

# Materializing Interaction

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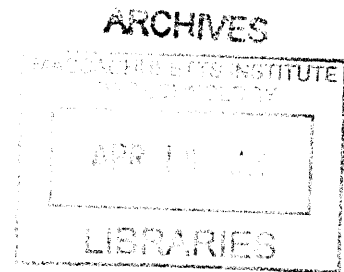
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Submitted to the Program in Media Arts and Sciences,  
School of Architecture and Planning,  
in partial fulfillment of the requirements for the degree of  
Doctor of Philosophy in Media Arts and Sciences  
at the Massachusetts Institute of Technology

September 2012

[FEBRUARY 2013]

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## **Abstract**

At the boundary between people, objects and spaces, we encounter a broad range of surfaces. Their properties perform functional roles such as permeability, comfort or illumination, while conveying information such as an object's affordances, composition, or history of use. However, today surfaces are static and can neither adapt to our changing needs, nor communicate dynamic information and sense user input. As technology advances and we progress towards a world imbued with programmable materials, how will designers create physical surfaces that are adaptive and can take full advantage of our sensory apparatus?

This dissertation looks at this question through the lens of a three-tier methodology consisting of the development of programmable composites; their application in design and architecture; and contextualization through a broader material and surface taxonomy. The focus is placed primarily on how materials and their aggregate surface properties can be used to engage our senses.

A series of design probes and four final implementations are presented, each addressing specific programmable material and surface properties. Surfex, Sprout I/O, and Shutters are continuous surfaces which can change shape to modify their topology, texture and permeability, and Six-Forty by Four-Eighty is a light-emitting display surface composed of autonomous and reconfigurable physical pixels. The technical and conceptual objectives of these designs are evaluated through exhibitions in a variety of public spaces, such as museums, galleries, fairs, as well as art and design festivals.

This dissertation seeks to provide contributions on multiple levels, including: the development of techniques for the creation and control of programmable surfaces; the definition of a vocabulary and taxonomy to describe and compare previous work in this area; and finally, uncovering design principles for the underlying development of future programmable surface aesthetics.

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# Materializing Interaction

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# Acknowledgments

The process of envisioning and creating this work involved a broad and fluid team of people whose friendship, understanding, help, and critique were invaluable to me. For all the direct and sometimes subtle ways in which they have contributed to this work, I would like to acknowledge them.

Thanks to Pattie Maes for providing the support and environment where I could pursue my unorthodox research ideas and, most importantly, for continuously encouraging me to see things in a new way.

I also would like to thank my thesis readers, Neri Oxman and Jeffrey Huang, for their invaluable guidance and support.

The ideas and work presented in this thesis are the results of six years of collaboration and discussions with members of the Fluid Interfaces Group at the MIT Media Lab: Pol Pla i Conesa, Doug Fritz, Valentin Heun, Seth Hunter, Anette Von Kapri, Natan Linder, David Merrill, Pranav Mistry, Susanne Seitinger, Sajid Sadi, Roy Shilkrot, Juergen Steimle, Aaron Zinman and Amit Zoran.

Thanks to Joanna Berzowska and the XS Labs team for blazing a path I could follow and sowing many of the ideas that have been cultivated in this thesis.

Many friends have helped with the conceptualization, design, and fabrication of the work described here: Jamie Zigelbaum, Najiyah Edun, Mark Feldmeier, Elena Jessop, Joshua Kopin, Kent Larson, Katie Puckett, Analisa Russo, Mette Ramsgard Thomsen, Hiroshi Ishii, Varun Perumal, Madeleine Claire Elish, Ryan Wistort, Jeff Lieberman, Mark Feldmeier, Vik Muniz, Rehmi E. Post, Tom Dixon, Jay Silver, Jean-Baptiste Labrune, Sanjay Sarma, Nicholas Zigelbaum, Staphany Park, Silas Maniatis, Grace Escano, Ambra Medda, Wava Carpenter, and the Design Miami team, among dozens of other students and professors who have passed through MIT and the Media Lab in the last six years.

Thanks to Linda Peterson and Amna Carreiro for making sure that all papers went to the right place with the right signatures at the right time, while keeping me sheltered from MIT's bureaucratic machine.

Thanks to Kyla Hygysician, for being the most incredibly patient, humorous and loving girlfriend one could ever ask for.

And finally, a very special thanks to the *Coelho* clan: Joaquim, Regina, Carlos and Thais. Your continuous support, irreverent humor and unquestionable love are the solid pillars beneath everything I have accomplished.

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# 1 Introduction

## 1.1 Problem

In recent years, we have come to expect an infinite amount of information to be accessible from anywhere, at any time of the day or night, while being catered to our personal needs and desires. This insatiable hunger for bits has been directing us towards a future where every physical surface in our environments is bound to be one day overlaid with displays or input devices. Unfortunately, these technologies today only engage a small portion of our senses, deeply neglecting the full range of material qualities we experience in the physical world.

