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 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 where 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.