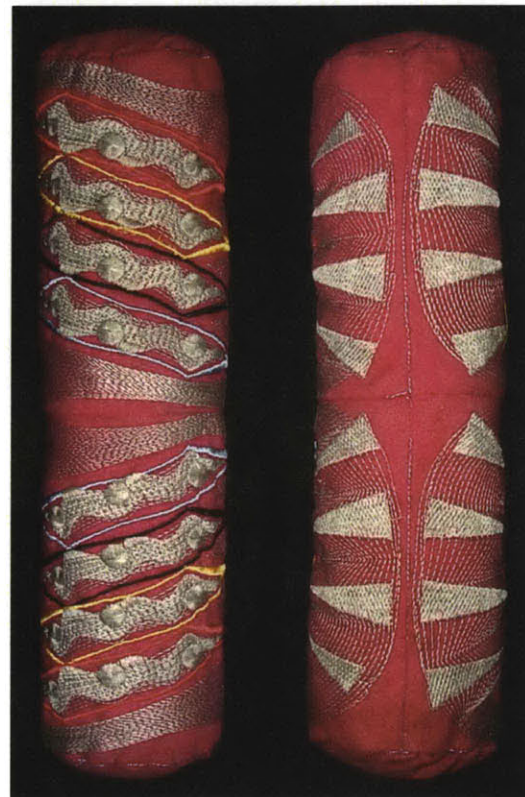


Figure 12.16 *Melody Tube*. Top shows relationship of sensors to player's hands. Below left, sensor design. Below right, ground electrode design.

to push against. The light contour over stitch is the final piece of my new sewing style for highly conductive electrodes. I empirically found that by over stitching any filled object with a light contour stitch, it substantially increased its conductivity. Over stitching tacks down the threads of a wide satin stitch. It also works to electrically improve and connect the relatively smooth tatami triangles in the ground electrode.

Problems with this instrument still remain. Having the four sensors in a line or row means that there is a very specific order or grouping in which they are triggered. For instance, the two middle sensors have a tendency to be triggered all the time. I have also found that it is easier to reach the maximum value on the outer sensors than the inner sensors because of the pressure your hand creates while squeezing. Ultimately, I would like to redesign these sensors in a more circular pattern, on the end of the tube.

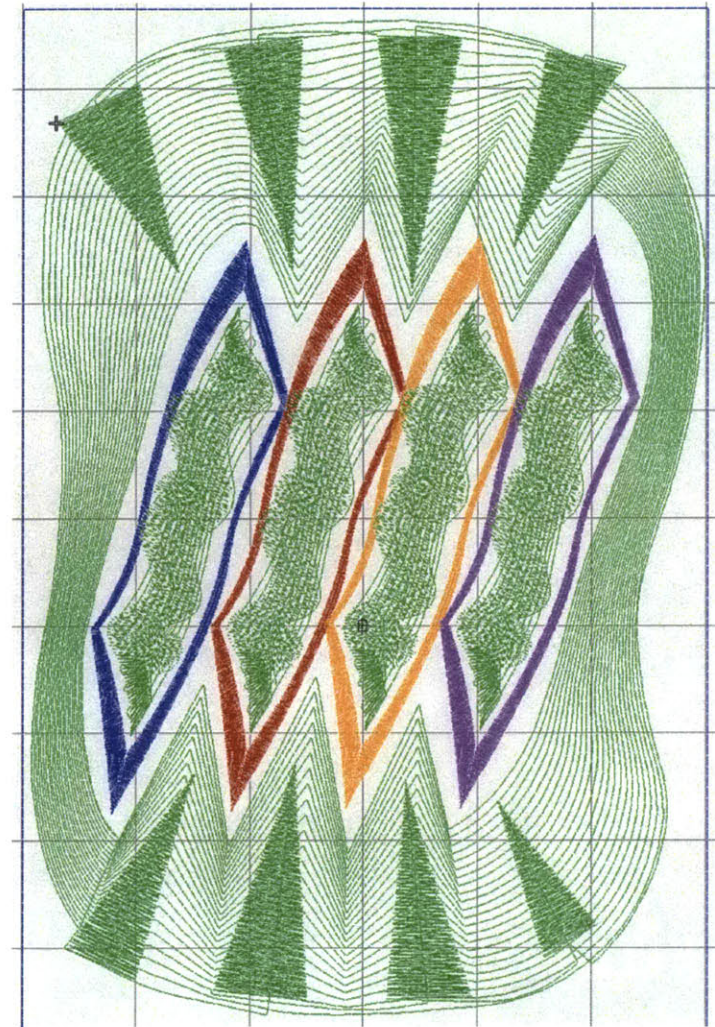


Figure 12.17 CAD file of *Melody Tube* design.

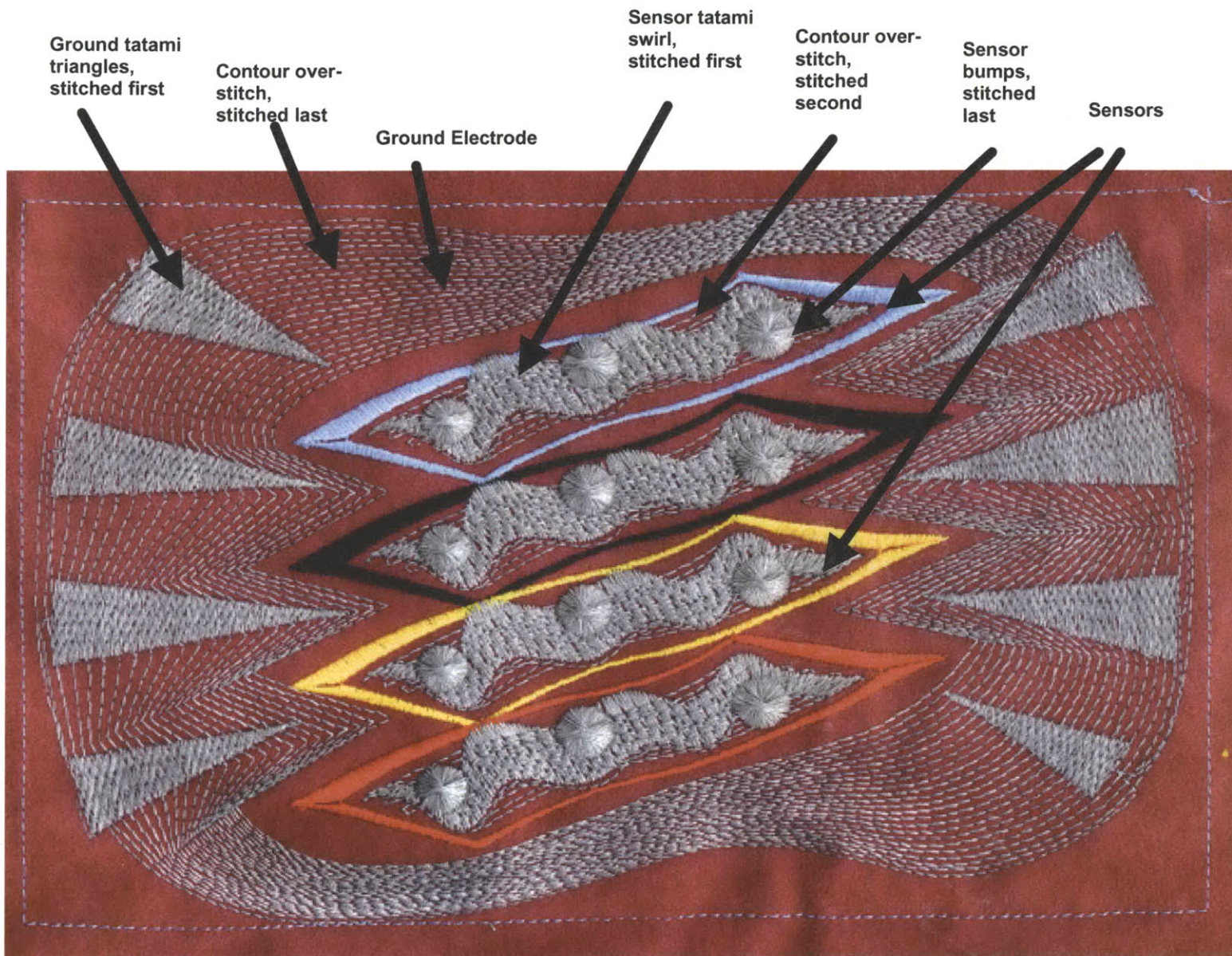
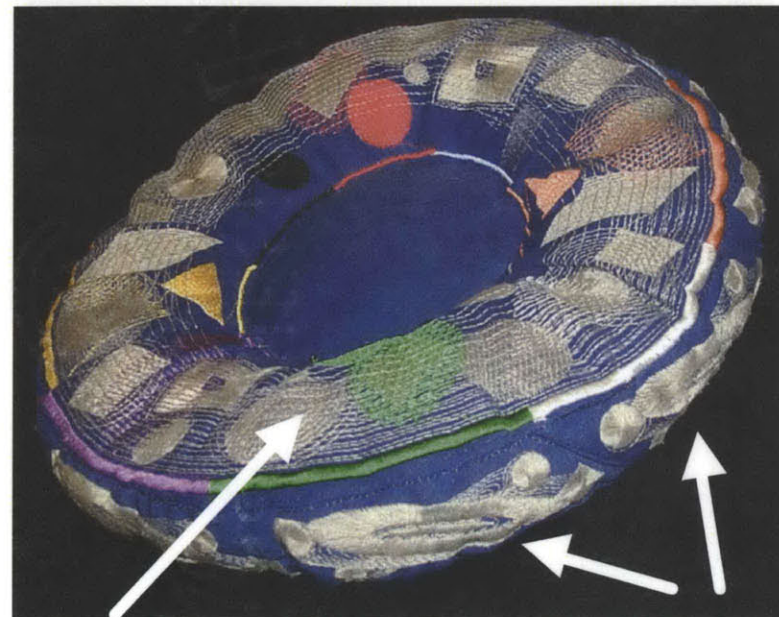


Figure 12.18 Flat panel of *Melody Tube* design.

Big Ring for Re-Composing Music*

Both the software and physical form of this instrument were designed to take advantage of what had been seen as a bug in the *Generic Musical Ball*: the limited number of sensors players can touch at a time. The music for the *Big Ring* is eight tracks of pre-composed music. If played at once, these tracks sound like a cacophony. The size and placement of the sensors on the ring force players to select and blend just a few (no more than four) tracks at a time. This process is designed to let players “recompose” the music.

The *Big Ring*'s sensors are wide, allowing players to cover only one at a time with a single hand. By designing the ends of the sensors to diagonally overlap, players can also trigger two at a time. The bumps at each end of the sensor let players know tactilely when they are about to touch two sensors. The placement of the sensors on the outside edge of the *Ring* guarantees that the player's hand contacts the sensors when it is first grabbed. The large ground on the top and bottom of these sensors is easy to reach. But while this design may seem almost identical to the *Generic Ball*, it is not. The ring around the ball is sized so that it can be grabbed with one hand and squeezed. This allows players to use the opposing pressure in a single hand grab to make a strong electrical contact to the ground and sensors simultaneously. In the *Generic Ball*, opposing hand pressure with a single hand could not be used because of the round shape.



Giant ground electrode

Sensors

Figure 12.19 *Big Ring*. Top, relationship of hands to sensors and ground. Bottom, ground and sensor design.

* Music software by Gili Weinberg.

With this instrument I was able to really experiment visually because of a new sewing technique that made it even EASIER to make highly conductive electrodes from the less dense tatami stitch. Using a loose contour both *under and over* the primary shapes of the electrode, (in the past I only used it under the objects), dramatically increased the conductivity and allowed me to use far less conductive, but more creative, stitches and object shapes. The result of this process is the visual layering of objects with different densities in the ground electrode of the *Big Ring*. Because of the new possibilities that this layered sewing process the ornate design of this ground electrode may have gotten away from me. I had observed that people playing the balls were drawn to touching ornate areas. Players who touch this instrument often think that the ornate ground electrode is the sensitive part of the instrument and attempt to touch the squares and circles to make music. But this was the first time I got to really visually experiment with different stitch styles and layering, so I was a little too excited to restrain myself.

Soft and pliable ultra-suede is the substrate of this instrument. Ultra-suede is thin enough that it does not add thickness and stiffness to the sewn electrodes. In the past I had tried to work with polar fleece, but found it became too stiff when embroidered. This fabric is water repellent (good for preventing sweat from shorting things out), and at the same time it has a velvet-like quality that makes it tactilely appealing.

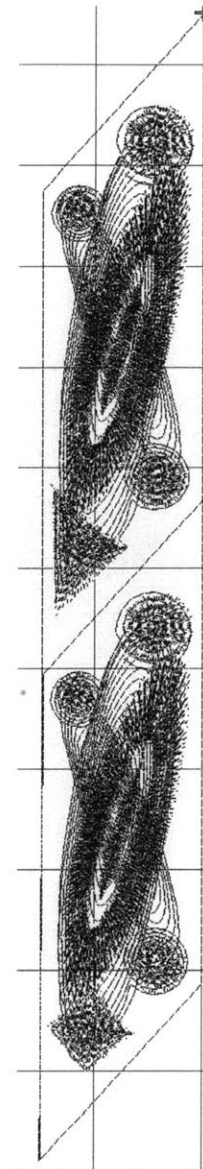


Figure 12.20
Sensor electrodes
of the *Big Ring*.
The diagonal
design makes it
easy for one hand
to play two at a
time.

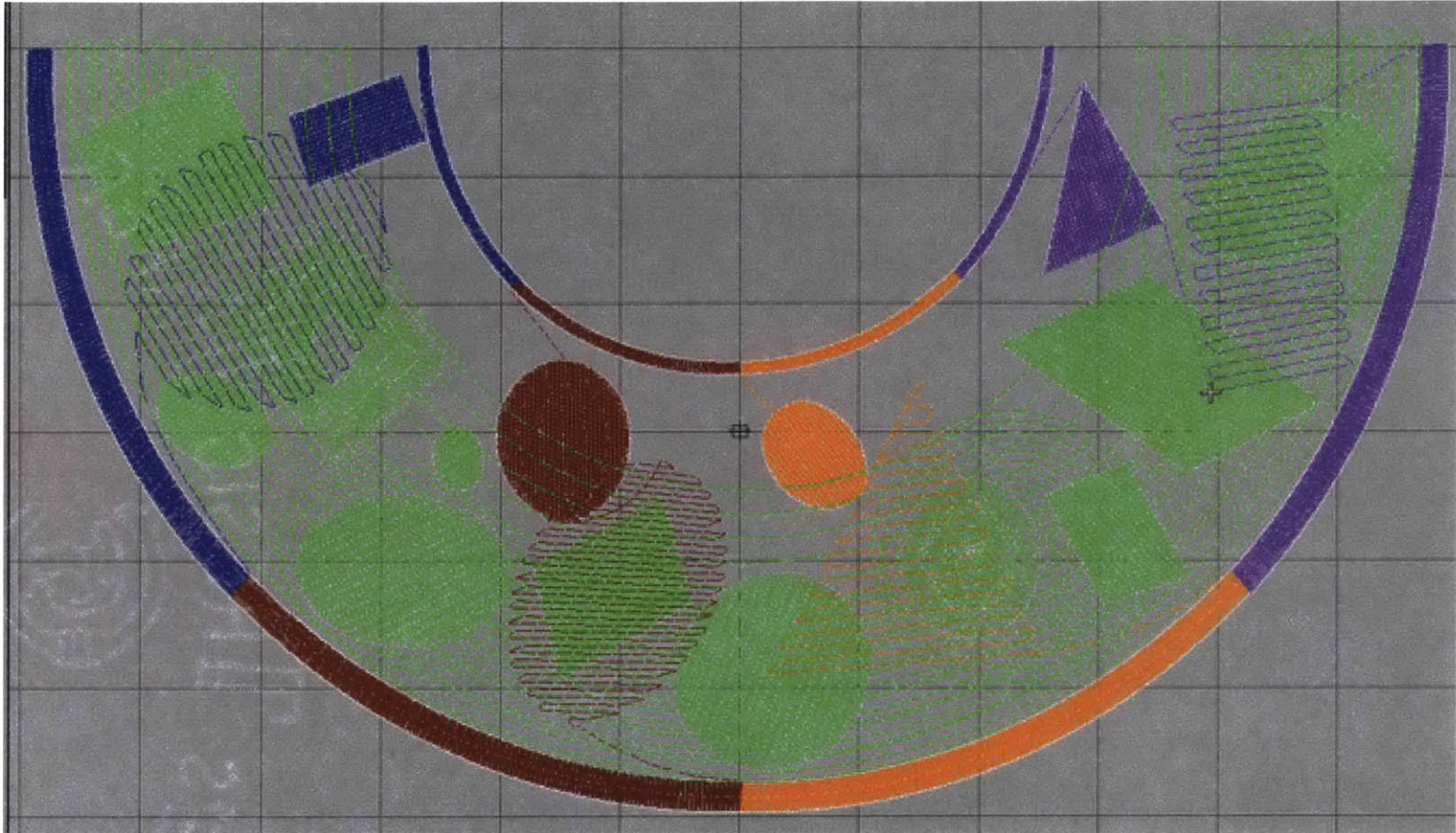


Figure 12.21 *Big Ring* ground electrode.

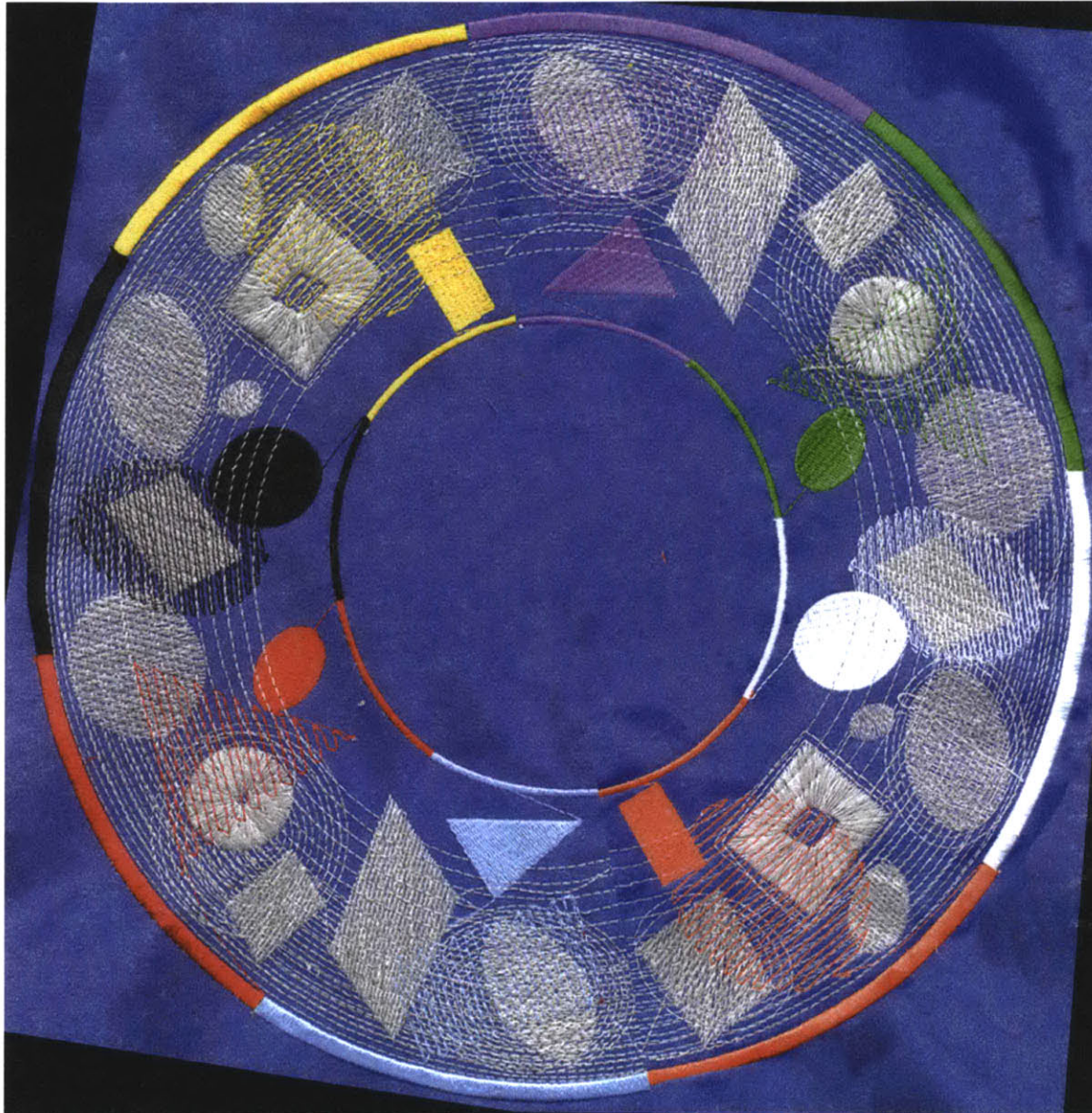


Figure 12.22 Flat version of complete *Big Ring* ground electrode.

Chapter 13.

Complex Impedance Sensing

Introduction to the Technical Story

The technical story of this thesis includes a timeline of developments in the sewing process, an index of electrically active textiles, a model of complex impedance sensing, and a definition and test for the sewability and flexibility of yarns with added conductive fibers. A summary of the technical contributions of this thesis includes various types of work, some of which is also explained in the project portfolio, rather than here in the technical story. These contributions include the first working prototype of a fabric keypad, a row and column switch matrix (with Emily Cooper), the first embroidered keypad, (with Rehmi Post). (I jointly hold a patent with Rehmi Post, Emily Copper and Josh

Smith on fabric circuit elements.¹⁾ After working to create the first high impedance embroidered keypad with Rehmi Post, (in the *Musical Jacket*), I further developed the embroidery and sewing process to create far more conductive and stable fabric electrodes, and sensors and circuit elements that were also soft, flexible and visually diverse. I directed and motivated the research that led to pressure sensing on fabric electrodes. I worked with Bekeart Corporation to create a new composite thread/braid that can easily tie an electrical/mechanical knot between a circuit and fabric electrode. (This yarn is now manufactured in small quantities by Beakart Co.) The machine embroidered electrodes and the knottable composite braid developed for this thesis both have been perfected to the point where the ultimate limitation on their conductivity is the fundamental conductivity of the cold-worked stainless steel. These two composite materials, (the machine stitched electrodes and the braid) combine high impedance textile materials with excellent mechanical properties, with low impedance materials that possess limited mechanical functionality. I created an index of electrically active textiles and described their mechanical and electrical properties. I also empirically developed an electronic model for understanding complex impedance sensing with fabric electrodes. This model provides support for the empirical observations made while designing the embroidered instruments and a guide for instrument design that enables better sensing. This model has

¹ Rehmi Post, Maggie Orth, Emily Copper, Joshua Smith, Electrically active textiles and articles made therefrom, US Patent# 6,210,771, (2001).

played an essential role in the design of my *Embroidered Musical Instruments*. I developed a definition and test for sewability and flexibility in conductive fibers. I co-invented and patented a new physical computing interface, the *Triangles*, and their new physical and electrical connector that allowed an immediate electrical and mechanical connection between two physical objects, specifically the *Triangles*.

Overview of the Sensing

This chapter presents a series of models, from simple to complex, of the sensing method used in both the embroidered keypads and *Embroidered Musical Instruments*. The sensing method used in all the *Embroidered Musical Instruments* is a measurement of the change in the RC time constant in an RC circuit. (Figure 13.2) The measurement is made in the time domain on a PIC microprocessor. The motivation behind creating these models was the empirical observations that I made while building the instruments. During this process, I noticed that measuring *pressure* required much more conductive electrodes, and a far more stable grounding of the player. It also required a *few black art* factors, like unwashed and warm hands, and lots of surface area and contact area. Understanding the role of these factors and the role of the human body in the sensing technique led me to look into a more precise model of the circuit and sensing method. My final model of the sensing circuit is based on a model of skin impedance from biomedical electrode technology. This model

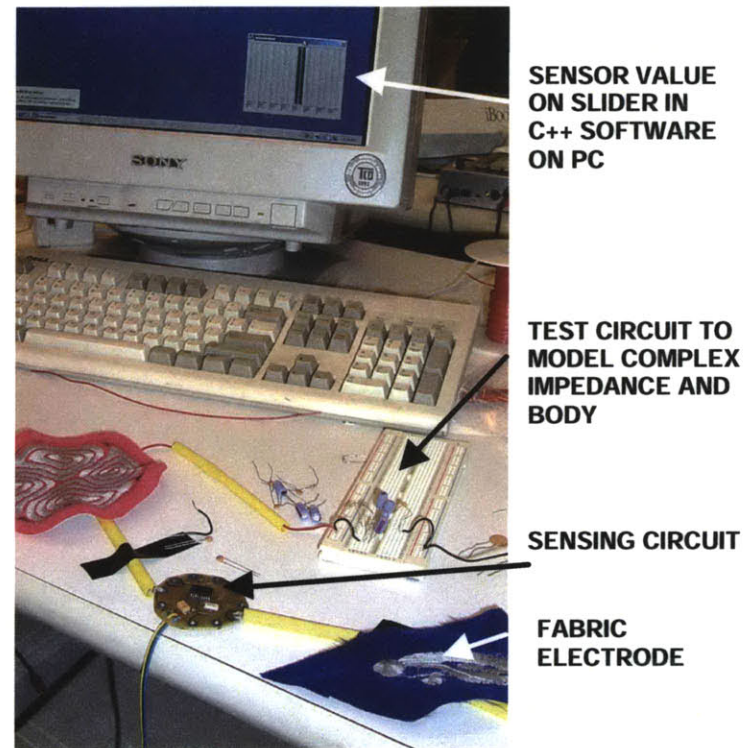


Figure 13.1 Mock-up of embroidered instrument and test circuit used to simulate the body, skin and electrode impedance.

demonstrates that the continuous measurement taken with the embroidered instruments is fundamentally a measurement of the change in skin impedance, and electrode to skin coupling. In the *Jacket*, this method is used to sense on/off. In the *Embroidered Instruments* it is used to sense a continuous measurement of *pressure*, or what I came to call *intimacy*. Empirically this appeared to be a combination of area of hand, area of electrode, pressure, temperature and conductivity of the skin and time.