Surfaces have historically played a fundamental and multifaceted role in how we live and communicate: the stone walls that provided shelter to the first humans also served as a canvas for visual representation and storytelling; clay tablets gave language a malleable and permanent medium in which it could be stored and transmitted; and textiles not only protect people from the elements, but also concurrently communicate individual aesthetic choices and social roles. How can we enable the designers of the future to preserve the rich palette of materials we have used for thousands of years, while also enabling programmability?

This thesis looks at surfaces and how their properties can be computationally controlled to serve dynamic functions and to provide information. The focus is placed on the relationship between materials and surfaces, in particular how programmable material properties can be aggregated to form the programmable surfaces through which one day we will interface with the physical world.

Apart from providing technical innovations and solutions for the creation of new materials and surfaces, the objective is to identify possible application areas and foster the development of a taxonomy and methodology that can help inform and guide the work of other designers towards future developments in this area.

## 1.2 Design Methodology

In order to fully comprehend how materials and surfaces can be programmed to adapt and respond, this thesis is interwoven by a three-tier methodology

consisting of technology development, its application in real-world use scenarios, and the positioning of this work under a broader theoretical framework.

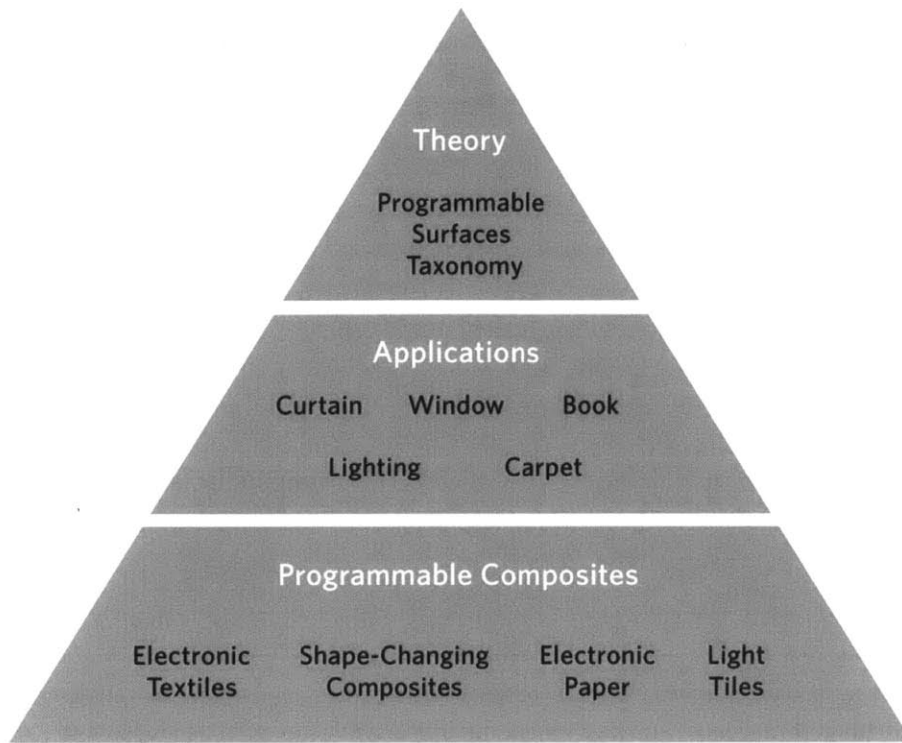


Figure 1. Three-tier methodology.

### 1.2.1 Technology

The technological foundation for this thesis is a design approach that combines the material properties and fabrication techniques of traditional materials, such as textiles, paper, and wood, with those developed for electronics manufacturing and control.

This hybrid technology association, which I refer to as Programmable Composites, is inspired by the material techniques used in architecture and engineering disciplines for the formulation of high performance composites, such as reinforced concrete, by carefully orchestrating the individual properties and organization of previously distinct materials, such as cement and iron. The focus however is on creating material units that can leverage input and output capabilities and be computationally controlled to sense users or their environments and respond with suitable property changes. Additionally, large scale behaviors and functionalities are derived from the aggregation of these material units by borrowing strategies for power distribution and control techniques used in electronics engineering and applying them through traditional fabrication techniques such as weaving, knitting, papermaking and wood work.



## 1.2.2 Applications

No technological exploration is complete without real prototypes that can give form to abstract ideas, push the limits of what is technically feasible today and capture people's imagination. With that in mind, I have developed a series of prototypes, installations and objects such as garments, curtains, and lighting, which reveal unique applications for the deployment of programmable materials and surfaces. The lessons taken from these works not only shed light on the technical limitations of computationally manipulating material properties, but also provide attainable design constraints, and uncover opportunities for further development.

## 1.2.3 Theory

The culmination of this work is a theoretical contribution which provides a taxonomy for mapping the breadth of properties desired in programmable materials, as well the impact of material organization strategies on the functional and aesthetic qualities of surfaces. This taxonomy is evaluated and supported by a classification of the properties of previous programmable surfaces and my own work. Additionally, this theoretical contribution requires a redefinition and re-contextualization of terms such as material, surface and programming, with the intent of providing a conceptual bridge connecting the design disciplines working with physical materials and those working with bits.

## 1.3 Design Probes

This thesis' theoretical foundation is exemplified by a series of design probes, prototypes and material explorations in textiles, paper, and food. These examples not only provide concrete examples for how programmable composites can be created, but they also highlight how the material and surface taxonomy can be used to describe the properties and qualities of each design exploration. In particular, I will focus on four design probes: PurePlay, Kukkia and Vilkas, Pulp-Based Computing and Cornucopia.

**PurePlay** is a garment whose neckline is outfitted with an array of thermoelectric elements and overlaid with thermochromic ink. Providing an example of both thermal and optical material transformations, the thermoelectric element allows temperature gradients to be perceived by the wearer while textile color changes are perceived by an outside viewer (but not the wearer).

**Kukkia and Vilkas** are two kinetic, sculptural garments which can change shape through small spatial material transformations distributed in both a radial and lattice patterns.

**Pulp-Based Computing** are a series of material explorations which strive to develop programmable materials which can retain the visual and textural qualities of paper.

Finally, **Cornucopia** is a concept design and prototype for a 3D food printer, which looks at how materials can engage our senses through chemical exchanges. Rather than exploring the programmable properties of materials, it focus on the development of fabrication tools for the control and creation of static, edible materials.

## 1.4 Programmable Surfaces

This thesis' narrative continues through a discussion of four programmable surfaces, namely Surfex, Sprout I/O, Shutters, and Six-Forty by Four-Eighty. Each embodies distinct programmable material properties and control techniques, while highlighting new application scenarios.

### 1.4.1 Surfex

Surfex is a prototype of a shape-changing surface for the design and visualization of digital forms. It combines active and passive shape memory materials, specifically shape-memory alloys and polyurethane foam, to create a material that can be electronically controlled, to deform and gain new shapes, without the need for external actuators. Surfex's hardware architecture is inspired by the way draughtsman used the intrinsic properties of wood and rubber rulers to draw symmetric curvatures, and provides the design for a fundamental shape-changing material pixel that could allow surfaces to transform their overall topology into any desired shape, within homeomorphic material constraints.

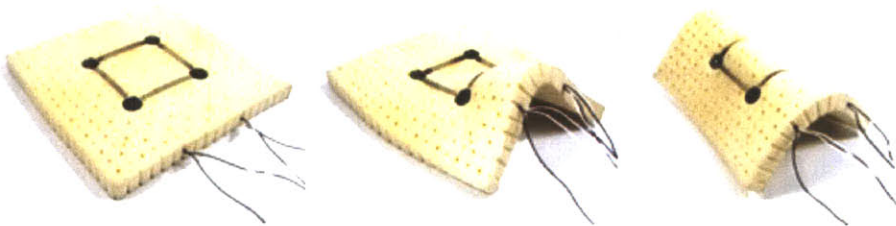


Figure 2. Surfex's surface deformation in three steps.

### 1.4.2 Sprout I/O

Sprout I/O is a prototype of a carpet for haptic and visual communication. It is composed of an array of fibers built from a multi-laminate textile and SMA composite which can sense touch, change stiffness to provide different degrees of comfort, and move to display images and animations. Through small shape

deformations at the surface boundary, Sprout I/O provides a technique for the creation of a programmable surface texture.



Figure 3. Sprout I/O animation.

### 1.4.3 Shutters

Shutters is a curtain composed of actuated louvers (or shutters) that can be individually addressed for control of ventilation, daylight incidence and information display. By introducing shape-changing apertures onto a continuous surface, Shutters allows for a programmable surface permeability and finer control of environmental exchanges, such as light and ventilation, creating living environments that can better respond to its inhabitants' activities.

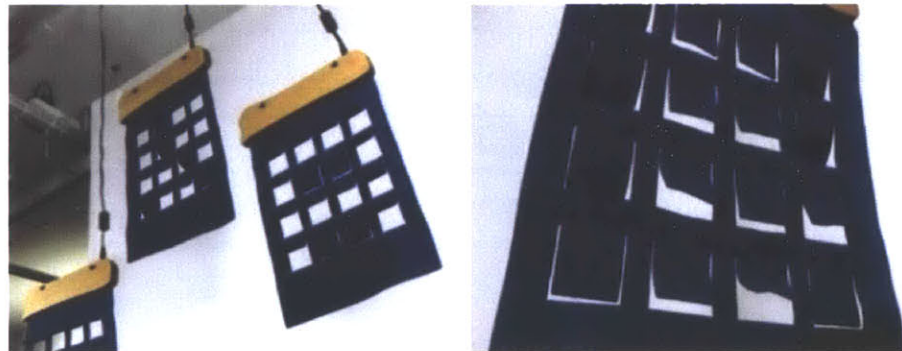


Figure 4. Shutters displaying the letter 'A' (left) and detail of louver motion (right).