All the *Embroidered Musical Instruments* use a similar central sensing circuit, which measures the change in the RC time constant and communicates that change serially to a PC. The PC maps the serial data to sliders and music software. The central circuit is tied to the embroidered electrodes with a low impedance stainless steel braid. All the models presented in this chapter were confirmed or discovered experimentally with the use of this same circuit. A mock-up embroidered instrument was built and connected to the C++ program, which mapped the sensor data to sliders. (Figure 13.1) The models of the body and skin were constructed in a test circuit and their effect on the sensing circuit was observed using the C++ software.

A Simple Capacitive Model

Simple Model 1 diagrams the player's hand in relation to the circuit elements. In this model, the internal body is modeled as a simple capacitor, which holds the charge in place, changing the RC time constant. The microprocessor measures change in the RC time constant by charging its pins to the upper TTL level

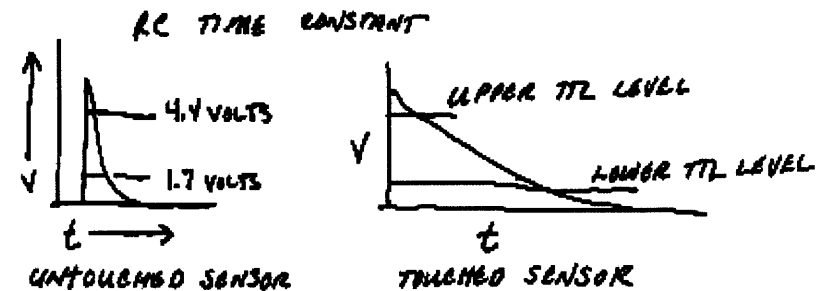


Figure 13.2 Change in RC time constant on touched electrode.

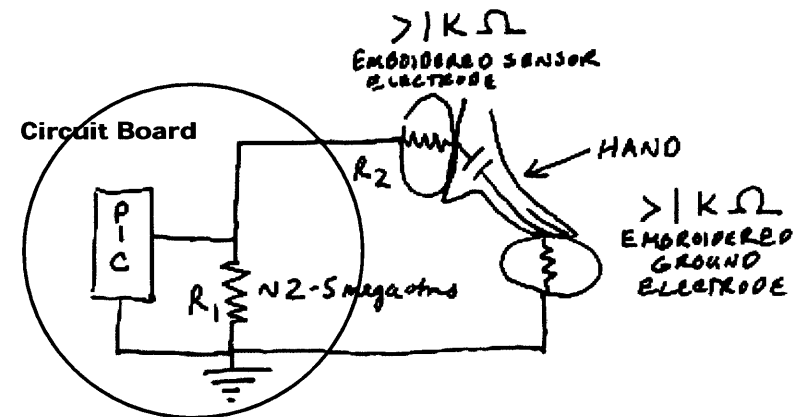


Figure 13.3 **Simple Model 1**, the body as capacitor.

and then watching until the charge or voltage level decays to the lower TTL level. (Figure 13.2) When the electrodes are touched the charge is held in place and the time constant increases. (Figure 13.2) If the time exceeds the normal time constant, it is assumed that the electrode has been touched and either an on/off switch is triggered, or measurement of the change in time is made.

When modeling the sensing method in the *Musical Jacket* it is possible to use **Simple Model 1** and imagine the body or hand as a capacitor. This is because ANY change in the RC time constant is valid to measure on/off and no continuous information is needed. Almost no environmental factors affect this sensing. Consequently, embroidered electrode resistances can vary up to 10K ohms.

Grounding Issues

On/off sensing in the *Musical Jacket* was functional when the player was AC coupled to ground. In the fully functional *Jackets*, (with MIDI synthesizer and speakers), this AC grounding between the sensing circuitry and the player was created by the fabric bus that distributed ground, serial, audio and power across the back of the jacket. In the *Buzzy Jackets*, (*Jackets* that had only audio buzzers directly attached to the sensing circuit), a fabric ground plane had to be ironed onto the back of the *Jacket* to establish a relative grounding between the players body and the sensing circuit. This is very different from continuous sensing, which requires direct DC coupling of the player's hand to the ground electrode to be effective.

What is Pressure in the *Embroidered Instruments*?

The *Embroidered Musical Instruments* measure pressure or continuous information by measuring the length of the RC time constant on the embroidered electrodes. This is not a forgiving process. Empirically, I observed a number of factors that directly influenced both the stability and the sensitivity of the sensing. (The stability refers to how *smooth* and continuous the measurement was, and the *sensitivity* refers to how quickly and easily the sensors reacted to the players squeezing.)

Black Art Sensing Factors

The *black art* factors that affected the continuous sensing in the embroidered instruments included:

- The contact surface of the electrode, or how much conductor the skin could contact easily due to the area and loft or fuzziness of the electrode.
- The area of the electrode.
- The conductivity of the electrode.
- The temperature of the player's skin.
- How recently the player had washed his or her hands.
- The part of the hand used to touch.
- The individual player.
- The quality of the grounding to the player.
- The time that the player was in contact with the electrodes.

Creating a more stable and reactive sensing process involved manipulating all these factors. It is worth noting that predictably, the sensitivity of the circuit

increased when the pull down resistor increased in size from 2 to 5 mega ohms. However, the instability or noise in the circuit increased also. Using a larger pull down resistor is an important design strategy when designing electrodes with smaller areas.

While building the *Embroidered Musical Instruments*, I noticed that decreasing electrode resistance and increasing area improved the sensitivity or the reactivity of the sensor. Over time I began to wonder why. If the rate of decay is *related* to RC directly, then why does the RC time constant increase when the resistance of the electrodes (R_2 in **Simple Model 2**) decreases? I also wondered why decreasing the resistance on the electrodes increased the stability of the sensing technique. **Simple Model 2** takes into account the resistance of the embroidered electrodes in the circuit. From this model I began to wonder where the continuous measurement came from. Certainly when a player squeezed the ball the RC time constant increased, but what did that mean? If the internal capacitance of a person's body is fixed, what was changing the RC constant when the ball was squeezed? Observation led me to believe that this measurement was a matter of contact. The better a person was in contact with the sensor, the longer the RC time constant and the more "pressure" was read. I defined contact as the area of the hand on the electrode, the time it was on the electrode and the quality of contact, i.e. the temperature of the hand, sweatiness and saltiness.

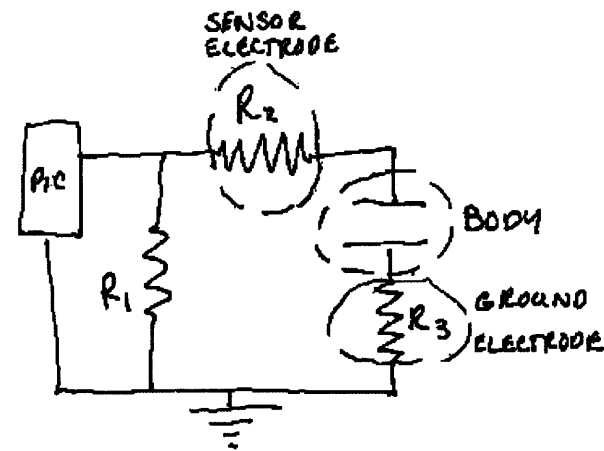


Figure 13.4 **Simple Model 2**, electrodes in series, body as capacitor.

Test Circuits

The following test circuits were built to model the body and skin and placed in the ball circuit to observe their results. The first test circuit that I placed in the *Embroidered Instrument* circuit was designed to understand the capacitance and/or complex impedance of the body. I started with a test circuits of the internal capacitance of the body. On the LCR meter the Cs and Rs (series resistance and capacitance) measured .5 pico farads and 10-100 kilo ohms respectively. According the Joshua Smith, the internal resistance of the body (beyond the skin) as practically zero and the internal capacitance of the foot as large as hundreds of pico farads.² In **Test Circuit 1**, with a capacitor in series, a minimum capacitance of 360 picofarads was required to change the RC time constant. The sensors reached their maximum range at 1200 picofarads. Varying the size of the capacitor varied the RC time constant. It is highly significant that NO sensing was accomplished when the body was modeled with ANY parallel resistance, (see **Test Circuit 2**).

Test Circuit 3 involved modeling the skin impedance, skin to electrode contact impedance, and electrode resistance as a simple resistor and varying that resistance. This model confirmed my observation that decreasing the resistance on the electrodes increased the sensitivity or change in the RC time constant. The lower the resistance of R1 and R2, the more sensitive

² Smith, J., *Electric Field Imaging*, Thesis for the Degree of Doctor of Philosophy, at the Massachusetts Institute of Technology, Cambridge, MA, (February, 1999).

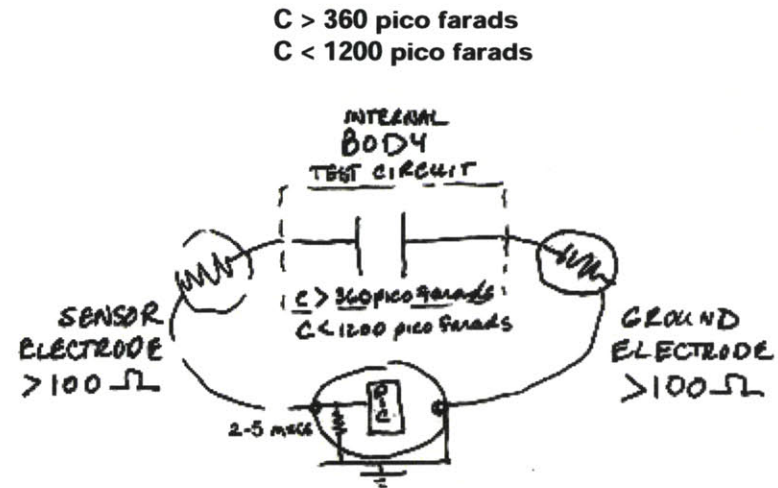


Figure 13.5 **Test Circuit 1**, the body as capacitor.

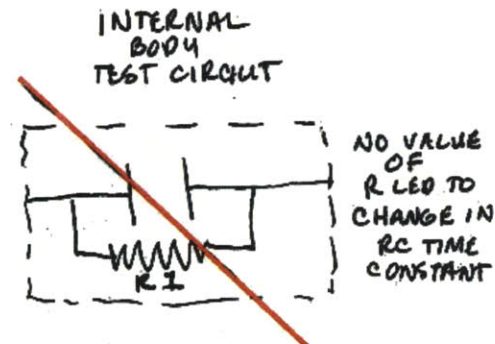


Figure 13.6 **Test Circuit 2**, the body as complex impedance.

the circuit was to lower capacitances in series. Larger body capacitances, (modeled with a real capacitor), were required to activate the sensor if large resistances were in place. Given a constant body capacitance of less than 1200 pico farads, (required for the maximum sensor value), the resistor values that affected the circuit behavior ranged from 1 K on both the ground and sensor electrode, for a minimal decrease in the RC time constant, to 13 k for the maximum.

This circuit also showed that the two embroidered electrodes (ground and sensor), could be modeled as a single resistor in series with the capacitor (the body), (**Test Circuit 4**). It is significant that a full range of sensing values could not be achieved with this sensing method without a DC connection to ground. An AC coupling to ground of the player only allowed for a small variance of the RC time constant. This circuit also demonstrated that as the resistance of the electrodes increased, the instability, i.e., jumpiness of the measurement also increased.

While modeling "what was going on between the skin and the electrode" as a resistor initially worked, further consideration led to thinking about it as a complex impedance. I also began to wonder which of the two were varying, the body capacitance or the series impedance? At this point I was excited to discover that models of skin impedance and skin to electrode impedance created for the biomedical industry supported much of my empirical findings. Figure 13.9 shows Swanson and Webster's Model for Skin

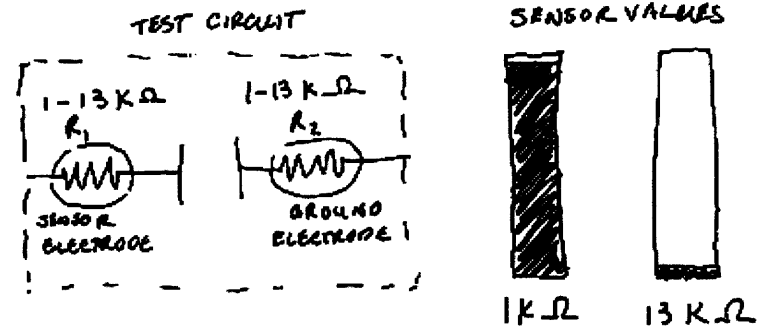


Figure 13.7 **Test Circuit 3**, skin to electrode as simple resistor. The greater the resistance, the less sensitive the sensing.

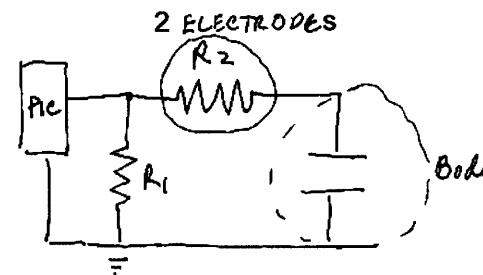


Figure 13.8 **Test Circuit 4**, the two electrode impedances are modeled as one.

Impedance³ designed for biomedical electrode technology. This model shows a complex impedance between the skin and the electrode and in the skin itself.

Swanson and Webster also list the factors affecting skin impedance as: "electrode paste concentration, emotional state of the subject, current amplitude, skin abrasion, electrode area and sweat."⁴ These factors align extremely well with the empirical observations that I have made about improving the sensing technique. Moreover, they point out that most of the impedance takes place in the epidermis, and that it can vary widely depending on the thickness of skin. Their model discounts the impedance of electrode to skin because of use of a highly conductive paste. My model has no paste, and this impedance must play a more substantial role.

Figure 13.12 shows the role of the body and skin impedance in the embroidered musical instrument circuit. Figure 13.10 reduces the electrode, electrode to skin impedance and skin impedance to a single impedance Z . This reduced model demonstrates the 2 possible variables in the circuit, the complex impedance Z and the internal capacitance of the body. The fact that body size and proximately to the sensors are constant as well as my own empirical observations

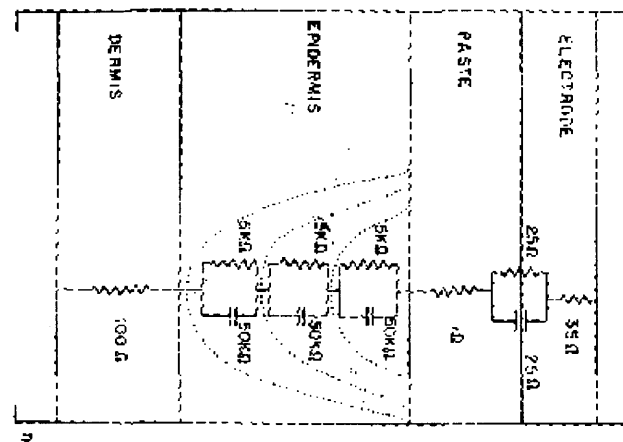


Figure 13.9 Swanson and Webster's Model for Skin Impedance.

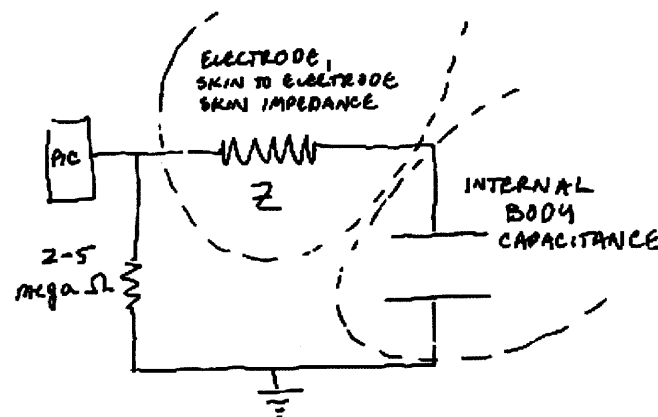


Figure 13.10 Complex Impedance of skin, skin to electrode, and electrode reduced to single impedance Z .

³ Swanson, D.K. and Webster, J.G., *A Model for Skin-Electrode Impedance*, in Miller, H.A. and Harrison, D.C. (eds.), *Biomedical Electrode Technology: Theory and Practice*, New York: Academic Press, (1974).

⁴ Ibid.

leads me to conclude that Z is the fundamental variable in this circuit. The reduced model is useful for understanding why decreasing the electrode resistance increased the RC time constant. If we model Z as R2 we find that a simple voltage divider has occurred. (Figure 13.11)

$$VR1 = \frac{R1 * v_o e^{-t/rc}}{R2}$$

This equation points out the inverse relationship of R1 and R2 to t, supporting my observation that R2 must be reduced.

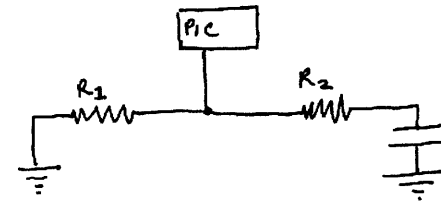


Figure 13.11 Circuit as voltage divider.

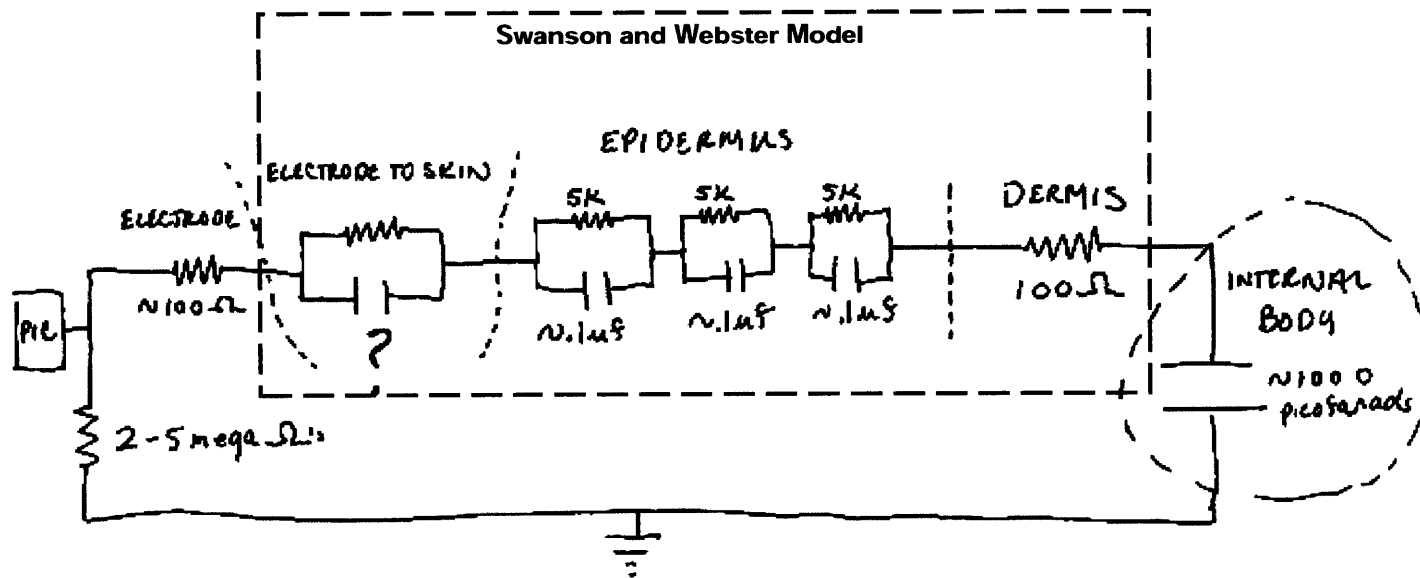


Figure 13.12 Final model of sensing circuit with skin and body.

Design Implications of Sensing Model

The consequences of using the skin impedance model for this type of sensing are significant to both the physical design and software of embroidered instruments. Clearly, electrodes must have a large area and lots of conductive material to touch. An excellent DC coupling of the player to ground must also occur when the ball is first touched. The ground must therefore, be touched immediately by the player when he or she grasps the instrument. Given the SIGNIFICANT role that skin impedance and skin to electrode impedance plays in this model, it is important that the design of such instruments does NOT constrain the placement of players' hands, nor require specific parts of the players' hands, like fingertips to play specific sensors. Due to calluses, each player may have different areas of skin on his or her hands that are more conductive. He or she must be able to experiment with hand placement to see what type of squeezing works best. Usually, the whole palm and multiple fingers work far better than single fingertips. Thus, it is important to make instruments that use a *natural squeezing style* for playing, rather than finger-by-finger control.

The requirements of reducing skin impedance result in two classes of instruments with different physical designs, and different music software styles. These two instrument styles are clearly represented in the final *Embroidered Instruments* designed for this thesis. They include large sensors for precise, single parameter

control, and smaller sensors that explore physical interdependency.

Large Sensors for the Precise Control of a Limited Number of Musical Parameters

Large sensors enable the precise control of one or two parameters at a time. Because large sensors reduce skin impedance, they provide stable sensing and more precise control. Consequently, they are better for direct one to one mapping to a musical parameter, like volume. Large sensors also require a smaller pull down resistor, which introduces less noise into the sensing process. Because the sensors are large, they do not let players trigger more than one or two at a time. As a result, they are not good for exploring the interdependency of many musical parameters. (The *Big Ring* is this type of instrument.)

Small Sensors for Intuitive Exploration of Numerous Interdependent Musical Parameters

The second instrument style has small sensors that explore interdependency. Small sensors are less stable because they require a larger resistor to ground to increase sensitivity. But small sensors let players trigger many sensors at a time. By using the less stable sensors to explore interdependency, some of the sensing instability is masked. (Both the *Melody Tube* and the *Sound Sculpture Pyramid* are this type of instrument.)

Software Filtering*

The artifacts created by both the skin impedance and electrode to skin impedance can be relatively easily filtered in software, using a variety of methods. The method that is currently used is a weighted average. The last ten sensor values are stored in a buffer. They are averaged. They are then added to the latest value in the buffer and averaged again.

N= array of values in buffer

X = New data

Nav = average of values N

Filtered value = $(N_{av} + x)/2$

This method smoothes the sensing noise and provides a limited lag in the filtered values over the raw values.

Given the fact that some players are not as reactive as others (either a function of their skin impedance or their body's capacitance), a calibration technique in higher-level software has been designed. This technique changes the maximum value of the sensor from 128 to a lower number, such as 40. While some resolution is lost with this technique, it is very helpful when working with children, who have small hands and bodies.

Beyond The Resistive Element

The artifacts produced by measuring skin impedance in the *Embroidered Musical Instruments* led to the

* In collaboration with Alejandro Sedeno.

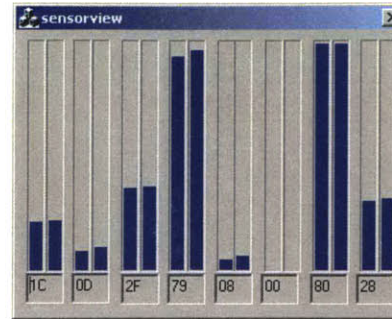


Fig. 13.13 Filtered sensor data on left next to raw data on right.

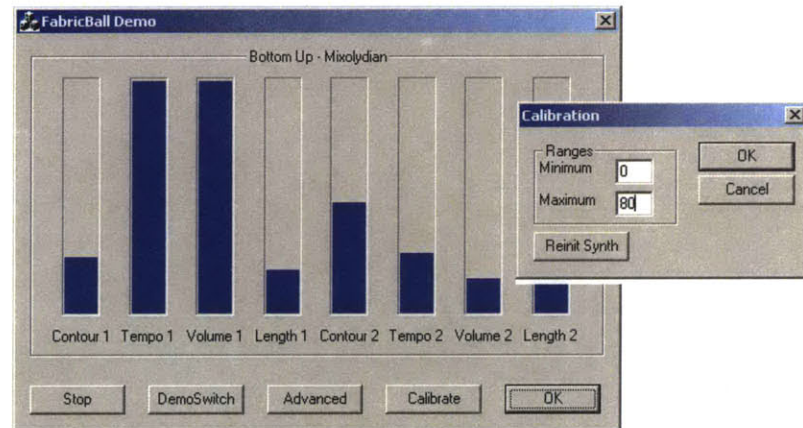


Fig. 13.14 Eight sliders of data and C++ calibration software that lets the player choose the maximum value best for him or her.

question of whether it would be possible to make a continuous, pressure or contact based measurement on the fabric electrodes that produced fewer artifacts as result of skin impedance. There is a broad history at the lab of continuous measurement in the capacitive realm for non-contact based measurement, using a variety of "Fish" sensors.⁵ To better understand this problem, a network analyzer was used to look at the frequency response of the fabric instruments when the hand is in contact with the two electrodes. This analysis was meant to look at whether it would be possible to reduce the skin impedance noise in the circuit by sensing at a higher frequency, and whether continuous sensing of contact or pressure, vs. non-contact gestures, could occur at a higher frequency. The following images and diagrams are a result of an analysis of frequency response using the geometry shown in Figure 13.15.

Frequency Response Across Skin and Fabric Electrodes

The network analyzer was used to look at the frequency response of the real and imaginary impedance and the log magnitude and phase in the fabric instrument circuit. The following images are from a frequency sweep from 50 KHz to 10 Mhz. (Figure 13.16) A strong circuit resonance appeared at approximately 6Mhz. This resonance is related to the electrode geometry and changes with different

⁵ Smith, J., Electric Field Imaging, Thesis for the Degree of Doctor of Philosophy, at the Massachusetts Institute of Technology, Cambridge, MA, (February, 1999).

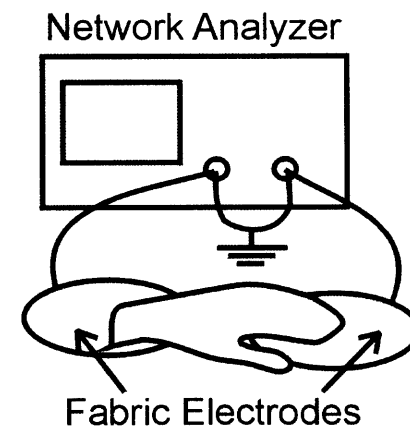


Figure 13.15 Geometry of the sensing circuit used to analyze frequency response.

electrodes and different relationships between the electrodes.

Three basic hand-to-electrode configurations were tried. The first was with no body or hand in the circuit, the second was with the hand just above the surface of the electrodes, and the third was with the hand on the electrodes. Significantly, there was little imaginary impedance response in the non-contact sensing regime (square 1, Figure 13.16), for frequencies below the circuit resonance, or less than 4 Mhz. There was however, a significant imaginary impedance response when the electrode was touched (Square 2, Figure 13.16). This implies that it might be possible to measure pressure on the fabric electrodes by designing a circuit that would look only at the imaginary component of the complex impedance of the skin. The advantage of looking at only the imaginary component of the complex skin impedance would be that it might eliminate the resistive artifacts of the skin impedance.

In retrospect, this makes sense. I have spent a lot of time trying to remove the resistive component of the RC time constant by reducing the resistance in the fabric electrodes. It would make more sense to simply ignore this component and measure only the imaginary impedance in a new circuit. Such a circuit would have to take into account the geometry of each instrument to avoid the unique resonant "bump" that each electrode design creates.

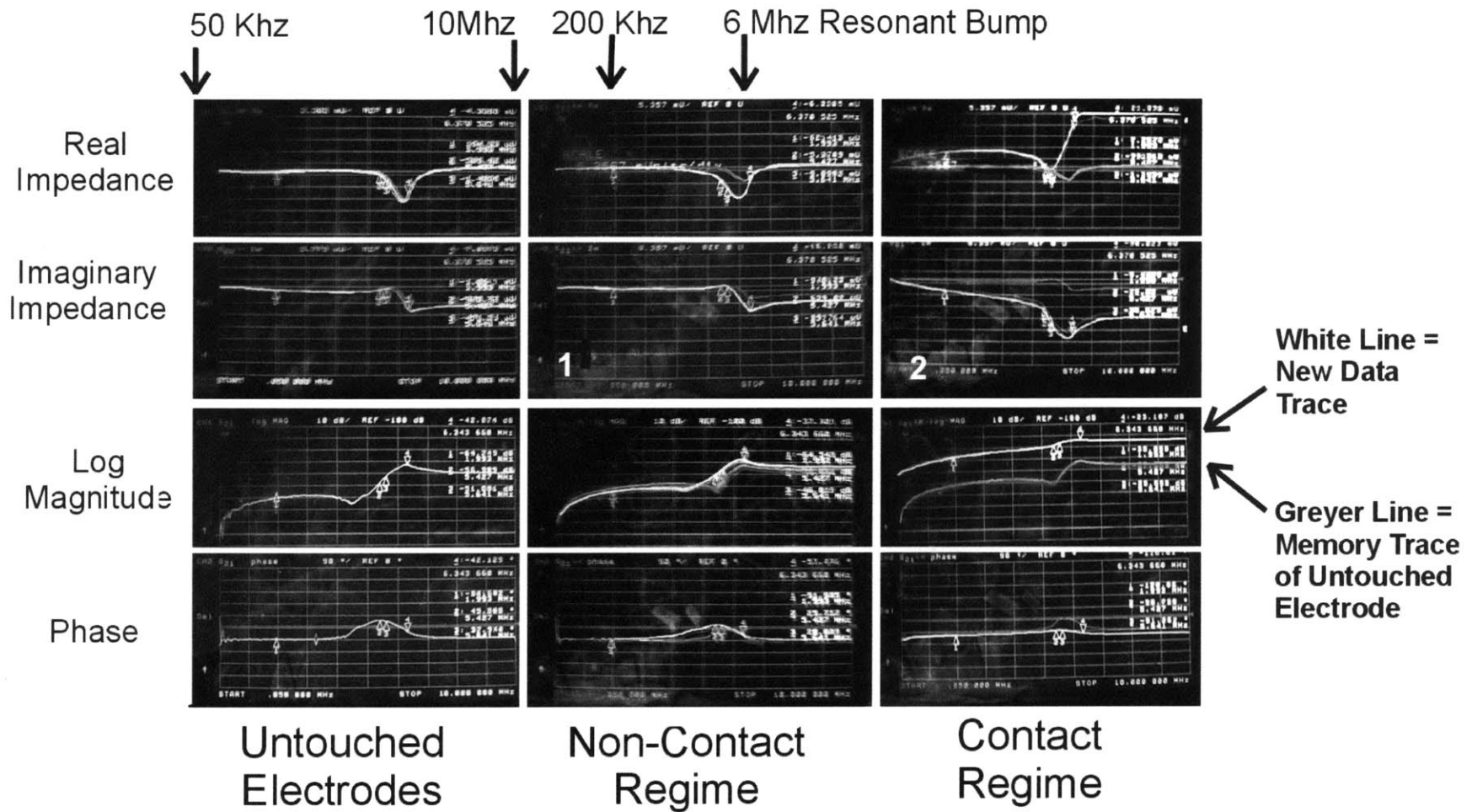


Fig. 13.16 Frequency response in *Embroidered Musical Instruments*.

Conclusions

The assertion that the *Embroidered Musical Instruments* are fundamentally measuring complex skin impedance strongly supports my empirical observations that the current sensing method primarily senses skin contact, or *intimacy* with the sensors. It supports my observations that decreasing electrode resistance, increasing electrode area, and increasing the surface area for contact (the amount of fuzzy conductive thread on the surface of the electrode), all improve the reactivity and stability of the sensors. It also supports my observation that if player's hands are cold, the instrument was less reactive. (Cold is cited as reducing skin impedance.⁶) Slightly more mysterious was the fact that recently washed hands worked badly. But rubbing players hands with salt created more sensitivity in the circuit. It can therefore be assumed that washing the player's decreases salt and increases skin impedance. This model also supports the mysterious observation that SWEATY hands work poorly. According to Webster, sweat decreases skin impedance. Therefore sweaty hands should make the embroidered instruments more sensitive. However, the circuit model demonstrates that sweat on the hands may cause a resistance parallel to the capacitance of the body. The absorption of sweat by the fabric actual creates a resistance parallel to the body's capacitance to ground. (Figure 12.) It has been demonstrated

⁶ Swanson, D.K. and Webster, J.G., *A Model for Skin-Electrode Impedance*, in Miller, H.A. and Harrison, D.C. (eds.), Biomedical Electrode Technology: Theory and Practice, New York: Academic Press, (1974).

earlier in this chapter that such a parallel resistance prevents the sensing technique for operating.

This model does not explain the artifact of time in the sensors. When a player touches the sensors, even if he or she squeezes no more tightly, the sensor value will rise steadily. I have attributed this to a charge build up on the electrode, based on the fact that it does not return to ground, but only the lower TTL level.

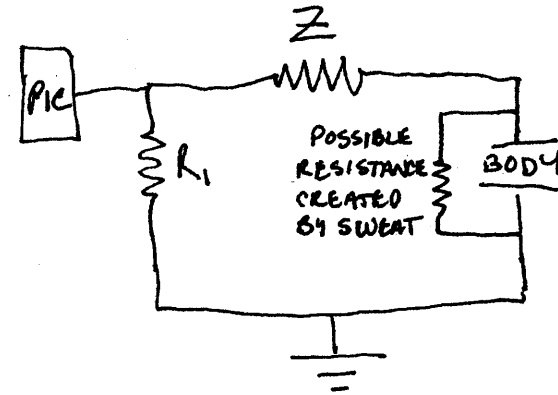


Fig. 13.17 Parallel resistance caused by sweat, which interferes with the sensing process.

Chapter 14.

Defining Sewability and Flexibility in Yarns

The idea of machine sewing an electrical trace element is highly appealing for many practical reasons. Machine sewing allows sewn electrical elements of almost any shape and size to be easily and quickly placed. Machine sewing allows continuous electrical traces to be sewn across the seams in a garment; this means that electrical continuity between two separate panels can be achieved. Machine embroidering electrical traces allows for the CAD control of the placement, size, texture and design of electrodes and other circuit elements. This chapter will define the necessary properties of machine sewable yarns and demonstrate a new *Curl Test* for judging the flexibility of yarns.

To make embroidered or machine sewn electrical elements requires using a thread that is machine

Summary of Characteristics of Machine Sewable Yarns

High tensile strength or tenacity. Tensile strength of ~580 to 1200 cN, or tenacity of 2.5 to 5.

Moderate % of elongation at breakpoint (between 12-30%).

Denier of under ~400.

Relatively smooth surface characteristics.

High flexibility, and resistance to shear and permanent deformation under bending. My *curl test* for flexibility will follow.

sewable, electrically conductive and maintains that conductivity under the mechanical stress of machine sewing. Over the course of this thesis, I have empirically observed that most conductive threads are NOT machine sewable. They simply cannot stand up to the compound mechanical stress of machine sewing through the needle. Conductive coatings can rarely withstand the forces of passing through the needle, and conductive fibers and yarns often jam the machine or simply break too easily.

One solution to this problem would be to create a new sewing machine. But this solution is flawed for two reasons. Practically, it is attractive to use the standard sewing equipment and facilities of the already huge and established textile industry. In addition, equipment that is used for sewing standard textile materials assumes that those materials have certain mechanical properties, including flexibility or the ability to resist permanent deformation under bending. These properties are not just suited to the machinery. They are ESSENTIAL to the appropriateness of a fiber or yarn for its use any textile that is intended for or human wear. Thus, the ability of a conductive fiber to be sewn or used in existing textile machines says a lot about how soft, durable, flexible and *wearable* it will ultimately be. This is not to say that non-sewable fibers cannot be incorporated into clothing. Certainly, there are fibers and methods that can incorporate these fibers into clothing. However, this does imply that the more flexible these fibers, the more suited towards use in clothing they will be. Currently, much work in smart textiles includes fibers that are appropriate for industrial purposes, and are not truly flexible. These

might include glass fibers and polymers. Such fibers simply cannot withstand the mechanical stretching, flexing and bending, that clothing undergoes. Thus, the *Curl Test* for flexibility, which was created for this thesis, says a lot about the appropriateness of conducting fibers for any use clothing.

Background

The history of the mechanical and material analysis of textile fibers, yarns and fabrics is extensive and dates back at least to the early part of the 20th century.¹ (Yarns are composite materials spun from the raw materials of fibers, like cotton, wool or rayon. All threads are yarns. Fabrics are composite materials made from fibers or yarns.) The analysis of fibers and yarns, while using many of the same terminology and tests as standard engineering materials, has also developed some of its own terminology and tests, partially due to some of the unique and non-quantifiable properties of fibers and yarn. For instance, traditional stress/strain tests of both yarns and fibers are only partially useful due to the non-Hookian and anisotropic behavior of these materials.² Material measures unique to textiles include *tenacity*, a measure of the force required to break a yarn or individual fiber, which is measured in grams/denier and

¹ Goswami, Martindale, and Scardino, Textile Yarns, Technology Structure and Application, New York, Wiley-Interscience Publications, (1977).

² Kaswell, E., Textile Fibers, Yarns and Fabrics, New York, Reinhold Publishing, (1953).

denier a measure of the weight in grams of 9,000 meters of yarn.

While the study of the mechanical properties of fibers, textiles and yarns is extensive and detailed, there is no universal standard by which to describe the mechanical properties of yarns and threads in industry.³ This may be a reflection of the fact that many yarns were used and developed long before they were described technically. In addition, textiles yarns are sold and spooled for a specific *function*, like machine sewing, warping, or knitting, and as a result many of the mechanical properties necessary for their *function* are simply ASSUMED when selecting the category of yarn. For instance, machine embroidery yarns are of higher tenacity, smoother finish, have less % of elongation at break and are spooled differently than woolen knitting yarns. They are also of a small enough denier that they can fit through the eye of a needle. Often these properties are not mentioned, but simply assumed in the term "machine embroidery yarn." For this reason, it is important to remember when buying or examining an industrial yarn, that there may be no standard description of its mechanical properties beyond its *function*.

Standard descriptions of the properties of textile yarns may include:

³ US Customs Service, *What Every Member of the Trade Community Should Know About: Fibers & Yarns, Construction and Classification under the Harmonize System An Advanced Level Informed Compliance, Publication of the U.S. Customs Service, US Customs Website, <http://www.customs.gov/imp-exp1/comply/fibryarn.htm#top>, World Wide Web, (1996).*

- Denier - the weight in grams of 9000 meters or Decitex weight in grams 10,000 meters⁴.
- Strength may be described in the form of tenacity, (g/denier or cN/dtex), tensile strength (cN) or breakpoint (grams or newtons).⁵
- % of elongation at break, or elasticity and ductility.

When buying a conductive yarn it is difficult to determine whether or not it is appropriate for machine sewing, or for any fashion oriented textile use. Most conductive yarns are generally used for industrial purposes (like tire reinforcement or static control), and are usually not categorized, designed or labeled for specific textile functions, like machine sewing or knitting. Therefore, it is has not been possible to buy a conductive yarn that is labeled by the industry as machine sewable conductive yarn.

Introduction to Flexibility in Textile Materials

The standard mechanical properties that may be used to describe a yarn, its strength, denier, elasticity, and % of elongation at break, are by no means the only parameters necessary for successful machine sewing. Textile yarns, fibers and fabrics also possess the inherent property of *flexibility*. Much technical literature on yarns and fibers describes *flexibility* somewhat qualitatively as a property necessary and inherent to

⁴ Ibid.

⁵ Ibid.

fibers, yarns and textiles. The Textile Institute of New Jersey (1970's) defined fibers as "units of matter characterized by flexibility, fineness and a high ratio of length to thickness, (at least 1/1000)."⁶ Qualitatively, *flexibility* can be understood as the resistance to permanent deformation under stresses like folding or bending. The importance of flexibility in any textile material or product simply cannot be overemphasized. A non-flexible fiber or yarn is simply not used in the textile industry.

While most textile fibers and materials are simply assumed to be flexible, many conductive fibers are not flexible. (Yarns are composite materials made from twisted or matted fibers.) The mechanical properties of yarns, including flexibility, are result of both the mechanical properties of the individual fibers from which they are made and the overall geometry of the yarn, which includes properties such as twist and continuous filament vs. spun or staple yarns, may be more important to the mechanical properties of yarns than the properties of the individual fibers themselves. As a result the flexibility of conductive fibers added to the yarn, as well as their geometry can affect the overall flexibility of the yarn. In addition, the amount of non-flexible fibers added to a yarn can directly effect the yarn's overall flexibility. Thus the flexibility of a yarn is related to the filler fiber's flexibility (its fineness or length vs. width, its flatness, young's modulus,⁷) the

⁶ Goswami, Martindale, and Scardin, Textile Yarns, Technology Structure and Application, New York, Wiley-Interscience Publications, (1977).

⁷ A more detailed description of flexibility is provided on page 235.

percentage of conductive fibers added to the yarn, and their geometry (for instance, continuous filament vs. non-continuous filament).

Machine Sewing

Machine sewing and embroidery, (essentially the same process), place enormous compound mechanical stresses on yarns. Machine sewing uses two threads, the top or needle thread, and the bottom or bobbin thread. The top thread must endure the mechanical stresses of tension, bending, shear and friction. The bottom endures far less stress.

1. **The top thread** must be able to endure compound mechanical stresses that include tension, bending shear and friction. The top thread must be able to withstand the tension of the pre-tensioning mechanism of the sewing machine, and the pull of the needle without breaking. This requires a yarn of relatively high tensile strength, high breakpoint, or high tenacity. The top thread must also withstand the lateral stress of bending and shear when it passes through the eye of a needle, is forced through fabric, looped around the bobbin mechanism and bobbin thread, and pulled tight to form a secure stitch. As a result, the top thread must be highly *flexible*, and able to change its shape, and bend from straight to looped quickly, and without permanent deformation. The top thread must also be relatively even and *dressed*; it have smooth surface characteristics, (there are few

standards for yarn dressings or coatings⁸), to reduce friction during the process of sewing. It must also be narrow enough to pass through the eye of the needle.

2. The bottom or bobbin thread is unwound from a bobbin spool. The top thread forms a loop around the bobbin thread to create a stitch. While the bobbin thread does not need to withstand the same bending stresses as the top thread, it is usually the same type of thread, or a thread with similar strength. There are many commercial threads or yarns that are designed and spooled for machine sewing in the bobbin. These yarns must be of high tenacity (for textile yarns), relatively low denier, smooth surface finish and high flexibility.

General Characteristics of Machine Sewable Yarns

Consequently, machine sewable yarns must be of high tenacity, high flexibility, have a reasonable ductility or percent of elongation at break, be of small denier, and have a relatively smooth and even surface finish. The characteristics of machine sewable thread include:

⁸ US Customs Service, *What Every Member of the Trade Community Should Know About: Fibers & Yarns, Construction and Classification under the Harmonize System An Advanced Level Informed Compliance, Publication of the U.S. Customs Service, US Customs Website, <http://www.customs.gov/imp-exp1/comply/fibryarn.htm#top>, World Wide Web, (1996).*

1. High tensile strength or tenacity. Tensile strength of ~580 to 1200 cN. Tenacity, 2.5 to 5.
2. Moderate % of elongation at breakpoint (between 12-30%).
3. Denier of under ~400.
4. Relatively smooth surface characteristics.
5. High flexibility, and resistance to shear and permanent deformation under bending. (My test for flexibility will follow.)

High Tensile Strength or Tenacity

Commercial embroidery yarns have a tensile strength of 580 - 1100cN. They have a tenacity that varies from 2.6 to 5. It is worth noting that *high tenacity* yarns are usually defined as industrial, not textile yarns⁹. Industrial yarns that are use in composite materials and tires may have tenacities as high as 7.2 to 8. Knowing the ultimate tensile strength or breakpoint of a yarn as opposed to just its tenacity may be important because a single ply of 2.5 tenacity yarn may not be machine sewable, while a double ply may be. It is important to note that doubling a yarn may impart additional tenacity or strength per denier to the yarn because twist adds to the strength of a yarn.

Moderate % of Elongation at Breakpoint

Machine sewable threads must resist both permanent lengthwise or ductile stretching, and elastic overstretching under tension. Commercial embroidery threads have 12-30% elongation at breakpoint. An elastic yarn, (generally not machine sewable) might

⁹ Kaswell, E., Textile Fibers, Yarns and Fabrics, New York, Reinhold Publishing, (1953).

have 100% or more elongation at breakpoint. In contrast, a 100% stainless steel yarn made from continuous untwisted filaments has 1% elongation at break. (Fiber geometry also plays a role here. This yarn is untwisted, which can increase separation of individual filaments and cause snags.) The role of individual fiber elongation in sewability is not straightforward, because both overall yarn geometry and fiber elongation can play a significant role in the behavior of yarns. Individual cotton textile fibers, (which in many ways are the ideal raw material for machine sewing yarns), have a % of elongation at break point between 4-17 %. But cotton fibers are also extremely fine and make for very flexible yarns. Individual nylon filaments, have an % of elongation at break of between 15-40%. Nylon yarns are also made from continuous filaments and often have a yarn elongation of 30%. Thus, the non-sewability of nylon threads may be related to the ductility of fibers, but may also be related to the fact that is a continuous filament yarn. The elongation of individual stainless steel filaments is 30%. Ultimately, it is the yarn geometry of continuous untwisted filaments that gives yarns made from these fibers their low ductility.

Denier of ~Under 400

Commercial embroidery thread has a denier of ~ 120/2, that means 2 plies of 120 denier thread, for a total denier of 240. Standard upright sewing machines can use larger needles and therefore accommodate larger thread. The machine sewable BK50/2 has a total denier of 360.

Smooth Surface Finish

Relatively smooth surface finish and evenness. While a high degree of evenness and textile lubricant is ideal for machine sewable yarns, practical experience has shown that it is possible to machine sew with yarns with relatively poor surface characteristics. The most machine sewable conductive yarns in this research have both low evenness and no surface lubricant. The effect of a high amount of textile lubrication (like wax) on the conductivity of a sewn trace is potentially detrimental. The conductivity of sewn traces may rely on the surface contact of multiple non-continuous conductive fibers, both within an individual yarn, and between multiple conductive yarns that have been overstitched, or are used in both the bobbin and top thread. Observation has shown that multiple stitch paths and the use of conductive yarns in the bobbin and top threads have dramatically improved overall conductivity. Heavy textile lubricants and surface treatments can prevent electrical contact between layers of stitched yarns, and decrease the overall conductivity of a trace. However, the yarns in used in this work have been soaked in silicon for lubrication with no detrimental effects to conductivity.

High Flexibility

Yarns that permanently deform when bent are definitely *unsewable* in the needle of a sewing machine. I have created the *Curl Test* to test the flexibility of yarns, and their ability to be sewn in the needle of a commercial sewing machine. It is important to note that there is no industrial measure of flexibility in textiles. This is because, as previously stated, the

flexibility of textile fibers, spun yarns, and fabrics is *assumed*. Moreover, there is little research into the mechanical definition of flexibility in textiles.¹⁰ This may be because traditional textile fibers and yarns can be mechanically modeled as perfectly flexible, like the long cables of a suspension bridge. Consequently it can be argued that shear and bending forces simply disappear in relation to tension forces in textile fibers.¹¹ Qualitatively, the flexibility of yarns can be described as related to the fineness of its fibers, the yarn's twist and its denier.¹² One mathematical model (which will be looked at more closely later in this chapter) derives fiber flexibility from the formula for deflection in a cantilever beam. This model describes the flexibility of fibers and filaments as inversely proportional to the Young's modulus of the fibers and the diameter of the fiber cubed, and directly proportional to the length and flatness of the fiber.¹³ Because the Young's modulus of fibers is highly non-Hookian, this equation can only be used as proportional guide for *fiber* flexibility. Many conductive fibers or filaments are not *flexible*, and may make the yarns that use them unsewable. Overall yarn geometry can also contribute to flexibility.

¹⁰ Ibid.

¹¹ Ibid.

¹² Goswami, Martindale, and Scardin, Textile Yarns, Technology Structure and Application, New York, Wiley-Interscience Publications, (1977).

¹³ Kaswell, E., Textile Fibers, Yarns and Fabrics, New York, Reinhold Publishing, (1953).

Curl Test for Flexibility of Yarns

Because the flexibility (resistance to permanent deformation under bending) of yarns is related to both the flexibility of the fibers and their geometry in the yarn, traditional stress/strain curves may not describe the flexibility of every yarn. This is because, while non-flexible fibers may make a yarn inflexible, when that yarn is placed under lengthwise stress these fibers may simply slide past each other, giving no indication of how their addition affects permanent deformation when *laterally bent* (sewing is a lateral stress perpendicular to the length of the yarn).