### 1.5 Six-Forty by Four-Eighty

Six-Forty by Four-Eighty is an interactive and distributed lighting system. Each material pixel in Six-Forty by Four-Eighty is a self-contained computer which can modulate its color and luminosity, as well as sense touch and transmit data through the human body. Six-Forty by Four-Eighty provides the material infrastructure for an amorphous light surface which can be sculpted into different physical configurations to illuminate spaces and convey information.

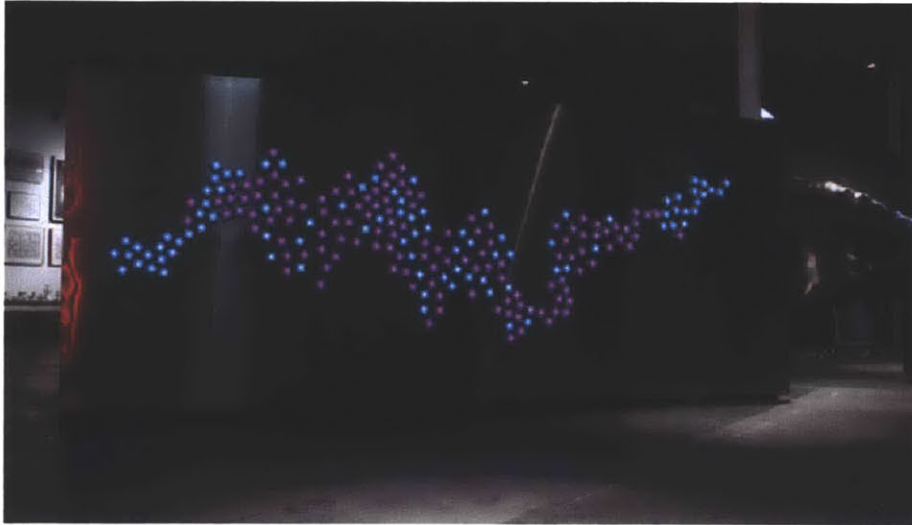


Figure 5. Six-Forty by Four-Eighty aggregate.

## 1.6 Contributions

As technology advances and we progress towards a world imbued with programmable materials, how will designers create physical surfaces that take full advantage of our sensory apparatus? This work's primary goal is to enrich our interaction with our physical objects and spaces through the development of programmable surfaces that embody a wide range of material qualities and convey information while supporting dynamic and adaptable functionalities. With that in mind, it hopes to provide the following contributions:

- The development of techniques for the creation and control of programmable composites and surfaces.
- The application of programmable composites to a variety of art and design contexts.
- The definition of a vocabulary and taxonomy to describe and compare previous work in this area, revealing new design opportunities.
- The uncovering of design principles for the development of a future programmable material and surface aesthetics

## 1.7 Thesis Overview

Few people are able to find the time to read a document of this length. In order to facilitate matters, this subsection provides a reading guide and chapter breakdown

that can be used to skip directly to the most relevant parts. Hopefully, they will be captivating enough to persuade you to continue reading the rest.

For the reader pressed with time, following the introductory chapters, chapters 3 and 4 address the connection between materials and surfaces, and how they can be programmed with behaviors. For those interested in the range of programmable material properties available to designers today and how they can be put together to create surfaces, chapter 4 also provides a material and surface taxonomy, and more specific implementation details are discussed in chapters 5 - 7. These final chapters also cover in more detail the motivations, applications and design process behind programmable surfaces which can change shape, and regulate light emission and opacity. Related work is spread out throughout the different chapters and below you will find a more detailed chapter-by-chapter breakdown.

**Chapter 1: Introduction** discusses the methodology used in this thesis and provides a short summary for the rest of this document.

**Chapter 2: Background and Motivation** exposes the driving problem behind this work and its historical development.

**Chapter 3: Material Transformations** provides new definitions to seed the proceeding discussion and reconsiders the meaning of programmability within a material context.

**Chapter 4: Taxonomy** provides a survey of the fundamental properties of programmable material units and how they can be distributed to form surfaces. Prior work is analyzed under this classification scheme.

**Chapter 5: Design Probes** introduces my approach for imbuing materials with behaviors and exemplifies it through four prototypes of programmable composites.

**Chapter 6: Shape-Changing Surfaces** describes the development of three programmable surfaces – Surfex, Sprout I/O and Shutters – based on material units which undergo a spatial transformation. Built from a custom shape-memory alloy composite, they can modify their form to dynamically regulate topology, texture and permeability.

**Chapter 7: Amorphous Display** takes a different approach and looks at autonomous, light-emitting material units which can operate both individually and in unison, as a continuous light surface that is stochastically distributed.

**Chapter 8: Contributions and Conclusion** recapitulates the primary contributions of this work and looks towards the future by envisioning probable directions for the development of programmable surfaces and some of the challenges ahead.