To test the flexibility of yarns with non-flexible fibers, I have created a *Curl Test* for bending yarns and threads. This test is appropriate for judging whether the yarn is flexible enough for machine sewing through the needle. This test creates a bending stress similar to what happens when you curl a piece of ribbon. It is designed to lengthen and one side of a yarn. Because this test is a measure of the flexibility of a yarn, it is also appropriate for understanding its use as a textile material.

The test involves 2 steps:

- 1) Bending or curling the yarn.
- 2) Reloading and straightening the yarn.

The final flexibility of an unsewable yarn is a reflection of:

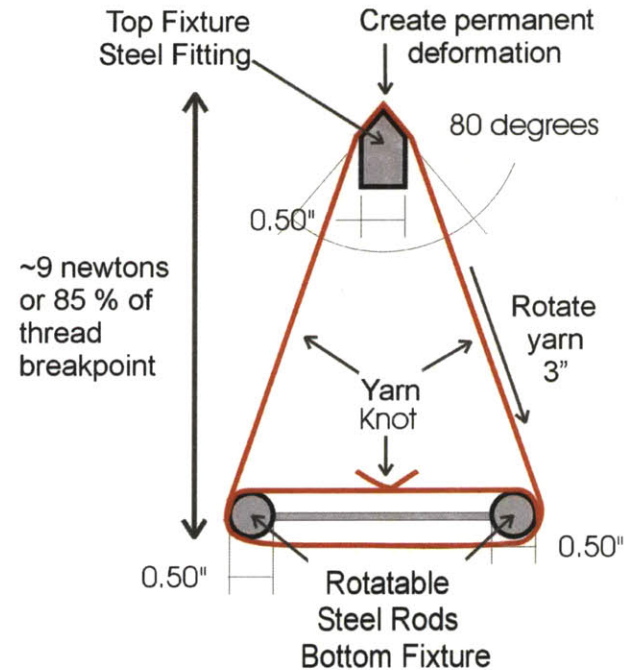
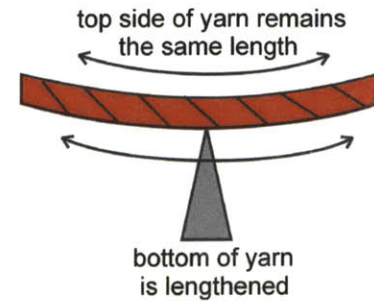


Figure 15.1, Yarn being curled, (above), and diagram of curl test, (below).

- 1) The diameter of curvature of the resulting curl. ($> .0625''$)
- 2) The tightness of the curl, or the ratio of the diameter of curvature of the curl, to the length of the curl. The ratio must be above $1/3$.
- 3) The number of curls created by this test. There must be at least three curls as described above.

1) Bending or Curling the Yarn

This step involves creating a loop of the yarn to be tested around a pair of fittings that are either independently attached to a materials loading system, or weighted. The top fixture is a metal point (similar to the blade of a scissors) that the yarn will run over. (The edge of this tool should be slightly broken so as not shear the yarn). The bottom fixture acts as a means for tensioning, looping, and then rotating the thread across this metal point. The yarn is tied in a loop around the top and bottom fixture. Once the fixtures are in place the thread is loaded to 85% of its breakpoint. (Different yarns will need to be loaded different amounts as a reflection of their tenacity or breakpoint.) This loading should make the yarn tight. (Machine sewable thread usually has a breakpoint of between 6-13n). I have found 9n to be a good load for many stainless steel threads. I have also found the breakpoint of some yarns to be less than what is given by the manufacturer, so a breakpoint test should be run on the yarn first. Once the yarn is looped around the top and bottom fitting, mark the yarn at the both first deformation point, and three inches away from it in the direction of the rotation. Once the yarn is loaded to

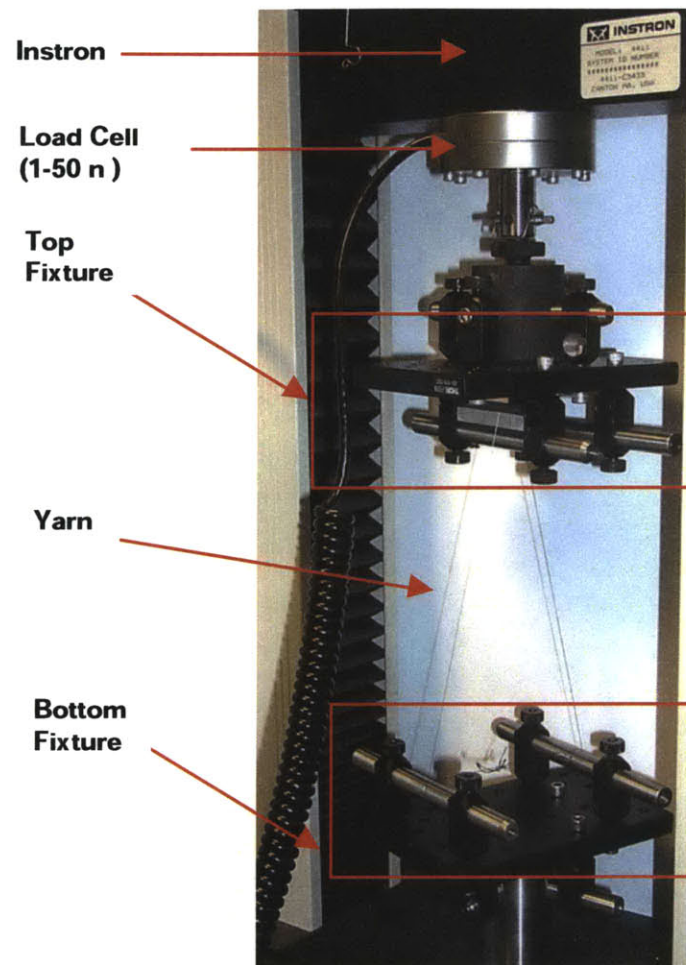


Figure 15.2 *Curl Test* on Instron materials measurement system.

85% of its breakpoint, it is then rotated around the fixture 3 inches. (This can be accomplished by turning the rods on the bottom fixture). The yarn is then cut, as far away from the top deformation point as possible.

At this point, a completely flexible yarn like rayon or cotton, will show no curl. Most yarns with non-flexible fibers will show some curling and twisting.

2) Reloading the Yarn

To truly judge if the yarn has been permanently deformed, the yarn must be reloaded. The fixture for reloading the yarn involves two rods with a 1/16" diameter hole drilled in the center. The yarn is threaded through the hole and the wound round each rod a minimum of three times.

If the yarn shows any curl at all after the curl test, it is then reloaded to 50-90% of the original load. (This varies for different yarns because the curl test can cause the yarn to yield and lower its breakpoint or tenacity.) This step involves loading the yarn to .5 of the original load and releasing it. If the curl remains identical, load to .6 of the original and so on, until 90% of the final load amount is reached. If the thread breaks before the final load amount, perform the curling test again and then reload the thread to the 10% less that the breaking point of the last sample.

Once the thread has been reloaded, it is ready for the final analysis.

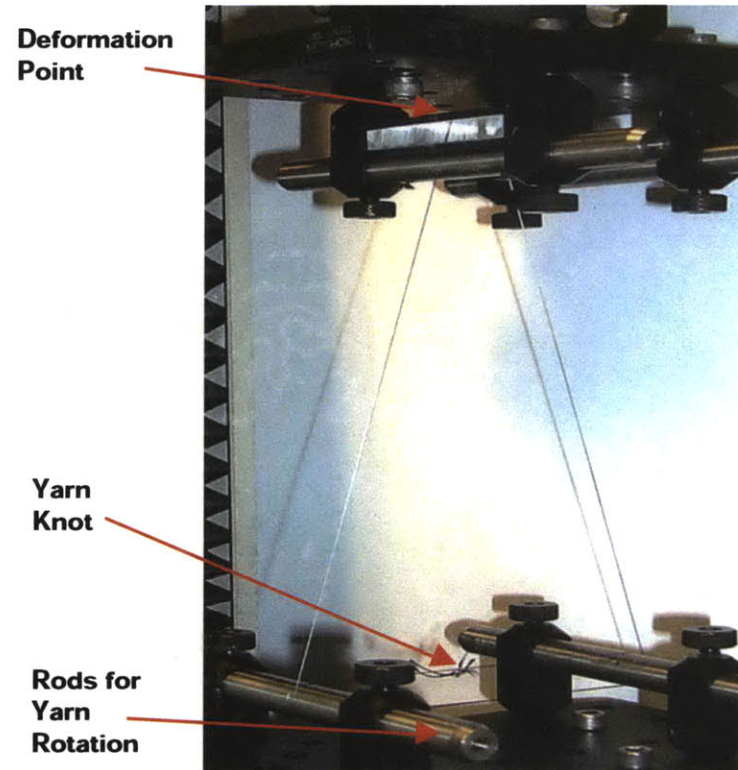


Figure 15.3 Close-up of *Curl Test* on Instron.

The Final Analysis

Three factors come into play in judging the flexibility of yarns after reloading.

- 1) The diameter of the curl of a yarn that is non-flexible as to be unsewable in the needle of a sewing machine is $>.0625"$, $(1/16)"$.
- 2) The ratio of the diameter of the curl to the length of the curl in the yarn must be between $1/3$ and 1 . In general, yarns with smaller ratios are more flexible. Yarns with a ratio of 1 are highly non-flexible. Yarns with a ratio of less than $1/3$ or one $1/10$ are flexible enough for sewing.
- 3) The curl caused by step one, must be repeated *at least three times*. A yarn with only one curl with a ration of $1/2$ and a diameter $>.0625"$ is still flexible enough for machine sewing in the needle.

Individual Yarn Results

Rayon Sewing Yarn (Machine Sewable)

No curling or deformation in Step 1.

BK 50/2 20% Non-continuous Stainless and 80% Polyester, (Machine Sewable)

In Step 1 this yarn was loaded to 7 newtons. Minimal curling occurred in step 1. The yarn was reloaded to 5 newtons. Curling was reduced to 3 curls with aspect ration well under 1/10 and diameter of under 1/16", and 1 curl with a larger aspect ratio and a diameter of ~.25". Therefore, the yarn is sewable.

70% Non-Continuous Stainless and 30% Kelvlar (Un-Sewable)

In Step 1, this yarn was loaded to 8 newtons. Substantial curling occurred. It was reloaded to 7 newtons. Curling was not reduced. There are 3 final curls, each with an aspect ration of .5. The final diameter of the curl is .25". It is not flexible enough for machine sewing in the needle.

100% Continuous Stainless Steel (Un-Sewable)

This yarn was loaded to 9 newtons and reloaded to 8 newtons, with significant curling occurring in Step 1 and no relaxation of curl in Step 2. There are 5 curls that result from the bending in Step 1. Their final aspect ration is close to 1 and the final diameter is between .125 and .25".

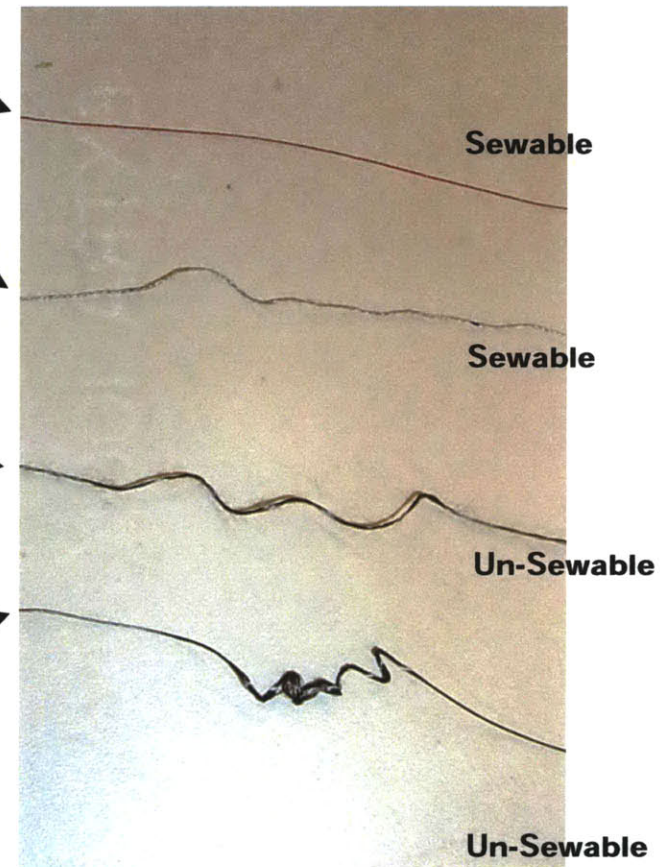


Figure 15.4 Yarns after Step 1 and Step 2 of the Curl Test.

More on Flexibility in Fibers

As stated previously, flexibility can be assumed as inherent to textile fibers, yarns, and fabrics. But while it is inherent, the technical exploration of flexibility is somewhat limited. In 1954, Kaswell stated that "...it is regrettable that little data are found in the literature on the topics of bending, torsion, and shear... It appears unnecessary to comment upon the importance of such deformations to fiber yarn or fabric performance." He also presented a mathematical model from earlier work done by Finlayson in 1946 regarding flexibility of fibers.¹⁴ In 1977, the authors of Textile Yarns¹⁵ choose to describe flexibility only qualitatively, stating that "the resistance to bending or flexibility of a fiber as depends on its shape, its tensile modulus, its density and above all its fineness (ratio of width to length)."

Finlayson's model of the inherent flexibility of textile fibers is significant for understanding the sewability of yarns made with conductive fibers. Finlayson makes an important comparison between flexibility in fibers and the standard physics of both the deflection of a cantilever beam under stress, and the bending modulus of a beam supported in the middle with deflected ends.

¹⁴ Kaswell, E., Textile Fibers, Yarns and Fabrics, New York, Reinhold Publishing, (1953).

¹⁵ Goswami, Martindale, and Scardino, Textile Yarns, Technology Structure and Application, New York, Wiley-Interscience Publications, (1977).

Finlayson derives this equation for inherent filament and fiber flexibility from the equation for deflection in a cantilever beam loaded at the end. Please note that this equation has some unusual notation.

$$f = (f) \frac{FLR^2}{EW^4}$$

where

f = deflection

l = length of cantilever

E = Young's modulus of fiber (isotropic material)

F = applied load modulus

R = eccentricity of cross section, or major axis width/minor axis width

W = average diameter

According to Finlayson, this demonstrates that "the flexibility of a filament is directly proportional to its flatness, as measured by the ration of major to minor axis of the elliptical cross section, and is inversely proportional to its modulus of elasticity and the fourth power of its diameter."

But while this equation can lead to a better understanding of flexibility in textile fibers, it does not provide a truly quantitative measure of this property in textile fibers. This is because textile fibers have

anisotropic properties rendering their Young's modulus unspecific for this equation. Textile fibers show a high degree of non-linear and non-Hookeian deformation under stress.¹⁶ However, it can be generally understood from this equation that the general stiffness, shape and above all the fineness of individual fibers contribute to their flexibility.

While this equation describes the flexibility of individual fibers, it is not necessarily relevant for yarns. Yarns are composite materials made from the twisting of fibers, that are held together by the forces between these fibers. As a yarn is tensioned, these fibers slide past each other allowing strain in the yarn to occur. This strain is non-Hookeian and anisotropic. The twist of most yarns imparts a far more complex geometric and mechanical relationship between fibers. While the documenting of these internal forces in twisted yarns is outside of the scope of this chapter, it is important to realize that the movement of fibers during the straining of a yarn may render the *stiffness* of the individual fibers irrelevant to overall fabric and yarn stiffness.¹⁷ At the same time it can be said, that qualitatively, the *flexibility* of fibers, or fiber fineness, as well as twist play an important role in yarn flexibility¹⁸. The diameter

¹⁶ Kaswell, E., Textile Fibers, Yarns and Fabrics, New York, Reinhold Publishing, (1953).

¹⁷ Kaswell, E., Textile Fibers, Yarns and Fabrics, New York, Reinhold Publishing, (1953).

¹⁸ Goswami, Martindale, and Scardino, Textile Yarns, Technology Structure and Application, New York, Wiley-Interscience Publications, (1977).

or denier of the yarn also plays a role in the flexibility of yarn.

Flexibility in Conductive Fibers and Yarns

Unlike textile fibers, many conductive fibers have a clear Young's modulus. Consequently, Finlayson's equation for the flexibility of fibers can be essential to understanding the sewability of yarns made from conductive fibers. For instance, metal fibers in yarns may have a Young's modulus anywhere for 80 GPa (Au) to 200 GPa (steel). In contrast, a spider's dragline has a modulus of 2.7-4.4 GPa and nylon a modulus of 3 GPa. The width and shape of non-textile fibers is also significant to its flexibility. In general, textile fiber widths can vary from 15 microns in fine cotton, to 50 microns for ramie. Wool fibers, which possess a width of 25 microns (which itself does not render them unsewable), a low tensile strength, and a circular cross-section is far less flexible than cotton and never used for machine sewing thread. Let's compare wool with the drawn stainless steel fibers that are incorporated into yarns. Stainless steel fibers have a larger diameter of 35 microns, and a generally circular cross section. Thus, looking at the diameter, cross sectional shape, and Young's modulus of stainless steel fibers may lead to the assumption that these fibers may simply be too inflexible to be incorporated into machine sewable yarns.

But it is important to remember that individual fibers are part of an overall yarn geometry. Thus, experiments with stainless steel yarns have shown that both yarn geometry, and the % of conductor

incorporated into a yarn also play a significant role in a yarn's flexibility, and therefore its sewability.

Sewing with Conductive Yarns

The goal of the sewing process developed in this thesis was to machine sew a trace that was as electrically conductive as a wire. So why not just machine sew a copper wire, or even tack it into a piece of clothing? Aesthetically, one's initial reaction is that it is not soft or flexible enough to be incorporated into a textile. Mechanically, it is simply not machine sewable in either the bobbin or needle. There are compound reasons for this. A very thin wire will break under the tension of sewing in the needle or jam the machine in the bobbin. The machine sewable spun stainless steel and polyester yarn BK 50/2 has a diameter of .14 mm and a breakpoint of 1270 cN. Given a tensile strength of 400 GPa, a copper wire of similar diameter would have a break point of only 6N. A continuous stainless steel strand of .035 mm has a breakpoint of 91 grams. So a copper wire simply cannot withstand the tension of sewing in the needle. In the bobbin, it jams the machine. This is because it is not flexible. Given a wire of the same thickness and aspect ratio as a spun embroidery yarn it is safe to say that the Young's modulus of Cu, (124 GPa) is at least ten times higher than the Young's modulus of a spider drag line at 2.8-4.7 GPa.¹⁹ I use a spider dragline for comparison because both are single filament continuous fibers and yarn geometry does not come into play when

¹⁹ Rolf E. Hummel, Understanding Materials Science: History, Properties, Applications, Springer, New York, (1998).

understanding their flexibility. Because of their Young's modulus, copper wires that are simply tacked down, or couched into clothing, are also subject to extremely high bending forces. They cannot resist permanently deformation, and eventually will break.

The conductive yarns experimented with during the course of this research gained their electrical properties from either a metal foil wrapping, or the incorporation of stainless steel metal fibers drawn from stainless steel wire. We favored stainless steel because it provided a conductor that was resistant to corrosion, inert, known to be safe when worn next to the body, and affordable. One drawback to stainless steel was that it not as conductive as copper or gold. As previously noted, most of the yarns that contained metal fibers were not machine sewable. There are compound reasons for this, including the flexibility of the metal fibers used in the yarns, the ductility, or % of elongation at breakpoint of the yarn, and the overall yarn geometry.

The most successful machine sewing process developed to date uses a high resistance, highly flexible and soft staple thread of 20% stainless in the needle, combined with a highly conductive yarn of nylon wrapped with 3 filaments of continuous stainless steel in the bobbin. This process takes advantage of the lower mechanical stresses that are placed on the bobbin thread during sewing. It also relies on coupling a material with desirable mechanical properties and poor electrical properties (the spun stainless and polyester yarn which is highly flexible), with a material with poorer mechanical properties and great electrical

properties (the yarn of nylon wrapped with continuous filaments of stainless steel.) It also relies on the layering and design of the stitch pattern. Certain stitch patterns create far more flexible and conductive electrodes. This process can create 4' electrodes with isotropic resistances of under 50 ohms. This remaining resistance is both a function of the conductivity of the yarns, and the fundamental conductivity of the cold worked steel.

Specific Yarn Analysis

Because each yarn's sewability is a compound property, (the result of its geometry, the flexibility and % of conductive fibers added), it is helpful to analyze each yarn used in this research specifically.

Metal wrapped Yarns or Gimped Yarns

Yarns wrapped in copper or gold foil, or *gimped* yarns, could not be sewn for two reasons. (Gimped yarns are yarns around which is wrapped another yarn or filament or strip.²⁰) The internal yarn, or mechanical center the gimped yarns, was simply not of high enough tenacity to machine sew. Metal wrapped yarns like these are generally woven in the weft of a fabric (weft weaving creates little mechanical stress on a yarn), or attached to fabrics for decorative purposes,

²⁰ US Customs Service, *What Every Member of the Trade Community Should Know About: Fibers & Yarns, Construction and Classification under the Harmonize System An Advanced Level Informed Compliance*, Publication of the U.S. Customs Service, US Customs Website, <http://www.customs.gov/imp-exp1/comply/fibryarn.htm#top>, World Wide Web, (1996).

with a process called couching. Couching puts little stress on the thread because it involves mechanically attaching the metallic thread to a substrate material by *tacking it down* or sewing another thread around it. Neither of these processes require the threads to be of high tenacity. Of course, a gimped thread with a stronger central core could have been made. But this would not have addressed the delicacy of the metal wrapping or foil. The metal foil of the gimped yarns is simply not flexible. Under bending and lateral stress the metal foil was easily permanently deformed, stripped, and broken, destroying the electrical continuity of the yarn. The metal foil would also jam the machine. The inflexibility of the metal foil was ultimately a function of its diameter and Young's modulus (copper 124 GPa and gold 82GPa). Yarn geometry also plays a significant role here. Gimped yarns are especially susceptible to the damage of the conductive wrappings because the foil is on the outside of the yarn, and is subject to a lot of stress and friction from the needle. It is worth noting that there are commercial embroidery threads available that are gimped with a metallized plastic coating. These coating are highly flexible due to both their diameter, and the Young's modulus of the plastic wrapping, which can be assumed to be very low. (Plastics can have Young's modulus as low as .003 GPa.) They also have smooth surface characteristics as a result of coating and lubrication.

Stainless Steel Yarns

The stainless steel yarns tested for machine sewability are of four types.

1. A **staple yarn of polyester and short stainless steel fibers**. (A staple yarn is a yarn twisted from many short fibers) Various blends were tried, 20 % stainless and 80 % polyester was the only one conductive enough and sewable.
2. A **100% continuous filament stainless steel** thread, untwisted. This yarn was not machine sewable as a needle thread.
3. A **staple yarn of 30% Kevlar and 70% stainless steel**. This yarn was not machine sewable in the needle, but successful in the bobbin.
4. A **continuous filament yarn of twisted nylon and 3 continuous strands of stainless steel**. The yarn was not machine sewable in the needle, but machine sewable in the bobbin.

Staple or Spun Stainless Steel Yarns

Two types of staple, or spun, stainless steel yarns were used and it is worth comparing them. Highly resistive yarns of spun stainless steel and polyester fibers with a steel content of >20% (BK50/2)²¹, and highly conductive yarns spun from Kevlar and stainless steel fibers with a content of 70% stainless steel²².

BK50/2 stainless steel and polyester threads were successfully used in both the bobbin and top thread of a commercial embroidery machine. The main failure of these staple yarns of stainless and polyester was under tension. Single strand yarns were not of high enough tenacity to withstand the tension of machine sewing. A double stranded twisted that yarn withstood

²¹ See Materials Index.

²² Ibid.

sewing has a higher break point, both by virtue of its twist and increased denier. A double stranded yarn of 20% stainless steel has a tensile strength of 1270 cN, and a % of elongation of 15%. Single ply yarns had a strength of 580 cN (less than half of the double ply), and a percent of elongation of 12%. Yarns with stainless steel contents lower than 20% were not conductive enough for our purposes. It is worth noting, that increasing the content of the stainless steel also increased the yarn's tensile strength. Single ply yarns of 5% stainless steel have a tensile strength of 355 cN, while 20% stainless tensile strength of 580 cN (tenacity of 2.9 cN/dtex). Threads with 70% stainless and 30% Kevlar have a tenacity of 18.89 cN. While this high content stainless steel thread was sewable in the bobbin, it was not machine sewable in the needle. It permanently deformed when sewn.

Yarns with lower stainless steel content were more sewable. It is known that fibers in spun yarns move significantly when the yarns are under stress. Thus, while a single fiber of stainless steel might be bent or deformed during sewing, it would be free to move between the highly flexible fibers of the polyester. Therefore, while yarns of spun polyester and stainless with higher stainless steel contents than 20% are not manufactured, it is clear that adding stainless steel will make the yarns less flexible and less sewable.

Adding additional stainless steel fibers to the yarn would also increase short circuits between sewn traces. Staple stainless steel yarns have long stainless steel fibers that extend beyond the radius of the yarn. This is because the stainless fibers are inflexible and

cannot be combed parallel before or during spinning. These fibers come loose in sewing and cause short circuits between traces. Small electrical connections in the 100's of mega ohms have been observed between adjacent sewn traces of 20% spun stainless steel. The 70 % content stainless steel yarns produced a higher the rate of short circuiting between traces, with short circuits as high as 100 ohms.

Yarns with Continuous Stainless Steel Filaments

This thesis looked at two categories of yarns made with continuous stainless steel fibers, a 100% stainless steel, a nylon wrapped with 3 continuous filaments and an untwisted yarn made of up to 200 strands of continuous stainless steel. The wrapped yarn was useable in the bobbin of the sewing machine. In the needle, the wrapping stripped. The continuous yarn made form bundled fibers was unsewable. It was simply too unflexible and did not have enough % of elongation at break.

Chapter 15.

Materials Index

The following is a list of materials that played a major role in the development of the projects in this thesis. While many materials were experimented with, only a few are listed as examples of materials that did not work. Because accurately measuring the resistance of conductive threads and sewn electrodes relies on creating a stable connection to the thread or electrode, as well as the fact that sewn electrodes vary in resistance across different axis and over time, most of the measurements in this section are an empirical average of repeated measurements taken in different places with different connections.

Stainless Steel Fibers

The bulk of conductive threads in this list are made from extremely fine fibers drawn from cold-worked stainless steel wire. These fibers have enormous advantages. Stainless steel is inert, so surface corrosion is not a problem. These fibers have been

Summary of Materials Index

- Gimped Thread, Wrapped with Metal Foil
- Metallic Silk Organza
- Conductive Hook and Eye Fasteners (Velcro)
- Stainless Steel and Polyester Blend, BK50/2
- 100% Continuous Stainless Steel
- 70-100% Non-Continuous Stainless Steel
- Nylon Wrapped with Continuous Stainless Steel
- Mechanical and Electrical Knot Tying Braid of 100% Continuous Stainless Steel Core
- Wrapped with BK50/2
- Snaps, Zippers, Earring Backs, and other Mechanical Fasteners

used in medical electrodes, and are known to have no side effects to humans. They are affordable. Cold-worked stainless steel yarns and fibers are also far more mechanically durable than either deposition coated yarns, or fibers and foils made from more highly conductive, non-alloyed metal fibers or wraps, like copper or gold. But while cold working provides excellent mechanical strength, it also means that stainless steel will never be as conductive a copper, or even hot rolled stainless. As a result, the circuit elements created with these fibers remain low impedance electrodes. Consequently, the applications that have been developed for these materials cleverly exploit low impedance electrodes.

Materials List

Gimped Thread, Wrapped with Metal Foil

Projects: *Firefly Dress and Necklace* and *Ball Gown*.

This thread has central core of cotton or silk, and is wrapped with a soft metal foil, usually color treated copper or silver. It has been used for decorative purposes in many cultures, including France, India and Japan. While this thread is *highly* conductive, it has limited mechanical properties, and cannot be machine sewn without stripping its conductive coating. Metal wrapped yarns like these are generally woven in the weft of a fabric (weft weaving creates little mechanical stress on a yarn), or attached to fabrics for decorative purposes with a process called couching. Couching puts little stress on the thread because it involves mechanically attaching the metallic thread to a

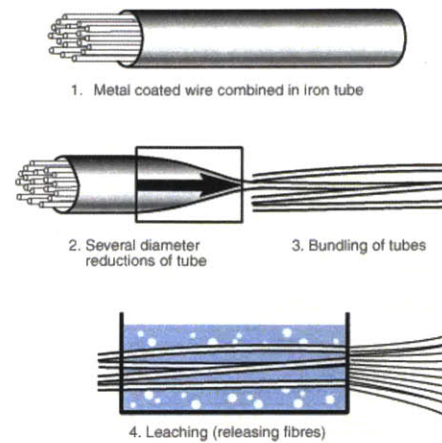


Figure 15.1 Image of the drawing of metal fibers, from Bekeart Website, 1999.

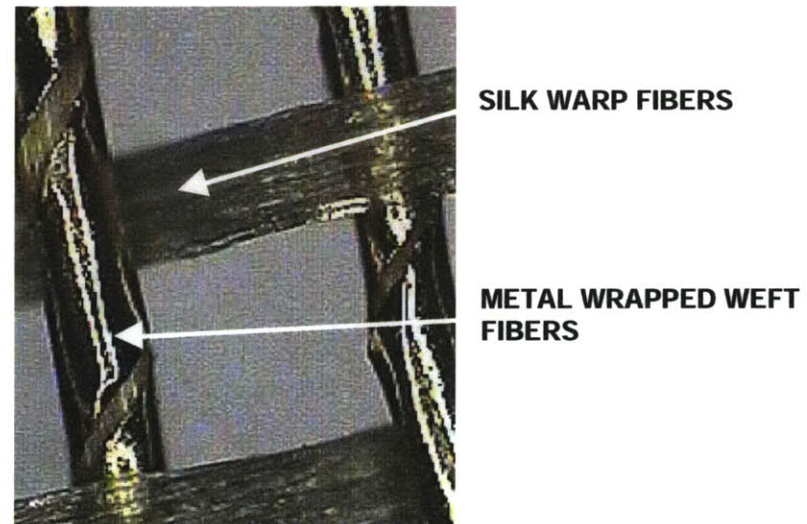


Figure 15.2 Gimped thread wrapped with metal foil, woven into metallic silk organza.

substrate material by "tacking it down", or sewing another thread around it. This thread was used to create the conductive and flexible tassels of the *Firefly Dress and Necklace*, and the hand embroidered circuit traces in the *New Year's Eve Ball Gown*. Its wire-like conductivity was essential in the tassels of the *Necklace* because the amount of current they passed to the necklace ultimately determined the color of the LEDs. The flexibility of this thread also let the beaded tassels swing far more freely than they could have with wires inside.

Metallic Silk Organza

Projects: *Piecework Fabric Keypad, Firefly Dress, Serial Suit, Musical Jacket, Ball Gown and Electronic Tablecloth.*

Metallic silk organza is a highly conductive fabric from India, where it has been used for decorative purposes for centuries. This organza is woven from gimped silk fibers wrapped with metal foil. These conductive threads run only along the weft of the fabric. The warp is uncoated silk. (Running the thread in the warp would cause the conductor to strip because of mechanical stresses.) Because the conductive fibers are slightly spaced, the fabric is anisotropic conductor, conducting in only one direction, and can be used almost like a ribbon cable. The resistance of the fabric is on the order of 5 ohms per meter. This can be improved if layered. Creating a plane of isotropic conductive material required edging the fabric with a perpendicularly conductive strip, to tie the conductors together. This fabric is not truly flexible, because of the ductility of the metal foil, which means it can be permanently deformed. For that reason, this fabric is

usually only used for decorative, or specialty clothing. This fabric was used as both sensors and power distribution in all the electric fashions, a switch matrix in the row and column *Piecework Fabric Keypad*, and a fabric ribbon cable that distributed power, ground, audio, and serial data in the *Musical Jacket*. It was used an *excellent* means to ground the body when doing capacitive sensing in both the *Musical Jacket* and *Ball Gown*. It was also appliquéd onto the *Electronic Tablecloth* to create a capacitive tag reader electrode capable of generating high frequency, and high amplitude voltage swings.

Conductive Hook and Eye Fasteners (Velcro)

Projects: *Firefly Dress* and *Triangles*.

This highly conductive, nylon hook and eye fastener (Velcro) is deposition coated with silver. It is primarily used in EMI shielding applications. It has a male and female component. In cross section (from top to bottom), its resistance is 1.5 ohms. In length, it's resistance is ~2 ohms per foot. The connection between a male and female piece, (if strongly pressed), is ~1.5 ohms. The resistance across two female pieces squished together is 5 ohms. Female conductive Velcro was used as an electrical contact in the *Triangles* and the *Firefly Dress*. Its fuzzy ends help ensure electrical contact between two things without rigid connectors. Magnets also in the *Triangles* insured a stable and accurate mechanical connection.

Stainless Steel and Polyester Blend, BK50/2

Projects: *Musical Jacket*, *Electronic Tablecloth*, and *Embroidered Musical Instruments*.

This high impedance composite thread is made from short stainless steel fibers bended with polyester and has excellent mechanical properties. The resistance of this thread is not consistent, but in general it averages 3k ohms per meter. In many ways, this thread feels and looks like a normal thread. It is soft, flexible and can be tied in a knot. This was the first thread that we could get through the needle of a commercial sewing machine without mechanical bunching or the damaging of its conductors. That is because the conductance of the thread is the result of lots of tiny steel fibers being in mechanical contact with each other, rather than a single continuous fiber. (As a result resistance across this thread drops dramatically when under tension.) The tiny stainless steel fibers in the thread are hairy and extend beyond the physical edge of the thread. This hairiness has two ramifications: 1) This thread provides lots of metal fibers and surface area to electrically couple to. 2) These fibers can reach out and find each other, creating extremely high impedance short circuits (50mega ohms) between individual traces if they are not sewn correctly. Six inch traces sewn with this thread in the top and bottom measure less than 3k ohms. The *Musical Jacket* and *Electronic Tablecloth* used this thread in both the needle and bobbin of a commercial embroidery machine to sew high impedance electrodes that sense on and off. This

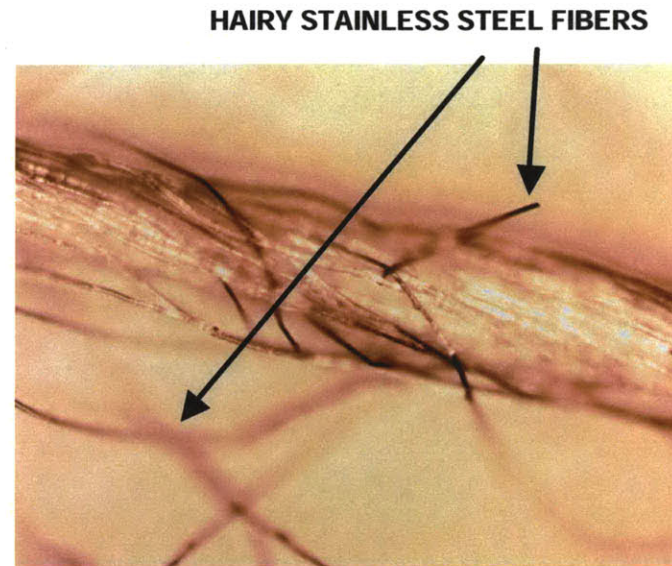


Figure 15.3 Microscopic image of stainless steel and polyester blend BK50/2.

thread is used to sew the top or needle portion of the electrodes in the *Embroidered Musical Instruments*.

100% Continuous Stainless Steel

This thread is made from 100% continuous steel. It is *highly* conductive (on the order of 2 ohms per foot), but has extremely poor mechanical properties. It cannot hold a knot, pass through the eye of a needle, or even be sewn through the bobbin of the sewing machine. Nor can it be well soldered to.

70-100% Non-Continuous Stainless Steel

Projects: *Balls 3 and 4.*

This thread is spun from 100% short stainless steel fibers, or a blend of Kevlar and short stainless fibers. It possesses the high conductivity of the 100% continuous stainless steel, combined with improved mechanical properties based on its structure of spun short fibers. It can hold a mechanical knot relatively well and despite its width (necessary for manufacturing), it can be run through the bobbin of a commercial sewing machine. Unfortunately, the same felting of short fibers that improves its mechanical properties causes other problems. The surface characteristics of both the Kevlar and the stainless fibers are smooth, so there is little friction to hold the fiber in place. This hairiness makes low impedance short circuits between circuit elements that are sewn on the same piece of fabric inevitable. Moreover, those hairs easily get loose from the structure of the thread and cause skin irritation. The hairs make it possible to create a solder joint to it, by literally forcing the solder in between them. (It is not possible to solder to continuous stainless). This thread can hold a

mechanical knot that forms an electrical connection with a sewn electrode. This thread was tied to embroidered electrodes in early balls and then soldered to, and wrapped around wires that connected to the central circuit. (If it was tied to the circuit-board or even got near it, the nearly invisible steel fibers got into the circuit and caused HORRIBLE short circuits.)

Nylon Wrapped with Continuous Stainless Steel

Projects: *Balls 5, 6 and Shaped, Embroidered Instruments*

This very conductive thread consists of a nylon core wrapped with three very fine strands of continuous stainless steel. Its resistance measures around 100 ohms per meter. While passing this thread through the needle of the sewing machine caused the conductors to break and strip, it was successfully used in the bobbin to create highly conductive sewn electrodes. The thinness of the conductors in this thread make it difficult to electrically couple to when it is used alone. (When used in conjunction with BK 50/2, which has lots of conductors near the surface, this problem disappears.) Its use in the bobbin virtually eliminated the high impedance short circuits that occurred between two closely sewn traces made with BK 50/2 in the bobbin and top thread. This thread is used in all the *Shaped Embroidered Musical Instruments*.

Mechanical and Electrical Knot Tying Braid of 100% Continuous Stainless Steel Core Wrapped with BK50/2

Projects: *Ball 5, Pyramid, Big Ring and Tube.*

I developed this braid with Bekeart Corporation to solve the problem of creating a mechanical and electrical

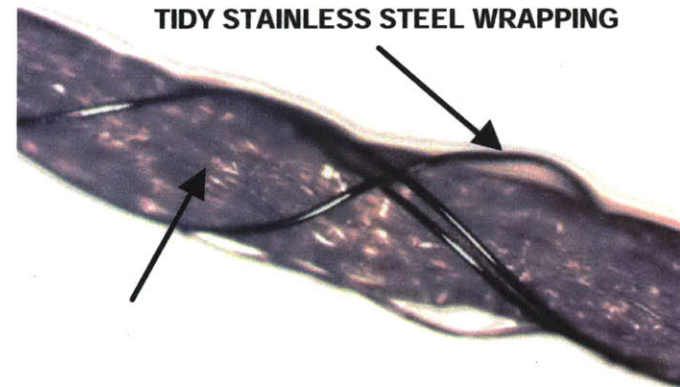


Figure 15.4 Microscopic view of nylon core wrapped with continuous stainless steel filaments.

Chapter 16.

Sewing Process Timeline

The final sewing process developed for this thesis allows designers to create highly conductive textile electrodes with a variety of visual and tactile effects, and relatively little intensive labor and design time. The early, electrode sewing process (used to create the keypad in the *Musical Jacket*), required the hand placement of almost every stitch with a commercial CAD embroidery program (Wilcom software), and limited the stitch patterns that could be used to zigzag and satin. In addition, many stitches had to be hand placed. This is because, most commercial embroidery programs create objects by generating a stitch pattern based on parameters. For instance, when creating a piece of embroidery text, like the letter T, the designer picks the font, size, stitch density, stitch pattern, and the number of underlay stitches. Then the program generates the letter T as an object, complete with stitch placement (more advanced designers can pick the way that the corner is sewn, etc.). In the early sewing process (as used in the *Musical Jacket*), if a single

Timeline Summary

Piecework Circuit Elements Sewn from Metallic Silk Organza.

Composite Stainless Steel Thread, (BK50/2) Passes Through Needle of Commercial Sewing Machine.

High Impedance Circuit Elements Designed in CAD Environment and Embroidered on Commercial Machine with Composite Stainless Steel Thread, (BK 50/2).

Electrode Impedance Reduced by 10X by using Composite Stainless Steel Thread, (BK50/2) in Bobbin.

Electrode Impedance Reduced by Improved Stitch Pattern and Continuous Stitch Path Between Objects.

Electrode Impedance Dramatically Reduced by using 100% Non-Continuous Stainless Steel in Bobbin, but Causes Short Circuits Between Close Elements.

Electrode Impedance Dramatically Reduced by Nylon Wrapped with 3 Continuous Stainless Steel Fibers in Bobbin without Sewing Problems.

Sensing Stability and Resolution Improves when Electrode Area and Density are Increased.

Tying a Knot Creates a Simultaneous Mechanical and Electrical Connection with a Twine of Continuous Stainless Steel Core Wrapped with Stainless Steel and Polyester Composite Thread (BK50/2).

Contour Underlay Stitch Decreases Electrode Stiffness.

Contour Stitch Overlay Decreases Stitch Density and Increases Conductivity.

needlepoint pierced a previously stitched thread, the conductivity would be dramatically reduced. This meant going through the labor-intensive, hand placement of many of the machine generated and placed stitches. Separate objects also had to be integrated in a painstaking manner. This process involved literally taking the layers apart and reordering how they were sewn. The final electrode sewing process lets the designer avoid most hand placement of stitches, and accept the objects and stitch configuration generated by the program. It also lets designers create electrodes using objects sewn with many different stitch patterns, including the tatami and contour stitches (Figure 16.1). Using a variety of stitch styles lets designers make electrodes that were bumpy or soft, and with different visual effects and density. The layered spatial effect in the *Big Ring* ground sensor was made possible by the use of different stitch styles.

The final sewing process consists of:

- 1) Using a highly conductive bobbin thread (one that is not necessarily sewable in the needle) and a less conductive, more flexible top thread.
- 2) Sewing a loose and flexible contour stitch as an electrical back plane.
- 3) Arranging denser and multi-layered, more tactile design objects over the plane. (These can be sewn in many stitches and densities, including tatami, or satin stitch). These objects should interconnect the parallel traces of the contour stitch.
- 4) Create a continuous stitch path between all objects.
- 5) Overstitch denser objects with another loose contour stitch, which should perpendicularly intersect with original contour stitch.

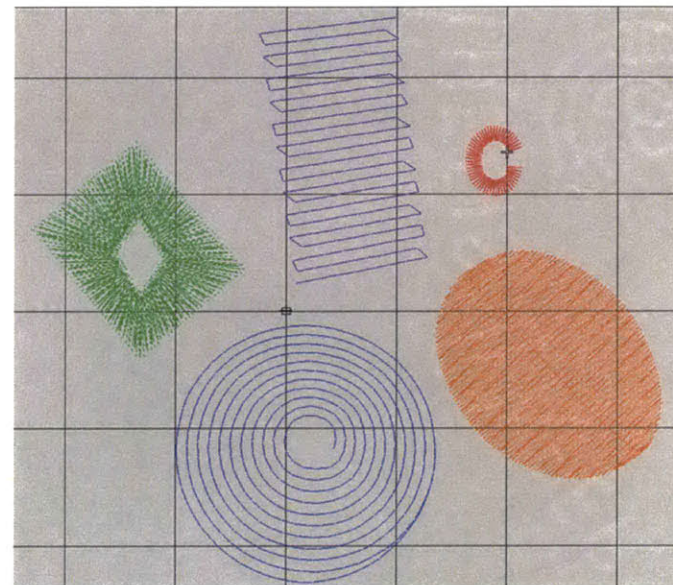


Figure 16.1 Stitch pattern examples:
Satin stitch (green square and "c").
Tatami stitch (orange oval).
Loose Contour stitch, (blue swirl and purple rectangle).

The final sewing process developed in this thesis involves the use of two different stainless steel composite threads. The very sewable, high impedance composite stainless steel thread BK 50/2 is used in the needle. In the bobbin, a less sewable, low impedance thread of nylon wrapped with three strands of continuous stainless steel is used. (The resulting structure is far more conductive on the bottom than the top.) A loose contour stitch (see Figure 16.1) is used as a flexible conductive plane. The contour stitch is then sewn over with many denser objects. These objects interconnect the paths of the contour stitch, creating massive resistive network. They also create a large conductive and fuzzy area for the player's hand to couple to. Finally, a second loose contour stitch is placed over the more densely sewn objects and the original contour under plane. This second contour stitch ties the less conductive top fibers more tightly to the highly conductive bottom fibers. It also creates a shorter conductive path between objects. Because of the long stitching, tatami objects were simply too resistive to use before the top contour stitch was used.

Expansion of the Sewing Timeline

Piecework Circuit Elements Sewn from Metallic Silk Organza

Projects: *Firefly Dress and Necklace, Serial Suit, Piecework Fabric Keypad*, and the fabric ribbon cable in the *Musical Jacket*.

These piecework circuits were sewn from the highly conductive, metallic silk organza, which was sewn onto a non-conductive fabric backing. Piecework is labor intensive, time consuming and limits shape and size of the circuit element. (Quilts are made from square blocks whose smallest size is one inch for a reason.) Moreover, creating electrical connections by sewing two pieces of conducting fabric together was time consuming and not electrically reliable.

Composite Stainless Steel Thread, (BK 50/2) Passes Through Needle of Commercial Sewing Machine

BK 50/2 is a composite thread of non-continuous stainless steel fibers and polyester. It was the first thread that we could get through the needle of the sewing machine without it stripping, wadding, or knotting. Though it created very high impedance traces, (mega-ohms), it was useful in tying together the conductors in the anisotropically conductive metallic organza.

High Impedance Circuit Elements Designed in CAD Environment and Embroidered on Commercial Machine with Composite Stainless Steel Thread, (BK 50/2)

Projects: *Embroidered Keypad in the Musical Jacket.*
Using a commercial CAD embroidery environment (Wilcom software) to design circuit elements was much like using a PCB program. It also meant that these elements could be made any shape and far smaller than piecework elements. Using commercial

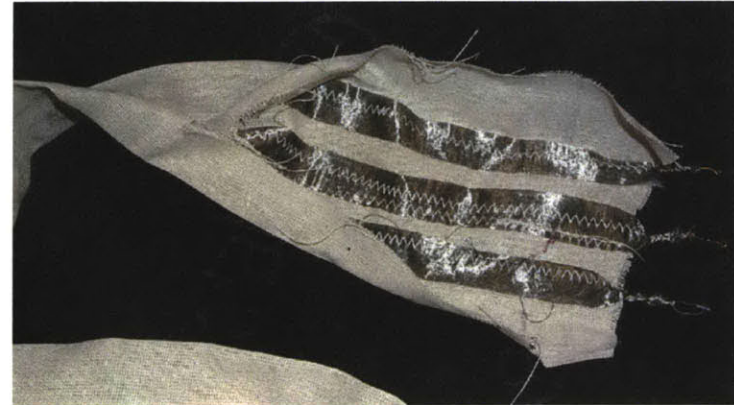


Figure 16.2 Piecework fabric ribbon cable from the *Musical Jacket*.

embroidery machines meant that multiples could be easily made.

Electro Impedance Reduced by 10X by using Composite Stainless Steel Thread, (BK 50/2) in Bobbin

Projects: *Embroidered Keypad in the Musical Jacket.*

The decrease in resistance, and increase in durability and reliability gained by using conductive thread in the bobbin made sewn keypads a reality. Running the conductive thread through both the bobbin and the needle decreased the resistance on the embroidered electrode by 10 times. This is a dramatically greater reduction than the usual change that occurs with parallel resistances $((R1+R2)/(R1 \times R2))$. This also made the electrode far more electrically reliable, varying less under wear and flexure.

Electro Impedance Reduced by Improved Stitch Pattern and Continuous Stitch Path Between Objects

Projects: *Embroidered Keypads in the Musical Jacket and Electronic Tablecloth.*

Altering the standard stitch pattern to improve conductivity involved a number of steps:

- 1) Creating redundancy by layering stitching.
- 2) Eliminating single object sewing by creating continuous inter-object sewing in layers.
- 3) Moving by hand any stitch that sent the needle directly through a previously sewn thread.
- 4) Loosening the density of stitches.

Achieving these steps was incredibly painstaking because it involved the hand manipulation of the stitch pattern on a stitch-by-stitch basis. Most embroidery CAD programs create a stitch pattern on the basis of parameters of individual objects. For instance, the outlines of square can be drawn, the program generates stitches to fill it. The designer can choose the type of stitch, like zig-zag or tatami. These objects can be created with under-stitching (multiple layers), which dramatically improves the conductivity of the object, by creating redundancy and numerous parallel resistance paths. A typical satin stitch object is first sewn with a single straight under-stitch, then a loose zigzag under-stitch, and finished with a dense satin stitch on the top. Then the next object is sewn. But simply sewing one object, like square, after or slightly on top of a previously sewn object will not create a good electrical connection between the two. To create a keypad involved making three objects, the trace, the pad for connecting to the circuit, and the number or key. But without the integration of the separate objects into one, the electrical connection between them was always poor. The objects had to be sewn as if one, with the understitching going continuously between each object. Stitch density in the top stitch had to be reduced. (This is an empirical observation). Any needle punch marks that passed through a previously sewn thread had to be moved by hand. This was painstaking, but reduced the resistance enough that the 12 inch traces and shaped keys used in the *Electronic Tablecloth's* keypads were still under 2k ohms. Unfortunately these electrodes were still not conductive or consistent enough for pressure sensing.