## 2 Background and Motivation

At the boundary between people, objects and spaces, we encounter a broad range of surfaces. Their properties perform functional roles such as to provide permeability, light control or friction, while conveying information such as an object's composition, origin or history of use.

In the last 300 years, this relationship has undergone a rapid revolution and surfaces have transitioned from being hand-crafted, static substrates to being mass produced in large scales to envelope our objects and spaces with dynamic changing skins. With the introduction of Basile Bouchon's semi-automated loom and eventually Jacquard's punch-cards at the dawn of the Industrial Revolution, our ability to address and direct a surface's material organization progressed from a labour-intensive process to one of infinite machine reproducibility.



Figure 1. Jacquard Loom, near to Matlock Bath, Derbyshire, Great Britain. Image by Ashley Dace.

Textile and machine developments were paralleled by improvements in chemistry which soon after led to the development of the daguerrotype and cyanotype, allowing static images previously crafted by hand to be mechanically registered and reproduced, providing a machine-driven alternative to painting.

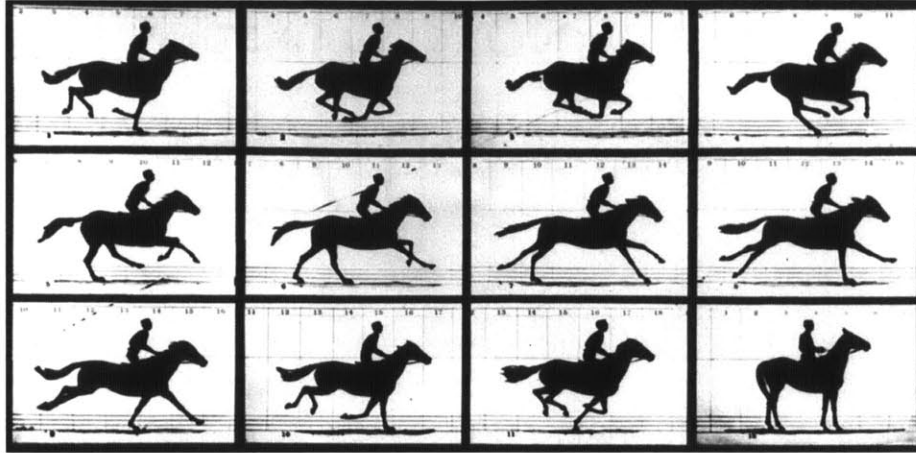


Figure 2. Galloping Horse, diagram based on motion photographs. Image by Eadweard Muybridge.

Photography later provided the technical basis for the development of film which brought about a new surface medium for dynamic visual representation and story telling. With the introduction and pervasion of electricity and the telegraph came the ability to scan and transmit images over long distances leading to the eventual development of the cathode ray tube and the television, finally freeing visual reproduction from its material substrate (Gleick, 2011).

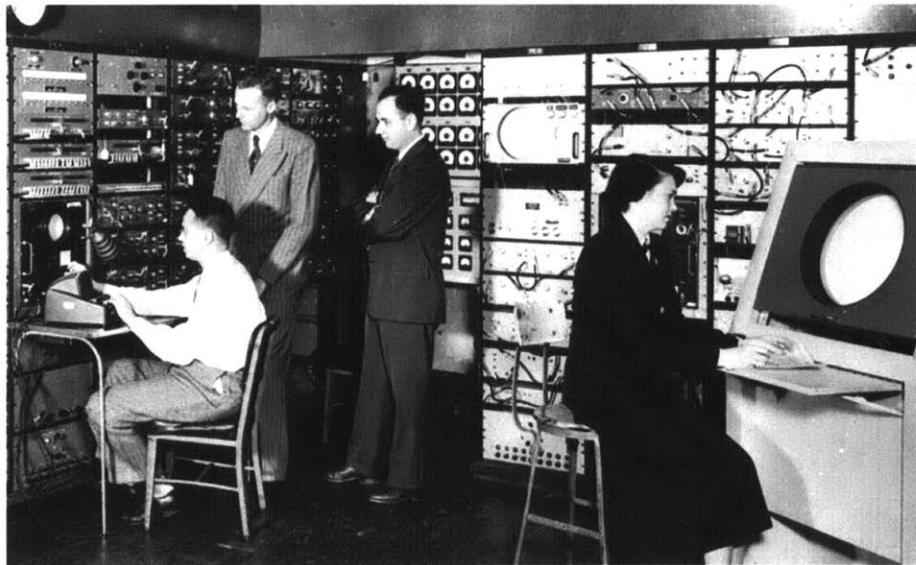


Figure 3. Graphic displays in use at Whirlwind I test control at MIT. Image from MIT archives.

In 1951, Jay Forrester was put in charge of developing a new general purpose and electronic digital computer for flight simulation, giving origin to MIT's Whirlwind I computer and the first use of a video display for output. For the first time, pixels became programmable. Since then, light emissive, programmable displays have become the primary surface through which we manipulate and consume



information and can be found everywhere from our pockets to our building facades, and in every shape and form imaginable.