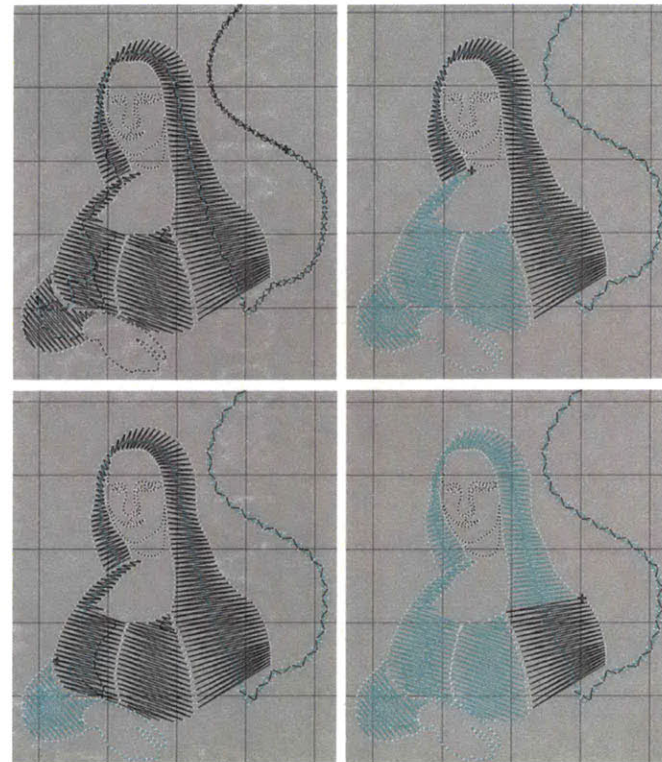


Figure 16.3 Continuous stitch path in Mona Lisa key from *Electronic Tablecloth*, blue lines indicate sewn stitches, black unsewn.

Electrode Impedance Dramatically Reduced by using 100% Non-Continuous Stainless Steel in Bobbin, but Causes Short Circuits Between Close Elements

Projects: *Ball 3 and 4.*

Using this highly conductive thread in the bobbin created EXTREMELY conductive electrodes. The top thread remained the highly resistive BK50/2, but because it only had to conduct the short distance from the topside to the underside of the electrode, its high resistance was not relevant. Unfortunately, the hairy bobbin thread caused many short circuits between electrodes, and skin irritation. Short circuits were eliminated by sewing each electrode on an individual panel, and then lining it with non-conducting cotton backing. Unfortunately, this process meant that there had to be a certain distance between the sensor and the ground electrodes. This did not allow for the creation of physically interdependent sensors. It was not easy to interweave the sensors, or create close proximity of the ground and sensor electrode, which created an easier and more natural playing style.

Electrode Impedance Dramatically Reduced by Nylon Wrapped with 3 Continuous Stainless Steel Fibers in Bobbin without Sewing Problems

Projects: *Ball 5, 6, Pyramid, Big Ring and Tube.*

This process replaced the hairy 100% stainless steel bobbin thread with a tidy, highly conductive, nylon yarn wrapped with 3 strands of continuous stainless steel. The electrodes it created were highly conductive. Using this thread eliminated much of the need for the stitch-

by-stitch editing that was necessary when using BK50/2 in the bobbin. The lack of hairy conductors and tidiness of this thread also eliminated the need for each electrode to be sewn on a separate panel and lined. Unfortunately, the initial electrode patterns that were sewn with this yarn in *Circle Ball 5*, did not work well as sensors. These patterns had worked well when the 100% non-continuous yarn was used in the bobbin, in *Circle Ball 4*. The only reasonable explanation for this was the dramatic reduction in the AREA of the conductor. Capacitance and in this case resistance is directly related to area, and while this new thread was highly conductive, it did not have a lot of conductor area. The sensor pattern of *Circle Ball 4* and *5* was thin. When sewn with the thick 100% stainless steel the conductor had a lot of area. When sewn with the wrapped thread the same electrode had too little area. This meant that the successful electrodes sewn with it (the *Generic Musical Ball*), were at first very dense and stiff. It is important to note that this thread really must be used in conjunction with the BK/50. The steel wrapping on this thread is very fine and almost impossible to electrically connect to. Using it with the BK/50, which has lots of loose little steel fibers, provided a good contact surface for both connecting to circuitry, and coupling with the hand.

Sensing Stability and Resolution Improves when Electrode Area and Density are Increased

Projects: *Generic Musical Ball*.

By increasing the density and size of the embroidered area of the electrode, the sensing stability and sensitivity increased. At this point, a satin stitch was

used to create a wide trace that was stitched in numerous layers. By folding the satin stitch traces against themselves, the electrodes became an almost continuous shape, with the maximum surface area filled in by dense conductors. (A tatami stitch is usually used to fill solid shape like a square, but they did not conduct well at this point.) The electrodes were still sewn on separate panels to prevent short circuits. This process gave the *Generic Ball* sensitive, durable, and isolated electrodes. The sensing was responsive and stable. From the success of this instrument I was able to iterate and experiment. Unfortunately, creating a good area made these electrodes a bit stiff and bulky. Because the satin stitch had to be continuous, the electrodes also had to be made in a sort of swirl-like pattern. This was both visually and tactilely limiting.

Tying a Knot Creates a Simultaneous Mechanical and Electrical Connection with a Twine of Continuous Stainless Steel Core Wrapped with Stainless Steel and Polyester Composite Thread (BK 50/2)

Projects: *Ball 6, Pyramid, Big Ring and Tube.*

The importance of this braid cannot be emphasized enough. Creating a reliable connection to the fabric is one of the main problems encountered when testing or working with it. Technically, this braid provided a quick, mechanically stable, and durable way to connect the central circuit to the fabric. I had used numerous strategies to do this, including wires coupled to 100% stainless steel threads. None them were mechanically reliable, and they all broke under the stress of squeezing. In addition, creating these connections was

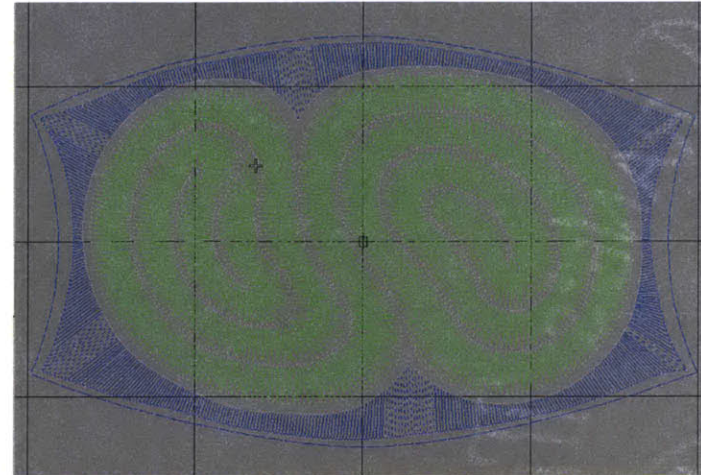


Figure 16.4 Embroidery CAD file of sensors electrode from *Generic Ball*. Green conductive thread is sewn in continuous satin pattern.



Figure 16.5 Close-up of mechanical/electrical knot with contact impedance of .2 ohms.

TIME CONSUMING. This braid of 100% continuous stainless steel wrapped with BK 50/2 allowed me to quickly mock up sensors, and tie them to the sensing circuitry. It let me test and iterate on both individual sensor and overall instrument design easily. Before this, yarn and electrode testing was difficult, because getting a good connection between the circuit and fabric electrode was so time consuming.

Contour Underlay Stitch Decreases Electrode Stiffness

Projects: *Pyramid* and *Big Ring*.

A large shape filled with a loose contour stitch provided a means to decrease electrode stiffness, but maintain surface area and therefore sensitivity. Sewing a single trace in a tight spiral spaced by 5-8 mm created a good electrical under plane and overall area for the sensor. Overstitching that plane with a satin stitch that crossed the perpendicularly tied the single thread together and created a surface area for the hand to couple to.

Contour Stitch Overlay Decreases Stitch Density and Increases Conductivity

Projects: *Big Ring* and *Tube*.

Using a contour stitch on top of a satin stitch, or a tatami object, not only increased the charge build up area, but also increased the overall conductivity of the electrodes, dramatically. This technique provides an enormous amount of design freedom. Using this technique I could work with the thinner tatamei objects, and build up visual depth. This over stitch also tied down long loose satin stitches that might come loose over time and wear. The electrodes I have created with

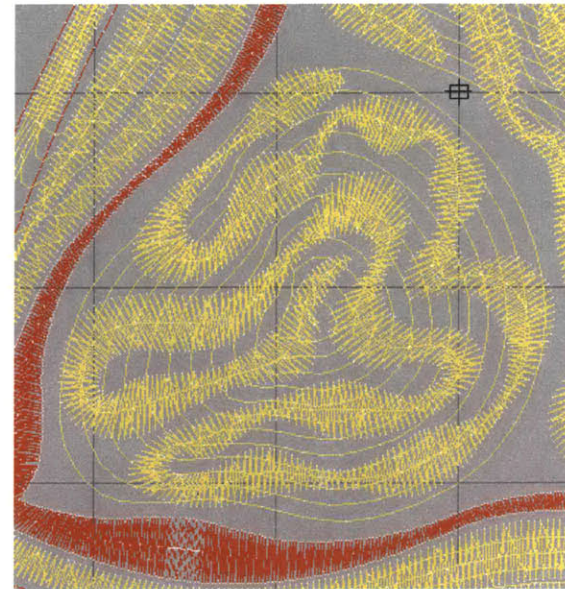


Figure 16.6 Contour underlay, beneath satin stitch swirl.

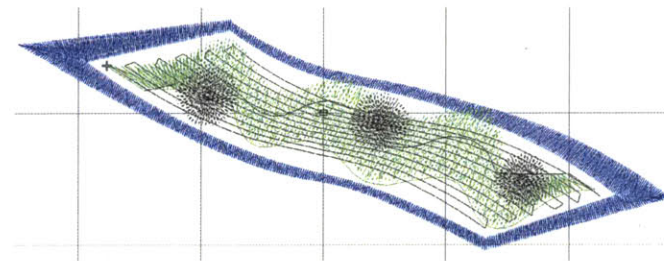


Figure 16.7 Contour overlay in *Big Ring* Sensor, black stitches represent contour overlay over green satin stitch.

this process can be designed quickly, and have a lot of visual and tactile variety. Moreover, their layered visual effect is directly related to their electrical needs.

Chapter 17.

Conclusion

When I began working with computers six years ago, I did not set out to work in smart materials or textiles. I set out to become involved in an artistic medium that was relevant. The fact that my work on the *Brain Opera* evolved into the making of many new physical computer interfaces, and consequently led to my deep interest in the material and physical transformation of computing objects, is of no surprise to me. I have always been driven toward the three-dimensional and the material in my artistic practice, and my experience in the *Brian Opera* presented me with an exciting and unexplored area of sculptural and artistic inquiry: the expressive relationship between physical form and computation, and the possibilities of physically and materially transforming computing technology. Ultimately, this is the fundamental area of artistic inquiry that ties together the work in this thesis. While today, this area of inquiry may seem broad, it is important to remember that when the work for this thesis began, there was so little other work going on in this area, that such broad goals were appropriate, if not artistically necessary. In the course of trying to achieve my artistic goals, I encountered a serious problem: the

physical materials of technology were simply inadequate for such an artistic exploration.

The fact that I worked on projects in fashions and musical instruments was in many ways serendipitous; wearables and musical instruments were areas of research going on at the lab. At the same time, I was drawn to work in these areas, because I saw that there was a void in how they were being explored. The fact that I chose smart textiles as a common means for creating these electronic fashions and embroidered musical instruments was the result of both my understanding of what it might take to *practically* create these kind of objects, as well as a reflection of my desire to create the fantastic, the unexpected, and the magical in three-dimensional and material reality. It seemed fantastic to me then, and still does today, to create beautiful, floral, and decorative fabrics that can light lights, participate in computation, sense, and even play music.

It was my hands-on and direct work with smart textiles that ultimately led me to ideas about smart and sculptural computing materials. So while the works and ideas about smart materials presented in this thesis are the result of an organic process, they are not without a central goal or artistic vision. Moreover, the fact that this vision has grown and emerged from a direct, hands-on process of making is entirely appropriate. This is one of the central tenets of my thesis. Without the direct hands-on exploration of the physical materials of computers, physical computing technology will not develop as an artistic form or medium. And indeed, it was my actual struggle and interaction with the *real*

materials of computers that led me to this proposal. I most likely could not, and would not have come up with the idea of smart materials or textiles, fabric sensors, or circuits, if I had not been struggling with the existing materials of computing technology. No scenario or CAD-based design practice would have gotten me where I am today, or satisfied my personal desire to touch, sensually explore, and create *real* material computing objects.

This is not to say that I do not go through a design process, or think, before I start to create. Of course I do. My extensive experience creating physical, interactive objects necessitates that. As soon as I think about a project, I cannot help but consider the design criteria on every level of scale, and how I might solve those numerous problems. Much of that process is based on my experience making things and extensive studio arts education. This process is not necessarily novel, but the result of my experience making things, and thinking among and learning from other artists and designers. But there is a novel part of my design process, both for traditional design practices and technology design practices. This is the part of my design process that emerged while working with and creating the physical materials of computing technology. This is the part that makes the proposal for a new future design/technology practice.

Summary

A Proposal for Future Design

The future design/technology practice presented in this thesis uses and creates new, sculptural, and smart computing materials to directly and sensually transform physical computing technology from hard plastic boxes into materially rich and physically diverse objects. I believe that this approach has widespread implications for many existing three-dimensional design practices, and that it will ultimately affect the role of computing technology in peoples' lives. This approach demands that artists and designers working with computing technology actively endeavor to change the materials of the computer into a more direct, tactile, sensuous, and sculptable artistic medium. Creating new computing materials can no longer be left to engineers and scientists; no longer is smaller and faster enough. Creating new computing materials must become part of the creative process itself. When designers and artists make the creation of new computing materials part of their expressive process, these materials will come to reflect the aesthetic needs of design and art. This change will create a broader range of possibilities for physical computing technology, enabling it to better reflect the vision of artists and designers and allowing it to spread out and interact with the material world as never before.

Practically and technically, smart materials will make it easier for computing technology to get into unusual places, like clothing and house wares. Artistically, smart, sculptural materials present entirely new

possibilities for changing the artistic and material vocabulary of physical computing technology. If done right, these new materials will provide artists and designers with a more direct and hands-on approach to sketching or creating with physical computing technology. They will also allow computing technology to be materially inverted, for instance allowing it to become *deeply* soft or rubbery. Radically changing the material properties of any object changes peoples' aesthetic or gut reaction to it, which ultimately changes their assumptions about its role in their lives. Making computing technology more sensually intimate will also change how, when, and why people use it. Finally, new smart or active computing materials will help artists and designers develop an aesthetic and meaningful relationship between physical form and computation.

A Personal Artistic Vision

More personally, this thesis has demonstrated my own artistic and aesthetic vision for materially transforming computers into objects that play a creative and expressive role in peoples' lives. The unusual smart computing materials I have chosen to focus on are soft, fuzzy, organic and intimate. One of my main goals in choosing these materials has been the democratization of computers. Computers are the most powerful tool of our time, yet I believe their creative potential is still not fully explored. Moreover, people often feel that technology is beyond their control, inaccessible, and unreachable. Symbolically, the square, plastic image and materials of many of today's computing objects have all reinforced the role of computers as tools for business and productivity, and as ultimately

inaccessible. In a more material and practical sense, the physical materials of computers have had direct limitations on how people use and create with them. People who want to use computers as expressive tools, like musical instruments or drawing tools, are often faced with rigid and awkward physical objects. People who want to use computers as a physical medium are faced with limiting materials that cannot be shaped to reflect their expressive vision

Proof is in the Projects

The diverse portfolio of artistic projects presented in this thesis strongly supports the broad implications of both my proposal for a future technology/design practice, and my personal artistic vision. I have used smart and sculptural computing materials to create new musical instruments, numerous fashions, tablecloths, and a new computing construction kit, the *Triangles*. These works span a broad range of three-dimensional design disciplines from fashion design to industrial design and musical instruments. Creating and using smart and sculptural computing materials in these projects improved both the design process and its results, and ultimately transformed the physical and sensual properties of the computing technology I was working with.

1. Smart textiles allowed me to directly sketch, iterate, and aesthetically experiment with the *real* materials of the object (as opposed to making physical or virtual models). With smart textiles I could quickly cut and sew fabric electrodes, sensors, switches and circuits, and

quickly make both electrical and mechanical connections between these various parts. This allowed me to make a hands-on aesthetic investigation of the physical materials of computing technology. For instance, the twinkling light effect in the skirt *Firefly Dress* (which was caused when the motion of the wearer made the conductive fabric ground and power plane come into contact with LEDs in the skirt,) is something that was sketched out and experimented with first in a simple panel and then developed through iteration into the design for the dress. CAD and scenario-based design could never have created the lighting effect or aesthetic understanding of what LEDs, suspended between two sheer layers of conductive fabric would do.

2. Smart textiles allowed me to directly and plastically sculpt and shape physical computing technology. Textiles are highly plastic. They can be cut, bent and sewn into almost any shape. Using smart textiles allowed me to plastically sculpt and shape active computing materials, and prevented prefabricated materials, like sensors and buttons, from determining the shape of my work. Smart textiles also allowed me to create sensors with specific shapes and designs. The variety of shapes of the final *Embroidered Musical Instruments* and their sensors demonstrate this, as do the shaped buttons on the *Embroidered Tablecloth*.

3. The use of smart textiles in the work presented in this thesis also suggests how smart, sculptural computing materials will help develop a more intimate and artistic relationship between physical form and computation. The *Embroidered Musical Instruments* demonstrate how sculptural materials can help designers and artists create objects that are not neutral in software, like a mouse, but are truly designed for specific applications. By virtue of its physical design, each instrument creates very different effects in music software when squeezed. In addition, the sensor design in these instruments suggests an even more intimate relationship between physical form and computation. The design of the final embroidered pressure sensors (for instance the bumpy sensors in the *Pyramid* and the ground electrode in the *Big Ring*), is a reflection of both the tactile, visual, electrical, sensing and ergonomic needs of the sensors. While this is not directly linked to software, it is linked to an active component of the computing, i.e. the sensing, which is then linked to, and effects, the music software. This suggests the possibility of an even more direct link between physical form and computation.
4. The use of smart textiles also allowed me to *deeply*, physically (both materially and sculpturally) transform computing technology into squishy, soft, intimate and truly sculptural objects. By replacing hard wires, sensors, circuitry, and what would normally be a rigid housing material in the *Embroidered Musical*

Instruments, smart textiles allowed these objects to be *deeply* squishy, rather than just soft covers over hard electronic shells, sensors or wires. Moreover, the shape of these instruments is not the reflection of the square, hard, and prefabricated parts, or fragile and awkward sensors. These instruments are the shape they are for musical, ergonomic, sensing, and visual reasons. Smart textiles also allowed computing technology to go into unexpected places (like clothing), and allowed for people to have a uniquely sensual relationship with it. My computing fashions clearly demonstrate that computers worn on the body do not have to be large metal boxes whose primary function is to display e-mail. Instead, they can be soft, physically intimate fashions that take the form of romantic dresses and musical jackets.

Technical Innovations

Technically, I have supported my personal, artistic vision, and broader design vision, for materially transforming the computer by inventing new types of physical computer interfaces, developing new sculptural, smart computing materials and processes, creating an electrical model of complex impedance sensing which plays an essential role in my design process, and developing a definition and test for the sewability and flexibility of yarns.

I co-invented and constructed the first working prototype of a fabric keypad, a row and column switch matrix. I collaboratively worked to develop the first

embroidered keypad. I jointly hold a patent with Rehmi Post, Emily Copper and Josh Smith on fabric circuit elements. After working to create the first high impedance embroidered keypad with Rehmi Post (in the *Musical Jacket*), I further developed the embroidery and sewing process to create far more conductive and stable fabric electrodes, sensors and circuit elements that are also soft, flexible and visually diverse. I directed and motivated the research that led to pressure sensing on fabric electrodes. I worked with Bekeart Corporation to create a new composite thread/braid that can easily tie an electrical/mechanical knot to both a circuit and fabric electrode. (This thread is now manufactured in small quantities by Beakart Corporation). I created an index of electrically active textiles and described their mechanical and electrical properties. I also empirically developed an electronic model for understanding complex impedance sensing with fabric electrodes. This model has played an essential role in the design of my *Embroidered Musical Instruments*. I developed a test and understanding for flexibility and sewability in conductive yarns. I co-invented and patented a new physical computing interface, the *Triangles*, and their new physical and electrical connector that allowed an immediate electrical and mechanical connection between two physical objects, specifically the *Triangles*.

Further Inquiry

Art and Design

Physical Form and Computation

Unquestionably, a broad artistic vocabulary and understanding of the interaction of physical form and computation is still in its infancy. And while the projects presented in this thesis use new smart and sculptural computing materials to explore specific relationships between physical form and computation, they only begin to suggest an overall artistic vocabulary for that interaction. The work in this thesis looks specifically at how physical objects can transcend their neutrality in software, interact in specific ways with software and have relationships between physical form, and electrical and sensing properties. It leaves open deep questions about how the process of directly and plastically shaping a computing material might influence software.

This thesis also leads to many questions about the use of networked objects or materials as an expressive medium. The *Triangles* demonstrates just a few of the problems that creative and artistic people are facing when working with networked objects. Creating software for the *Triangles* made it clear that as content authors, we did not yet understand how to use all the information coming from the *Triangles*. We created no applications that interpreted the overall shape of the system for some higher-level creative purpose. In addition, we often discounted information coming from individual sides. Sometimes, we even ignored who was

connected to whom and just made a "glob" that only recognized if a single *Triangle* was connected to the system. Moreover, the *Triangles* project demonstrates that creating content for a complex network of communicating objects will demand new ways of algorithmically generating narrative and storytelling content for complex physical systems with a factorial number of possibilities. Hard-coding a factorial number of story lines or narratives is simply not possible.

A Process for Exploring Physical Form and Computation

The methods used to develop the projects in this thesis suggest some very practical design processes that can help expand the artistic vocabulary of physical form and computing. Clearly, one of the main goals of any such investigation should be to understand how the shape of computing objects can effect software. A mouse is a neutral physical object. If you change its shape, it has no effect inside the computer. Exploring physical computing objects that are not neutral requires their specific shape and form to directly affect what happens inside the computer, or in software. Because computers generally deal with neutral forms, understanding what the effects of physical form and new materials are on software can be a confusing and unclear process.

My experience creating new physical computing objects with new materials suggests a practical and iterative design process for understanding the *formal* interaction between physical shape and computation.

This process can be generally divided into two stages of development:

- 1) The development of a *generic design control object* with stable materials and technologies and cognitively clear design.
- 2) The changing of the *generic* design to the specific in order to investigate how different shapes relate to software.

In the initial stage of development a *generic design control object* is created. This object should demonstrate that the technology and any new materials are working and relatively stable. This object should use these stable materials and technologies to create a cognitively simple design that is visually clear, simply arranged, and able to be tried with many types of software. The *Generic Ball* was in many ways the ideal design control object. The sensing and sewing techniques used in the *Generic Ball* were developed enough to create stable electrodes and sensing. The electrodes were equal-sized, equidistant and arranged in clear, symmetric pattern. While the creation of this *generic design control object* may seem counterintuitive to the process of developing a real relationship between software and physical form, it is an essential jumping off point. Without this control object, there is no reference for how the materials, software, and physical form may interact when they are changed or manipulated. In the case of the *Generic Ball*, I could not determine how varying the sensor size or placement affected the musical output and sensing, until I saw that sensors of all the same size behaved in the same way.

The second stage of development uses the *generic design control object* to more closely examine the expressive interaction between the materials, physical form and software. At this stage, a variety of software should be tried with the object. In some cases this may be the final process. For instance, after the initial prototypes of the *Triangles* were made, numerous applications to explore how they interacted with software were then developed. (Many more could still be experimented with.) While the physical design of the *Triangles* did change after the first applications, this was only to improve the mechanical functioning of the *Triangles*. In the *Embroidered Musical Instruments*, a more iterative process between physical form and software developed. The *Generic Ball* was tried with a few applications and played by many children and viewers. As result of the software experiments and observation of players, new physical designs and software were developed. The many iterations that the *Embroidered Musical Instruments* went through, demonstrate how important the development of stable technology and highly sculptural computing materials is to facilitating creative iteration and experimentation. Because the technology was stable, I was able to quickly try different sensor configurations. Because my materials were so sculptural and direct, I was able to quickly try different shapes and forms.

Working with *generic design control objects* will ultimately help artists and designers develop a sort of basic vocabulary and understanding of physical form and computation.

Future Materials

Smart Textiles

The problem of creating *integrated* smart textiles is still large. Currently, smart textile research tends to involve a close examination of a single smart or active fiber, like stainless thread, fiber optics, conductive polymers, shape memory alloys, or other types of phase change materials. But having only one type of active fiber integrated into a textile does not solve the problem of creating a flexible addressing scheme for the smart fibers, or of creating more complex structures, like displays or logic. Creating a single textile with all the different fibers and materials that, for instance fully addressable camouflage would require, will involve work on individual fibers, yarns, and textile processes, not to mention deep materials science.

Beyond material integration is the problem of creating smart textiles that are truly flexible, and therefore truly wearable. Within the domain of textiles, there are fibers, yarns and textiles that are appropriate either for fabrics that are worn, or for industrial purposes, like reinforcement in composite materials or shielding. Industrial fibers may include fiberglass and steel. In addition, there are materials that are called fibers that are not necessarily used in textiles products at all, like shape memory alloy fibers. Currently, there seems to be some confusion in the smart textiles field about using industrial textile materials and non-textile oriented fibers in smart textiles. At the recent *Intelligence Textiles Conference*¹, the idea of *flexible*

¹ Intelligent Textiles Conference, Providence RI, (2000).

seemed to be that a fiber could be bent around a one-inch radius of curvature without breaking or permanently deforming. Truly wearable textile materials demand a far higher degree of flexibility. Any textile material that is wearable must be highly flexible and resistant to permanent deformation under bending. It is essential that there be a clear distinction between industrial smart textile materials and wearable smart textile materials, and that an emphasis put on creating smart textiles and textile materials that are truly flexible.

Future Sculptural Smart Computing Materials

How to create better sculptural computing materials remains a huge technical question. How can we make computational clay? Or paint? Solving this problem is not fundamentally one of processor design. It is a problem of the materials and the interconnectivity between different parts. And while micro and nano technology are thriving, I believe that creating new sculptural, smart computing materials must be driven by human-scaled goals. New computing materials must be designed for their artistic properties, and therefore, with the scale of the human senses and perception in mind. While future sculptural, smart materials will need to be engineered microscopically, the focus of their design needs must be their humanly perceived, mechanical and sensual properties.

Today, we are surrounded by technological marvels we cannot perceive. A microchip has a level of complexity and detail never encountered before. People are building miniature engines and assembly systems. But

no one can directly perceive these things. On a macroscopic scale, projects like the current *Big Dig* in Boston are engineering and creative marvels so large, that we cannot perceive them. New materials for computing technology must achieve on a human scale, and perceived on that human scale. This is particularly relevant for the practice of demo making. How can technology researchers and artists tell the story of nano technology and its amazing achievements?

The materials and processes developed in this thesis suggest a few possible approaches for addressing some of the problems that creating integrated, humanly perceived, smart computing materials will face. This thesis has centered on the idea of using a single smart material to replace numerous, separate, prefabricated materials in a computational object. It has also put forth smart textiles as a way to create highly flexible, shapeable, bendable, and cuttable circuit elements. I believe that there are a few unique ideas in these two approaches that have ramifications for future physical computing materials in general.

Because smart materials are about integrating functionality, they insist that new electronic or computing materials go beyond creating a *single* flexible component of a computational object, like a display or speaker. Today, even the most flexible display, speaker, or circuit element must still be mechanically and electrically connected to the rest of the computing object. Thus, the sculptability and mechanical benefits of any flexible component are limited by the process of joining. What makes the wood of the violin so wonderful is that as a single material it

performs so many functions. This is not to say that the violin is not made of many pieces of wood, but because many of its parts are all wood, they can be easily cut apart and joined together. Different materials with different physical properties, including flexibility and porosity, are extremely difficult to join together. Joints in computing objects are extra hard because they must also be electrical as well as mechanical. If computing materials cannot be easily mechanically and electrically joined, rigid structures must emerge to support them. These are the packages and rigid circuits of most electronic items. For this reason, making as many parts of a computing object out of the same material as possible, is essential to making the object more robust, and the process by which it is made more direct and sculptural.

The design benefits of using even *limited* smart computing materials in the *Embroidered Musical Instruments*, (only integrating the functions of wires, circuitry, sensors and housing material into a single smart textile), suggest the possibility of an entirely integrative material, a material that can be simultaneously sensors, circuitry, processors, and displays. In many ways, silicon is already the ideal *microscopic* electronic integrated material. Through doping, oxidation, and metalization, one single hunk of silicon can become insulator, conductor, or semiconductor. Through lithography processes these materials can be laid out as thousands of transistors on single chip. But of course the silicon chip is rigid, must be protected from the environment, and then connected to larger circuit elements and to input and output devices. Couldn't there be a sort of human-

scaled silicon for computing objects? Imagine taking a computing clay, shaping it, and then applying a sensor or display glaze. Firing it might then activate the whole system.

While creating a totally integrated smart material that can replace sensors, displays, speakers, circuitry, batteries, and chips, is incredibly challenging, I believe that the next logical step for sculptural smart computing materials is what I call *sculptural, input/output materials*. *Sculptural i/o materials* should integrate housing, some sort of basic circuitry, sensors and some sort of visual or acoustic display. Creating a material like this will truly advance the design of computing objects. While these objects will still need central circuitry, these hard materials can always be carefully hidden.

Making smart computing materials sculptable (shapeable, bendable, and cuttable), also presents a unique series of problems. Extremely promising is the development of printed circuits, logic and displays on flexible materials, as well as flexible conductors and displays with printed circuit logic. But while film-based electronic structures provide a certain degree of flexibility, they do not provide the mechanical strength or flexibility of textiles. The sewn circuits in this thesis are so mechanically flexible and durable because of the electrical redundancy created in the three-dimensional structure of the yarns and the traces sewn from multiple stitch paths. Within a single yarn or thread, multiple, long, conducting stainless steel fibers build a network of electrical redundancy. Doping with long fibers, as opposed to a granular powder, creates a

more durable three-dimensional conductive network. Within the stitched trace, multiple threads within build another conductive network. If one yarn breaks, or fails it does not affect the conductivity of the overall trace. Redundant conductors and multiple stitch paths of embroidered electrodes provide mechanical and electrical stability of a high degree, because they do not rely on a single continuous film, but a mesh of conductors. If these threads relied solely on a single coating, they would electrically fail quickly. No embroidered electrode stitched with the process I have used has yet to fail electrically under any amount of squeezing. New flexible and conductive materials should look at creating more mechanical redundancies and three-dimensional meshes, not just film based electrical continuity.

The idea of creating three-dimensional electrical structures or networks leads to a more abstract possibility for transcending two-dimensional electronic fabrication methods, and emphasizing more three-dimensional processes and materials. Today, most circuit and silicon chip manufacture relies on a two-dimensional, planar manufacturing process that has some relationship to printing processes that can be traced to lithography in the 15th century. There are good reasons for this. Lithographic processes lead to high throughput, or numbers of devices for numbers of process steps. They are also suited to the electrical nature of silicon, which requires a single crystal structure or solid piece of material that is then treated. Moreover, the manufacturing processes and equipment that do both silicon and circuit fabrication are highly developed. This has created a sort of two-dimensional

convention for micro-fabrication. As a result, much micro-fabrication that takes place in silicon, creatively uses two-dimensional fabrication processes to make three-dimensional structures, even three-dimensional MEMs. In fact, most of these structures are stacked extrusions of etched layers. I believe that just as square screens kept visual computer expression and art in the realm of the square and the pictorial, so do two-dimensional fabrication processes keep electronic materials in the realm of the non-sculptural and the flat. Transcending two-dimensional manufacturing conventions is necessary for more three-dimensional electronic materials to emerge. I cannot tell you how to do this; I just know that it is necessary for getting beyond the flatness of today's electronic materials.

A more three-dimensional material might be a sort of *microscopic connector goo* for connecting thousands of tiny processors. This goo might have thousands of long and skinny conductors, (for instance carbon nanotubes) with differently shaped ends or connectors. One shape might be for ground, one for power, and one data, (data could also be done wirelessly). Currently, models of amorphous computing like Jerry Sussman's *Pinless Processor* and Bill Butera's *Paintable Computing* rely on hard wiring for powering their processors and wireless data transmission. This prevents these materials from being truly amorphous or mechanically paintable. But *connector goo* might let all these wirelessly communicating devices distribute power and ground, while swimming around in a sort of amorphous gel.

Future Computational Objects

What can future sculptural computing objects become?
What are their possibilities?

In my far-flung imagination, I see flocks of small (less than three inches), musical robots. Their mechanical wings allow them to create a limited range of audio sounds. Using flocking behavior, they can move around a room and surround an audience, or form a larger mass of different shapes. Such a mass could then form the skin of a larger coherent instrument, with its own, larger resonant interior cavity, that could then create a different range of sound. Possible networked objects that are more grounded in reality, might involve walls covered with mechanical eyes and ears that can hear and then watch the people in that space. Such an environment would invert the gaze of the viewer in a novel and unexpected way.

I imagine far-flung materials like *electronic object clay* with speaker, sensor, and display glazes that could be painted right on. Creating an object with such materials might involve shaping the clay and then painting the displays, sensors, and speakers, right on to surface of it. A "firing" process could activate the glazes. Broadly and theoretically, this might not be that different than the sort of *firing* processes that silicon undergoes. Such direct materials could radically change how artists create electronic objects, and what these objects might do. More immediately, just being able to directly paint the electrode design of a single pixel display could be incredibly expressive and change how and when designers work with display technology. Large,

expressively designed single pixel-displays might be used to create innovatively designed furniture and house wares.

My next fantasy for squeezable musical instruments would be a squeezable material that was simultaneously sensors, speakers, and visual display. Such a material would both create music, light, and make sound at the same time. This would be incredibly transformative, even if the instruments still contained central circuitry and on-board processors.

While I see many artistic directions for these new objects, I find that my imagination is also limited in many ways by current experience. I find that today I am ready to branch out, and open my mind again, away from smart textiles and into other materials and other forms of dynamic output aside from music. But while I am branching out, I know that the expansion of physical computing technology as an expressive medium cannot happen without an aggressive and transformative material attack; nor ultimately without an intimate, technical and aesthetic knowledge of the *real* physical and active computing materials from which it all is made.

Design Appendix.

The *Big Thing*

I have included in this appendix the *Big Thing*. The *Big Thing* was a *Toy Symphony* project, which I worked on for one year, during the course of this thesis. This instrument was originally the final project proposed for this thesis. It was part of the larger *Toy Symphony*, for which I was the design director. Though many working prototypes and the communication hardware were completed for this project, for many reasons it was not finished. Collaborative work is complex. This project was originally intended to be a giant construction kit that allowed kids to compose music. Aligning the physical object with the composing of the music was difficult. In addition, the music concepts for this project took longer far longer to develop than the actual hardware. One major conceptual hurdle was the difference between a composition tool, (which analyzed the built structure and then "performed" the music), and a live instrument, (which reacted in real time to the actions of its player). This piece was also very expensive to build, because it



Figure A.1 Five foot, looks-like model of *Big Thing*, with upholstered base. This model had no electronics, but did have bungee cords for mechanical movement of the outer ring.

relied on the manufacturing of a limited number plastic objects, which involved expensive injection molds.

Though the project was not finished, there are a few very nice design decisions that might be helpful for later projects, including the sensing design for the individual *Chunks*. The following description is taken from my thesis proposal.

Description of The *Big Thing*

The *Big Thing* is a musical construction kit that gives kids a physical and direct way to twist, poke, prod, construct and perform their own musical compositions. The most basic building block of the kit is the *Chunk*. Chunks are both instruments for controlling real time music, and construction blocks for representing that music symbolically. In the *Poking Area*, Chunks can be poked and prodded into simple musical building blocks. They can then be constructed into a physical and musical arrangement on the construction *Islands*. *Operator Poles* are pieces that represent musical algorithms, which will rearrange the musical parameters of the Chunks. Kids will be able to use default algorithms in the Operator Poles, or program their own algorithms for the poles. *Stack Connectors* let the kids establish relationship between different parts of their composition. Kids can then perform and interpret their musical creation, just as they might perform and interpret a traditional composition, by manipulating the bouncy outer ring and stretchy the sensor bungee cords, or by adding their own feather sensors.

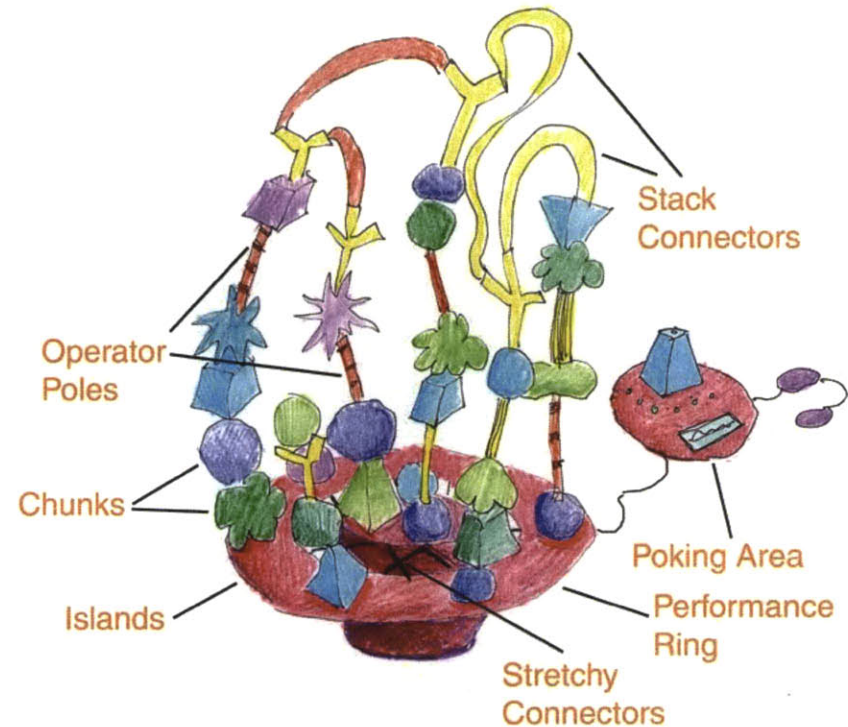


Figure A.2 Drawing of the *Big Thing*, Maggie Orth, 1999.

List of Kit Components

- 1 Construction Island
- 1 Poking Area
- 50 Musical Chunks
- 5 Reverse Direction Chunks
- 10 Stack Connectors
- 10 Y Connectors
- 10 Operator Poles
- 8 Stretchy Connectors
- 10 Feather Sensors
- 1 Musical Software GUI

The *Big Thing* is made for the stage and designed for performance in the *Toy Symphony*. In the *Toy Symphony*, there will be twelve musical islands, scaled UP to life size, for visibility from the stage. By keeping the underlying technology of the kit simple, The *Big Thing* can easily be scaled down for home play and produced as a commercial toy. In this way, the kit can be both a professional performance instrument and a home musical exploration tool. In the *Toy Symphony* there will be 1,000 Kit Components.

Description of Components

Islands

The Islands are the basic building platforms for the composition. Each Island contains 12 nodes into which chunks can be stacked. 4 of these nodes are located on the stable inner ring or base. This base houses speakers and other equipment. 8 of the nodes are located on the bouncy outer ring. The outer ring transforms the Island into an instrument that can be physically manipulated to create music. By pulling the

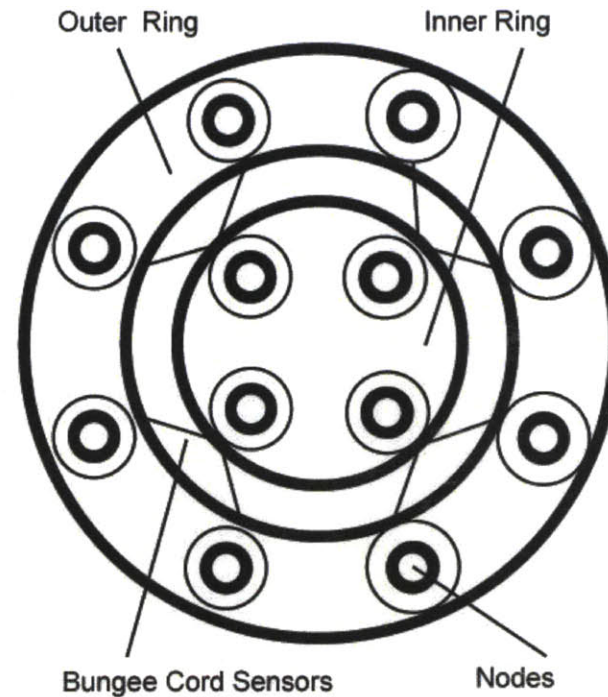


Figure A.3 Island from the *Big Thing*. Above, layout and plan. Below, artists sketch, Maggie Orth.

ring up and down, the Bungee Cord strain gauges are stretched, generating continuous data, which affects the parameters of the composed music. The Islands are 31 inches in diameter, allowing kids easy access to the building area, but providing enough room for a generous number of nodes.

Chunks

Chunks are the most basic building blocks of the BIG THING construction kit. Each Chunk represents a simple musical element that kids can compose themselves. When the Chunk is plugged into the Poking Area, its soft exterior can be used as a sensitive instrument. Careful design allows the Chunk to trigger pressure sensors located in the Poking Area, meaning it requires no on board sensors itself. Once the music is composed in the poking area, kids can move the chunk to the Islands and make it part of a bigger composition. Each chunk contains a PIC, which has a unique ID for the Chunk and software to control serial and Chunk to Chunk communication. When a Chunk is plugged into a node, it transmits its ID serially to a main computer, which generates music. The software communication and physical building structure of the Chunks let players create simple linear stacks of Chunks. Both the identity and location of the Chunks can be known. The Chunks pass power, ground, serial communication and local communication over a 4 pin DC connector.

Poking Area

The poking area is flat base with a female connector where kit pieces can be plugged in. It contains four pressure sensors and few buttons. When a Chunk is

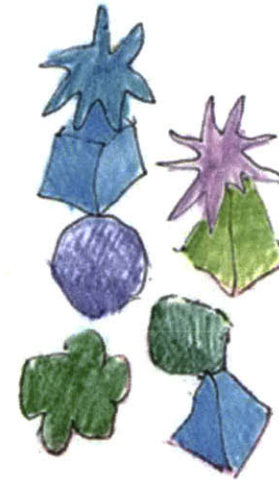


Figure A.4 Artist's drawing of Chunks, Maggie Orth.

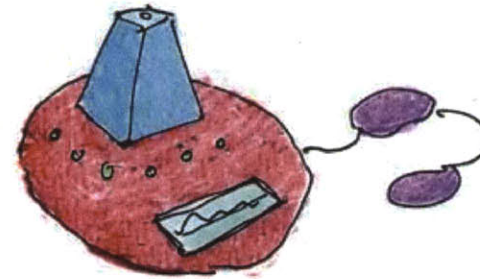


Figure A.5 Artist's drawing of Poking Area, Maggie Orth.

plugged into the Poking Area, kids can squeeze it to trigger sensors built into the base of the Poking Area. In this way, Chunks need no on board sensing capabilities. The Poking Area is also where kids can plug in Operator Poles to create their own musical algorithms.

Operator Poles

Operator Poles are long building blocks that represent musical algorithms. When an Operator Pole is plugged into a stack of Chunks it rearranges the musical parameters. Kids can plug the Operator Poles into the Poking Area and compose their own musical algorithms as well.

Stack Connectors

Stack Connectors let kids connect stacks of chunks together and establish a relationship between the stacks. Currently, the plan is to use stack connectors to pull a longer musical melody form a sound and music texture.

Stretchy Connectors (Conductive Bungee Cords)

Stretchy Connectors connect the out ring to the inner and let players manipulate and interpret the musical composition in real time. These bungee cords are made from woven conductive thread, (Stainless steel and polyester composite) and non-conductive thread around a stranded rubber core. When the bungee cord is stretched, the conductive fibers tighten together and the resistance across the woven structure of conductive threads drops. The change in resistance is measured in simple voltage divider.

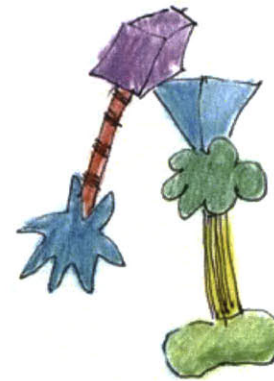


Figure A.6 Operator Poles.



Figure A.7 Stack Connectors

Feather Sensors

Feather sensors will use the actual piezoelectric effect in real feathers to measure their movement when plugged into the construction base. Each feather will control a single stack of Chunks, and in particular, the amount of the musical algorithm that affects the Chunks.

Implementation of *Big Thing*

Overall Schematic of *Big Thing* Infrastructure

One of the main goals of the *Big Thing* is to design a digital construction kit that can be easily translated into an inexpensive and manufacturable commercial toy. To do this, the physical construction kit will use the simplest technology possible, while the major computational and musical functions will take place on a PC and synthesizers. In the toy version, the PC and synthesizers can be replaced with less expensive elements, for instance, a SEGA game system, or simple on board, "toy" synthesizers.

The *Big Thing* will communicate serially with a PC, which will send MIDI to synthesizers, which will generate music in the speakers built into the Island. On each Island, each Node will send serial information from the Chunks plugged into it, to the PC. The PC will keep track of the physical configuration of the Chunks, changing the music accordingly.

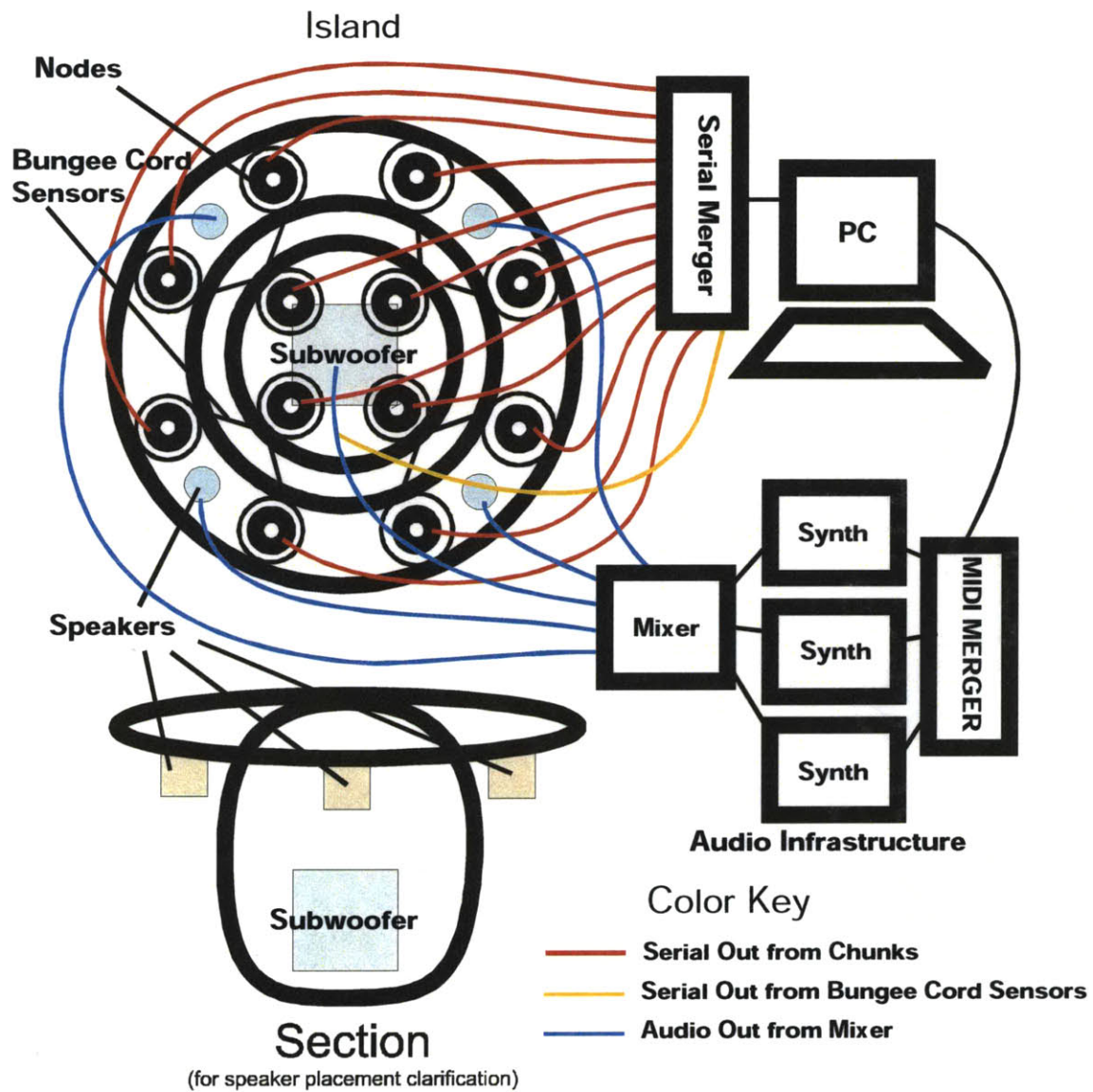


Figure A.7 Overall layout of *Big Thing*.

Physical Chunk Design

Each Chunk will contain the minimum hardware required to keep track of its identity, light LEDs (to communicate that it is musically active), and to communicate its location over a serial bus with a central processing unit, (PC). The Chunks communicate through a 5 pin, custom, DC electrical connector. While the Chunks have no sensors of their own, they can be used as a sensitive instrument when plugged into the Poking Area, where their soft, foam wings can be squeezed to manipulate the 4 pressure sensors, (and consequently music) that are built into the Poking Area itself. Building the sensors into the Poking Area keeps the Chunks simple and cheap. Each Chunk's central connector and wings will be injection molded. The Poking Area will be manufactured by hand.