Today's designers have a much broader palette of materials and surface treatments at their disposal. This rich palette allows us to create surfaces to perform a wide range of functions (e.g. permeability, comfort, heat insulation) and convey information (e.g. white lines on a road tell you where you should, or should not, drive). However, today these surfaces are for the most part static and can neither sense and adapt to our changing needs, nor communicate information that is dynamic. As our ability to fabricate and control displays improved, we confined them to a small set of properties and aesthetic qualities bound by the physical limitations of our visual system. Materials such as textiles, wood, leather or paint are being superseded by rectangular light grids encapsulated by plastic and glass shells, which ultimately neglect the full bandwidth and capabilities of our complete sensory apparatus.

However, recent developments in materials science, robotics and fabrication promise to change this. Electrophoretic inks and interferometric modulators are supporting the development of new display form-factors, which are non-emissive or pliable to support new use scenarios and interaction modalities (Schwesig et al., 2004); research in programmable matter is providing the underlying mechanisms and programming infrastructure for materials that can reconfigure themselves to any desired shape (Gilpin & Rus, 2012); and computer controlled machines that manipulate matter at a micro-scale are allowing us to create new material behaviors that were previously unimaginable (Ahn et al., 2012).

This thesis is motivated by the assumption that our future objects and spaces are destined to be built from a rich palette of materials and surfaces that can be programmed to adapt and respond to our changing needs and desires, while embodying the same information capabilities we encounter in displays today (Addington & Schodek, 2004) (Ritter, 2006). As computers shrink to nano scales, and programmable materials becomes a reality, our capacity to manipulate matter is drifting away from the limitations of fabrication processes and becoming a lot more like manipulating pixels on a computer screen. This will not only allow us to program our physical world to render the rich aesthetic qualities and behaviors of traditional materials, but it will also open new opportunities for inventing new kinesthetic materials that fully engage our senses. Quoting Ivan Sutherland (1965),

“The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal. With appropriate

programming such a display could literally be the Wonderland into which Alice walked.”

# 3 Material Transformations

## 3.1 Introduction

The dawn of computing drove a wedge between materials and information, endowing bits with tremendous versatility and rendering them immune from the degradation, physical limitations and expense of atoms. This separation poses an interesting challenge to the creative disciplines dealing with the interface between our senses and the material environments we live in: how can seemingly static materials and surfaces be processed and organized to engender the versatility of bits?

This chapter tries to answer this question by looking at how physical things can be programmed with dynamic behaviors and by developing a definition for materials and surfaces which is more akin to the needs of artists and designers working with both computers and physical materials in their practice.

## 3.2 What Are Materials?

Before diving into a more in depth discussion of the programmable nature of materials, it is important to bring into question what materials are. Different disciplines define and categorize materials and their properties based on specific usage scenarios and abstractions that support the objectives, execution and advancement of their practice.

Materials science studies the relationship between the structure of materials at atomic or molecular scales and their emerging macroscopic properties. Through a process of formulation and characterization of material properties, materials scientists relate the desired properties and relative performance of a material in various applications in science and engineering to their atomic structure and phases.

The various engineering disciplines, such as a mechanical, civil or structural engineering, in large part seek to optimize the use of materials in the design, manufacture, installation and operation of structures and machines. Their focus is placed on the characterization of operation conditions, determining the required

material properties and forecasting future behavior under safety and economic considerations.

The biological sciences study the physicochemical processes of living matter, which is particularly characterized by properties such as responsiveness, growth, metabolism, energy transformation and reproduction. Where it intersects with engineering, biologists work to manipulate matter to synthesize new animals or plants, process chemicals, produce energy, and help maintain or enhance human health and the environment.

Architects and industrial designers focus on the other hand on both the practical and expressive nature of design, by selecting, transforming and applying materials for their combined functional, aesthetic and communicative qualities. This process is highly dependent on materials' situatedness, requiring an understanding of how they are positioned within an environmental context and affect human behavior and experience.

With the pervasion of computation across previously disparate disciplines, digital fabrication has been driving a multidisciplinary effort towards the development of **digital materials**, characterized by the controlled composition of discretized functional material units at multiple length scales. For instance, researchers at Cornell University have developed a recyclable multi-material additive 3D printing technique based on the hexagonal close packing of spheres which allow for inherently digital characteristics such assembly reversibility and error-correction (Hiller & Lipson, 2005). At MIT, researchers have developed a system of electromechanical cubes at the centimeter scale capable of 2D shape formation through programmable subtraction from an initial crystalline lattice structure (Gilpin et al., 2010).



Figure 1. Multiple states of glass, from left to right: sand, silica, ITO impregnated glass, fiberglass, stained glass and an iPhone screen.

In spite of these multidisciplinary formalization efforts, conventional distinctions between materials, composites and objects are made based on choices about composition, origin, homogeneity, scale, application and the context in which a material is inserted. The images in figure 1 illustrate different configurations in which one would experience the multiple states and configuration of glass,

transitioning from its origin in sand towards complex and multifunctional glass composites.