Chunk Communication and Electronic Design

Each Chunk will contain a PIC programmed with a unique ID and a number of LED's. The Chunks will connect linearly into one of 12 Nodes in the Island. Each Node has its own serial management board, which manages communication between the Chunk stack and the PC. The Chunks use both serial and PIC to PIC communication, enabling them to communicate quickly (serial) and to know the order of the Chunks in the stack (PIC to PIC). The PC polls them over an serial bus. If a Chunk recognizes that it is the last Chunk (it sees no connection to ground on its "Last Chunk Identifier Pin"), it sends it's ID to the Chunk below it, which adds its ID to the one it received sends that ordered list of ID's to Node board, which forwards the ordered list to the PC.

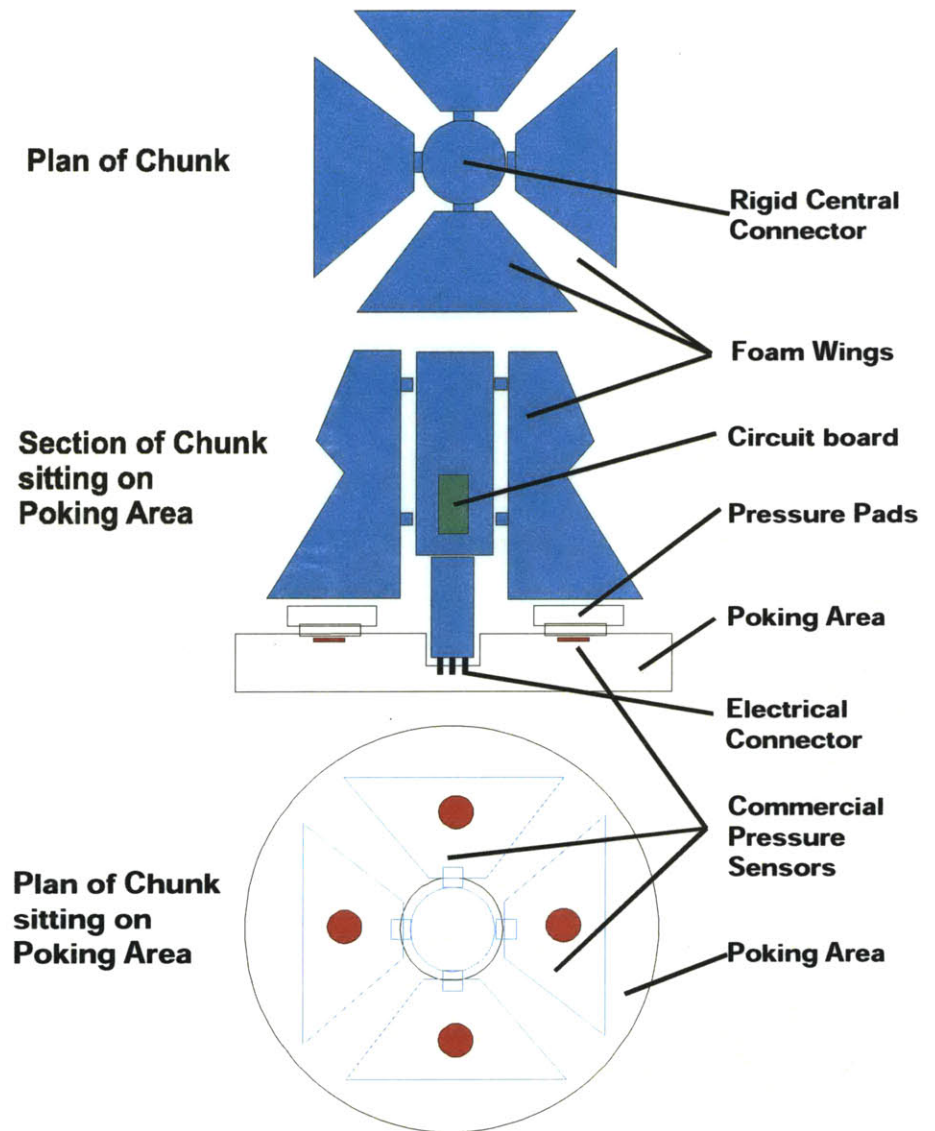


Figure A.8 Diagram of Chunk.

All the pieces of the kit that connect together, i.e., Y Connectors, Operator Poles and Stack Connectors, use the same hardware, the Chunk board. Stack Connectors contain one Chunk board at each end, but no internal connection. Y Connectors are merely wires. Operator Poles contain one Chunk board as well.



Figure A.9 Working prototype Chunk with electronics.

General Schematic

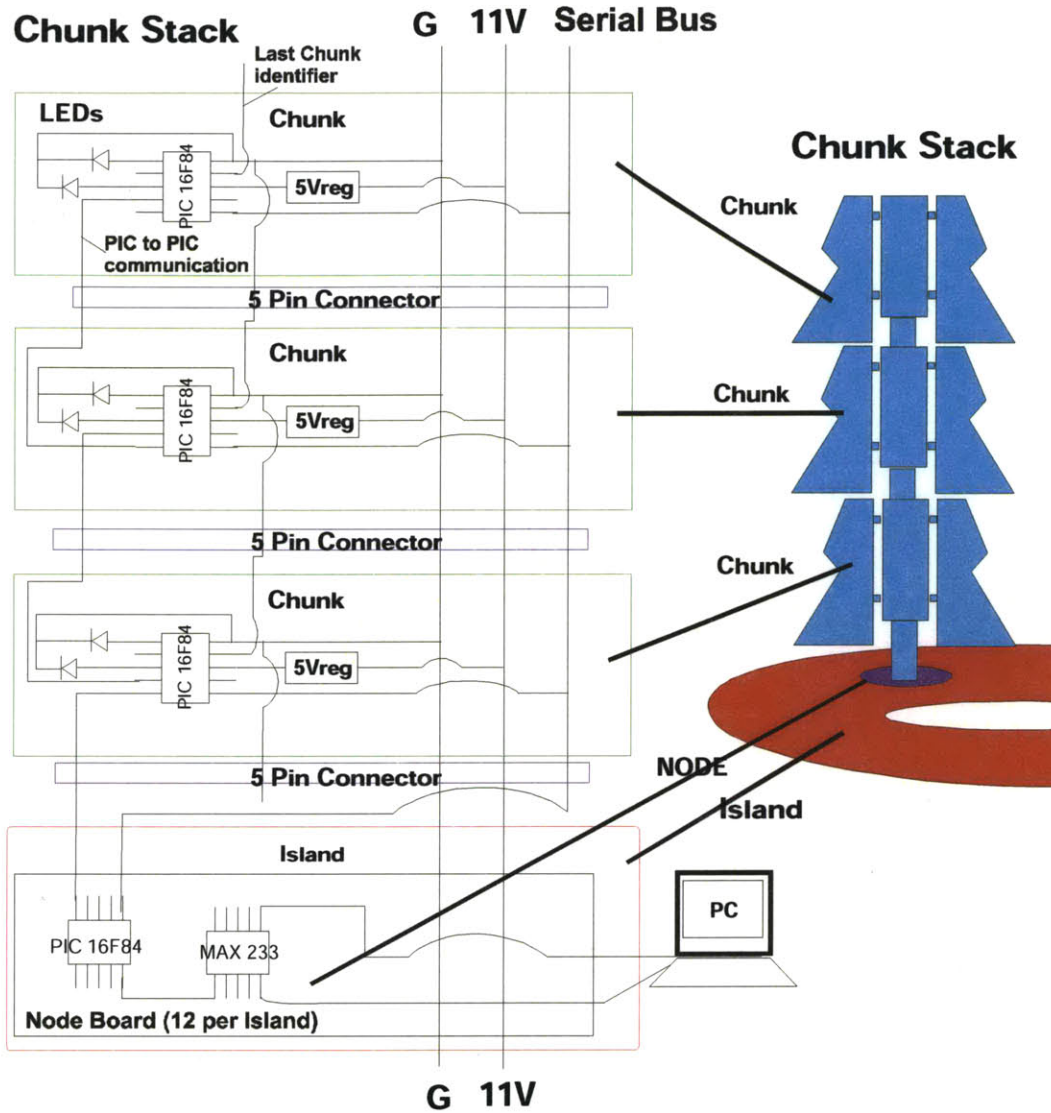


Figure A.10 Diagram of communication scheme and circuit design for a Chunk stack.

Bungee Cord Sensors

Each Island will have 8 bungee cords sensors woven from non-conductive and conductive thread. When the bungee cords are stretched, the resistance across them decreases in a predictable manner, allowing a microprocessor to measure this change with voltage divider. Because the conductive threads' resistance varies under tension in a non-repeatable manner, it is the woven structure of non-conductive and conductive thread together that creates a repeatable variable resistance in the sensor. As the sensor is tensioned, the conductive threads get closer together, increasing the sensors overall conductivity. For the sensor to work properly, it must be pre-tensioned, eliminating the change in resistance that occurs at the thread level, and letting the change in resistance that occurs at the woven level dominate the measurement.

Bungee Cord Sensors

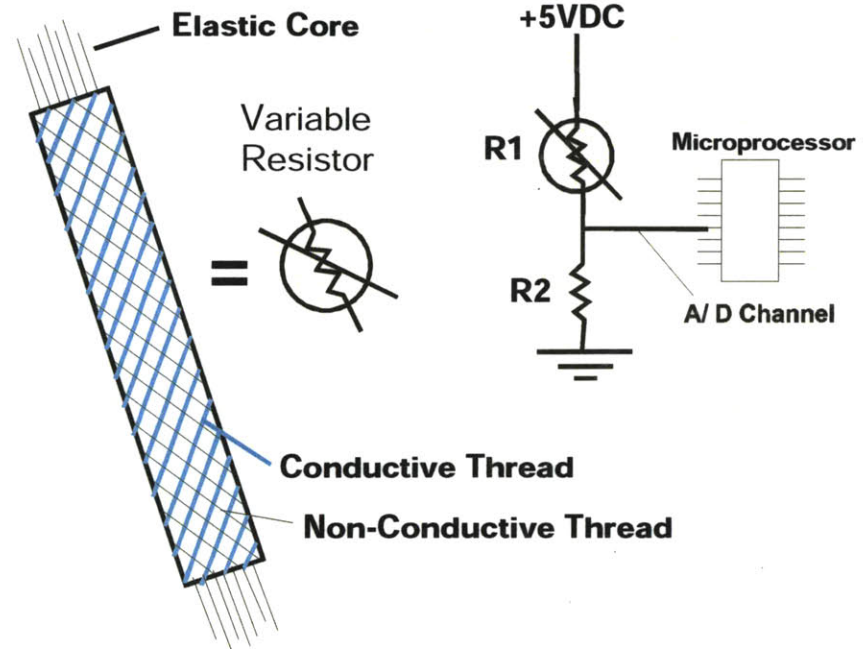


Figure A.11 Proposed bungee cord sensors, (not completed).

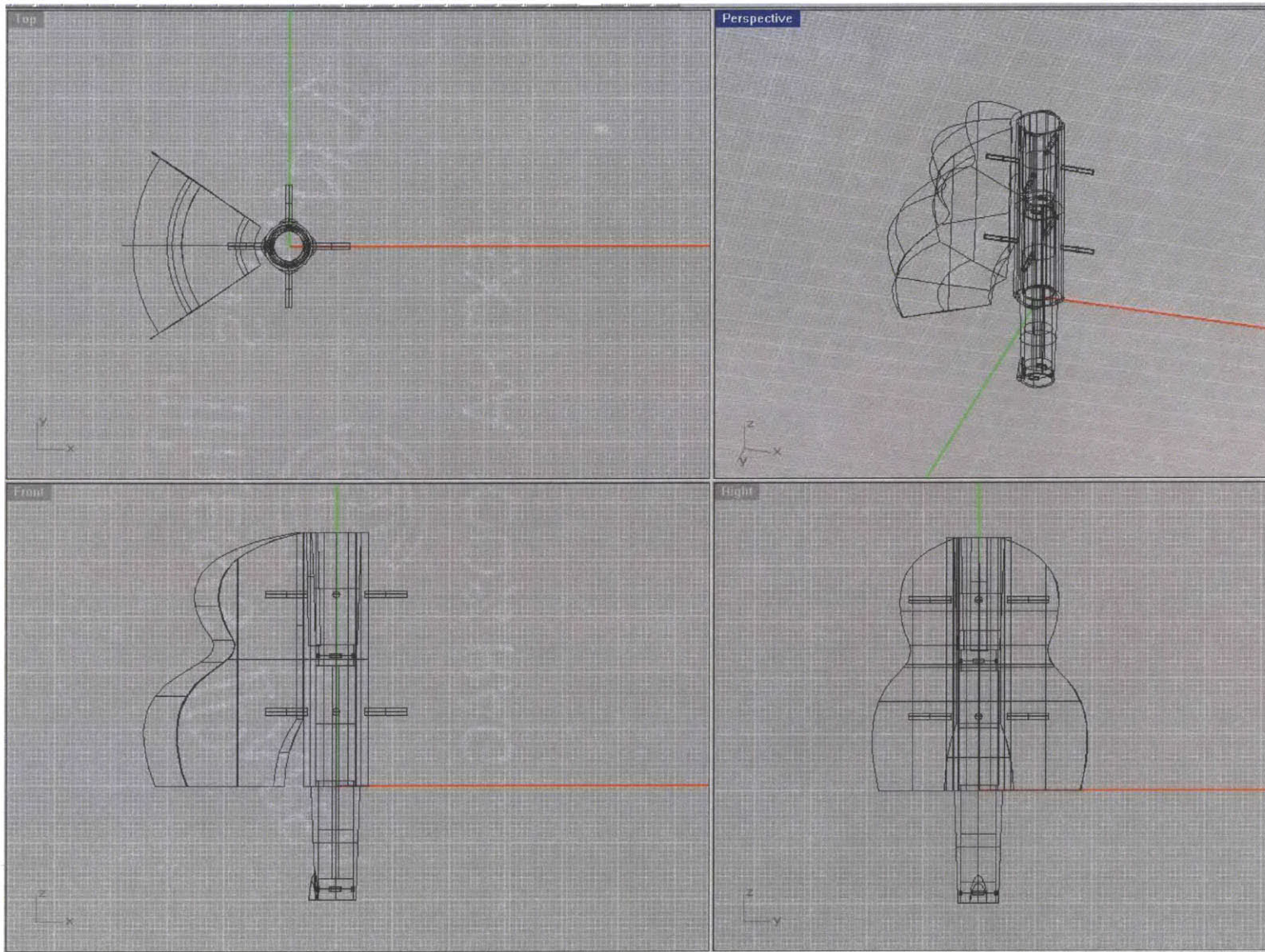


Figure A.11 CAD file of final Chunk design, with foam wing and connector core.

Bibliography

- Abelson H., Allen D., Coore D.I, Hanson C., Homsy G., Knight, T. F., Nagpal, R., Rauch E., Sussman J., Weiss R., *Amorphous Computing*, Communications of the ACM, 43, 5, (2000)
- Abrams, R., Adventures in Tangible Computing, the Work of Interaction Designer, Durrell Bishop, in Context, *Masters Thesis for the Royal College of Art*, (1999)
- American Heritage Dictionary On-line, World Wide Web, (2000)
- Bahn, Curtis, Homepage, <http://www.music.princeton.edu/~crb/Activities/bubba%20ball.html>, World Wide Web, (2001)
- Ball, Phillip, Made to Measure: New Materials for the 21st Century, Princeton, University of Princeton Press, (1997)
- Barlow, Margaret, Women Artists, Levin, Hugh Lauter Associates, (1997)
- Breton, Andre, *What is Surrealism*, Selected Writings, NY, Monad, (1978)
- Bishop, D., *Marble Answering Machine*, Director Animation, (1992)
- Borer, Alain, The Essential Joseph Beuys, Cambridge, MA, MIT Press, (1997)
- Brave, S. and Dahley, A., *inTouch: A Medium for Haptic Interpersonal Communication* (short paper), Extended Abstracts of Conference on Human Factors in Computing Systems, (CHI 1997), Atlanta, ACM Press, (1997)
- Carpenter, Rhys, Greek Sculpture: A Critical Review, Chicago, University of Chicago Press, (1960)
- Gan, Seum Lim, Squeezables, Tactile and Expressive Interfaces for Children of All Ages, Thesis for the Degree of Masters of Science of Media Arts and Sciences at the Massachusetts Institute of Technology, Cambridge, MA, (September, 1998)
- Goldberg, Ken, (ed.), Robot in the Garden, Cambridge, MA, MIT Press, (2000)
- Goldberg, Ken, homepage, <http://www.ieor.berkeley.edu/~goldberg/>, World Wide Web, (2001)
- Gorbet, M., Orth, M. and Ishii, H., *Triangles: Tangible Interface for Manipulation and Exploration of Digital Information Topography*, in Proceedings of Conference on Human Factors in Computing Systems, (CHI 1998), Los Angeles, ACM Press, (1998)
- Goswami, Martindale, and Scardino, Textile Yarns, Technology, Structure and Application, New York, Wiley-Interscience Publications, (1977)
- Heaton, Kelly, Physical Pixels, Thesis for the Degree of Masters of Science of Media Arts and Sciences at the Massachusetts Institute of Technology, Cambridge, MA, (2000)
- Hirasuna, Delphine, *Sorry No Beige, Apple Interview*, Apple Website, World Wide Web, (2001)

- Ishii, H. and Ullmer, B., *Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms*, Proceedings of Conference on Human Factors in Computing Systems, (CHI 1997), Atlanta, ACM Press, (1997)
- Johannsson, Hans, Violin Making, <http://www.centrum.is/hansi/>, Iceland, World Wide Web, (2001)
- Kaswell, E., Textile Fibers, Yarns and Fabrics, New York, Reinhold Publishing, (1953)
- Krauss, Rosalind E., Passages in Modern Sculpture, Cambridge, MA, MIT Press, (1977)
- Kuronen, Darcy, Dangerous Curves, The Art of the Guitar, Boston, MFA Publications, (2000)
- Laurel, Brenda, Computers as Theater, Reading Massachusetts, Addison-Wesley Publishing Company, (1991)
- Loos, Adolf, *Ornament und Verbrechen in Trotzdem 1900-1930*, Innsbruck, Verlag, (1931)
- Machover, T., Opera of the Future Website, <http://www.media.mit.edu/hyperins/projects.html#TOYSYM>, World Wide Web, (2001)
- Maeda, J. and McGee, K., *Dynamic Form*, International Media Press, (1994)
- Majozo, E., *To Search for the Good and Make it Matter*, from, Lacy, S. (ed.), Mapping the Terrain, New Genre Public Art, Seattle, Bay Press, (1999)
- Marrin, Teresa, *Possibilities for the Digital Baton as a General-Purpose Gestural Interface*, (short paper), Extended Abstracts of the Conference on Human Factors in Computing Systems, (CHI 97), Atlanta, ACM Press, (1997)
- Marrin, Teresa, Paradiso, J., *The Digital Baton: a Versatile Performance Instrument*, Proceedings of the International Computer Music Conference, Thessaloniki Greece, (1997)
- Teresa Marrin, Joseph Paradiso, Tod Machover, Christopher Verplaetse, and Margaret Orth, Apparatus for Controlling Continuous Behavior Through Hand and Arm Gestures, United States Patent # US5875257, (1999)
- MIT Media Lab Website, <http://www.media.mit.edu>, World Wide Web, (2001)
- Newman, Lenore and Spak, Jan L., *Is Ornament a Crime?*, Eidleberg, Martin (ed.), Designed for Delight, New York, NY, Flammarion and the Montreal Museum of Decorative Arts, (1977)
- Newman, Lenore and Spak, Jan L., *Inversion and Transformation*, Eidleberg, Martin (ed.), Designed for Delight, New York, NY, Flammarion and the Montreal Museum of Decorative Arts, (1977)
- Oliver, W., Yu, J., Metois, E., *The Singing Tree, Design of an Interactive Musical Interface*, The Proceedings of Design of Interactive Systems, (DIS 1997), Amsterdam, ACM Press, (1997)
- Orth, Margaret, Gorbet, Matt, Digital Communication, Programmable Functioning and Data Transfer Using Modular, Hinged Processor Elements, US Patent # US5941714, (1999)

- Orth, M., *Interface to Architecture: Integrating Technology into the Environment of the Brain Opera*, The Proceedings of Design of Interactive Systems, (DIS 1997), Amsterdam, ACM Press, (1997)
- Orth, M., Post, R., and Cooper, E. B., *Fabric Computing Interfaces*, (short paper), Proceedings of Conference on Human Factors in Computing Systems, (CHI '98), Los Angeles, ACM Press, (1998)
- Oxford English Dictionary On-line, World Wide Web, (2001)
- Paradiso, J., *The Brain Opera Technology: New Instruments and Gestural Sensors for Musical Interaction and Performance*, Journal of New Music, Research, Vol. 28, No. 2, (1999)
- Paradiso, J., *Electronic Music Interfaces: New Ways to Play*, IEEE Spectrum Magazine, Vol. 34, No. 12, pp. 18-30 (1997)
- Post, E.R., Orth, M., *Smart Fabric, or Washable Computing*, The Digest First IEEE International Symposium on Wearable Computers, Cambridge, MA, (1998)
- Post, E.R., Orth, M., Russo, P.R., Gershenfeld, N., *E-broidery: Design and Fabrication of Textile-based Computing*, IBM Systems Journal, Vol. 39, Nos 3&4, Armonk, NY, IBM Corporation, (2000)
- Rehmi Post, Maggie Orth, Emily Copper, Joshua Smith, Electrically active textiles and articles made therefrom, US Patent# 6,210,771, (2001)
- Reyner Banham, Theory and Design in the First Machine Age, Cambridge, MA, MIT Press, (1996)
- Rolf E. Hummel, Understanding Materials Science: History, Properties, Applications, New York, Springer, (1998)
- Weinberg, G., Lackner, T., and Jay, J., *The Musical Fireflies - Learning About Mathematical Patterns in Music Through Expression and Play*, Proceedings of XII Colloquium on Musical Informatics, A'quila, Italy, (2000)
- Weinberg, G., Orth M., and Russo P., *The Embroidered Musical Ball: A Squeezable Instrument for Expressive Performance*, (short paper), Proceedings of Conference on Human Factors in Computing Systems, (CHI 2000), The Hague: ACM Press, (2000)
- Weinberg, G., Expressive Digital Musical Instruments For Children, Thesis for the Degree of Masters of Science of Media Arts and Sciences at the Massachusetts Institute of Technology, Cambridge, MA, (1999)
- Swanson, D.K. and Webster, J.G., *A Model for Skin-Electrode Impedance*, in Miller, H.A., and Harrison, D.C. (eds.), Biomedical Electrode Technology: Theory and Practice, New York, Academic Press, (1974)
- Weiser, M., *The Computer for the 21st Century*, Scientific American, (September, 1991)
- Williams, Raymond, Keywords, A Vocabulary of Culture and Society, Rev. Ed., New York: Oxford UP, (1983)
- REM Homepage, <http://www.remdesign.com/port4.html>, World Wide Web, (2001)

- Small, D., White, T., *An Interactive Poetic Garden*, (short paper), Proceedings of Conference on Human Factors in Computing Systems, (CHI 1998), Los Angeles, ACM Press, (1998)
- Smith, J., Electric Field Imaging, Thesis for the Degree of Doctor of Philosophy, at the Massachusetts Institute of Technology, Cambridge, MA, (February, 1999)
- Smith, J.R., *Distributing Identity*, IEEE Robotics and Automation Magazine, Vol.6, No.1, (March, 1999)
- Stelarc, homepage, <http://www.stelarc.va.com.au/third/third.html>, World Wide Web, (2001)
- Stella, F., Working Space, Cambridge, MA, Harvard University Press, (1986)
- Takiff, Jonathan, *Laurie Anderson Interview*, Philadelphia Newspapers Inc., World Wide Web, (1998)
- Tangible Media Homepage, <http://tangible.media.mit.edu/projects/strata/strata.html>, World Wide Web, (2001)
- Toy Symphony Website, <http://www.media.mit.edu/hyperins/toysym/phaseiframes.html>, World Wide Web, (2001)
- Truman, D., Reinventing the Violin, Thesis for the Degree of Doctor of Philosophy at Princeton University, Princeton, New Jersey, (2000)
- Ullmer, B., Kim, E., Kilian, A., Gray, S. and Ishii, H., *Strata/ICC: Physical Models as Computational Interfaces* (short paper), Extended Abstracts of Conference on Human Factors in Computing Systems, (CHI 2001), Seattle, Washington, ACM Press, (2001)
- US Customs Service, *What Every Member of the Trade Community Should Know About: Fibers & Yarns, Construction and Classification under the Harmonize System An Advanced Level Informed Compliance, Publication of the U.S. Customs Service*, US Customs Website, <http://www.customs.gov/imp-exp1/comply/fibryarn.htm#top>, World Wide Web, (1996)