This thesis departs from the assumption that regardless of its composition all of the glass states portrayed by these images could be considered to be a material based on their engagement with people and the environment where they are situated. Few people would say for instance that an iPhone, on its own, is a material, but rather a composite or assembly of distinct components, such as glass, integrated circuits, printed circuit boards, etc. However, a pile or a wall covered with phones would gain a new aggregate dimension which presents a very different environmental engagement. An iPhone within this context could be perceived as a single material substrate, but one which carries very unique properties.

This thesis' definition for materials takes a multidisciplinary approach and is inspired by the definition proposed by social anthropologist Tim Ingold, which cares about materials for their composition, how this composition affects performance and behavior, and finally how these performance and behaviors are situated within a material and human context. Quoting Ingold (2007),

Stoniness, then, is not in the stone's 'nature', in its materiality. Nor is it merely in the mind of the observer or practitioner. Rather, it emerges through the stone's involvement in its total surroundings - including you, the observer - and from the manifold ways in which it is engaged in the currents of the lifeworld. The properties of materials, in short, are not attributes but histories.

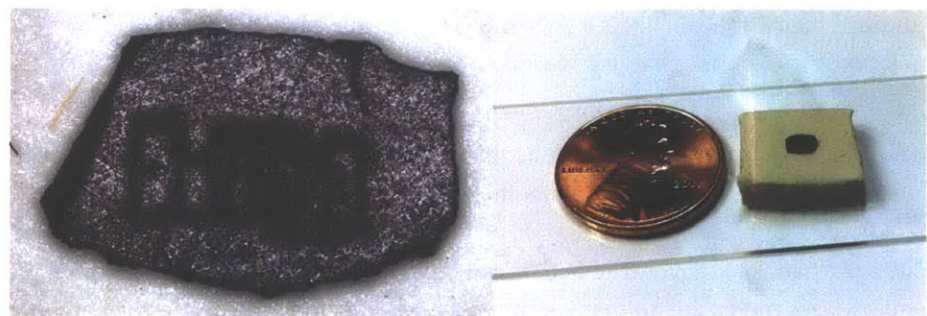


Figure 2. Drawing of a castle micro-machined onto a grain of sand. The material which is traditionally used to build a castle becomes the canvas for representing it. Author's collaboration with Vik Muniz and Rehmi E. Post.

This focus on perception and context is derived from an understanding that material complexity is a poor metric for a working definition, since it is not always transparent and our mental model of what materials are is highly influence by how they are experienced by our senses and used in the world. Regardless of where the material definition line is drawn, the overall goal of this thesis is to expand the

palette of programmable materials available to designers and provide a language for discussing their uses and capabilities. But how are materials distinct from surfaces?

### 3.3 What Are Surfaces?

Ever since Donald Norman introduced the term affordance into the HCI community - a term originally coined by the perception psychologist James J. Gibson in 1977 - it has been seen as a concept which can lead to improved usability and the inevitable enrichment of our interactive experiences. Norman defines affordances as action possibilities which are readily perceivable by an actor and, while many other interpretations have derived from his, they have in common the idea that affordances invite, guide and limit users to particular actions (Norman, 1990).

When we interact with the physical world, affordances are a product of properties, such as form, texture or color, which we extract and interpret from the surface properties and topologies of material aggregates. Most of the discourse on the nature of surfaces focuses on two aspects: surfaces as theoretical abstractions and surfaces as physical entities, grounded in our experience of the physical world. In general, a person's idea of a surface develops through a process of visual and tactile observation and interaction, making itself clear only in contrast with things which are not a surface. As Mark Taylor points out "surface of a lake generally means the uppermost layer of water; a shadow has a boundary and an edge, but no surface; and we withhold surface-talk from water that does not lie smooth, such as when gushing or spraying" (Taylor, 2003). Surfaces are also discussed relative to the operations performed on them - painting, carving, finishing, etc - as well as the materials manipulated by these operations. We can also identify surfaces through their haptic qualities - soft, smooth, cold, etc - or their spatial relationships - surfaces on the wall, floor or enveloping objects.

Gibson distinguishes three components of the environment, medium, substances and surfaces, which make the material and surface distinction more clear (Ingold, 2007). Medium is something like air, which allows us to breathe, but also provides little resistance to movement, and transmits radiant energy, mechanical vibrations and diffuses molecules so that we can see, hear and smell. In short, medium affords movement and perception. Substances, on the other hand, are the physical material things, such as rock, a wooden chair or pavement, which allow us to sit, stand up on firm ground or grab an object, but which do not allow us to see or move through them. At the interface between medium and substances, we encounter surfaces. They have properties such as a degree of resistance to deformation, a persistent layout, and texture. It is at this surface boundary where radiation is reflected or absorbed, where vibrations are transferred to a medium, where vaporization or diffusion occurs and where touch takes place when our

bodies come up against a substrate. As far as perception is concerned, surfaces are 'where most of the action is' (Gibson 1979) (Ingold, 2007).

Without diving into the philosophical problem of perception through a discussion of how we define and perceive surfaces, they are relevant here as the boundaries through which we interact with things, where things end and begin, separating them from space, other things and ourselves. Also, they are important here as material aggregates, since the static and dynamic properties of surfaces derive from the properties of the materials they are composed of and how these materials come together.

### 3.4 Definitions

In summary, this thesis puts forth a new definition for materials and surfaces which is more akin to the work of architects and designers struggling to integrate programmability in their work.

**Materials** are defined here as the physical matter from which things are made, as determined by the context in which they are part of and their relation to other materials.

On the other hand, a **surface** is the boundary through which we interact with materials, where materials end and begin, separating them from space, other things and ourselves.

Ultimately, surface boundaries define how we perceive and interact with their world. But in a world that is bound to be one day to be covered with programmable matter, how can we extend beyond simple material changes to build complex programmable surfaces that can serve dynamic functions and be used to communicate? Before we look at the dynamic properties of materials and surfaces in more detail in the following chapter, we will examine different forms of material transformation and how they shape our experiences of surfaces.

### 3.5 Material Transformations

Humans have imbued materials with complex behaviors and functionalities, since we first walked on this planet. These acts of transformation can be divided into five overarching categories, progressing from simpler to more complex forms of behavior: static, directional, bidirectional, programmable and reprogrammable.

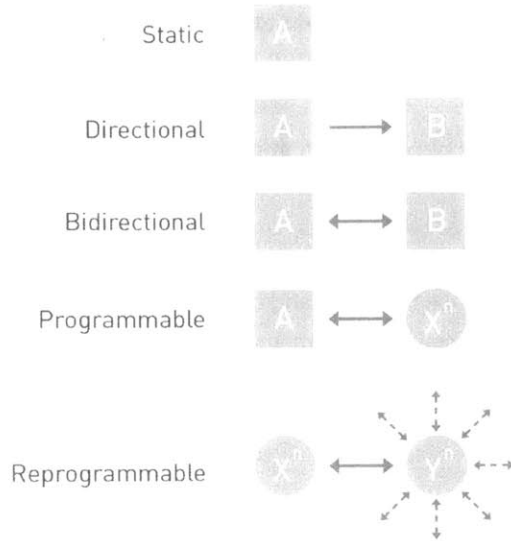


Figure 3. Material Transformations

Each one of these categories imply a certain degree of intentionality from an artist, designer or engineer regarding the function they desire a material to perform. It also takes into account that the environment and the people within it play a role in how materials perform their functions and behavior, and that these relationships develop with the passage of time.

Most importantly, this categorization is based on the premise that any attempt at transforming a material from a 'raw' substrate, such as carving a block of wood or glazing a piece of ceramic, is an attempt at imbuing it with function and behavior, and could be considered a form of 'programming', albeit a very limited one. This is analogous to software in so far as 'material programmers' use a set of tools and a language for crafting desired transformations. As we progress from static to reprogrammable forms of transformation, the role played by computation becomes more evident and reveals unique opportunities for exploration.

### 3.5.1 Static



Figure 4. Static transformation.

A static material transformation is the act of manipulating materials to bring them to a final, end-all state, where their properties are supposed to remain the same regardless of the passage of time and changing environmental conditions. Static transformation is the more traditional and readily understood use of materials. The



one we encounter in paintings, sculptures and most of the objects we use on a daily basis.



Figure 5. Bird in Space (1923),  
by Constantin Brâncuși.

A particular interesting example is Constantin Brâncuși's Bird in Space (Figure 5), a series of sculptures carved in bronze or marble which aim to represent the essence of a bird's movement rather than the physical attributes of a bird. Through a static form of material transformation, Brâncuși manipulated material properties to give the dynamic appearance of flight to a fundamentally static form. Part of what makes this work successful is the artist's choice and treatment of materials, which sought to accentuate the surface's reflective properties, further detaching the viewer from any strict adherence to a specific form or notice of the material.

### 3.5.2 Directional



Figure 6. Directional transformation.

A directional material transformation goes a step further and treats the changes that materials undergo over time as a desirable quality. In this case, materials are manipulated for their dynamic behavior so their property changes are pre-determined and non-reversible.

Examples of this category include for instance the use of copper cladding roofs in architecture (Figure 7), which over time reacts to air and rain, and develops an oxide layer, undergoing a transformation where the material transitions from its original orange-copper color to a green patina. This color change in copper is a well known and desired quality which is taken into consideration during the alloy selection and external use of the material.



Figure 7. Canada's Parliament Buildings.

Another interesting example of this form of material transformation is, graphic designer and artist, Stefan Sagmeister's Banana Wall (Figure 8). Using the natural properties of a banana which changes color as it ripens, Sagmeister assembled 10,000 bananas closely together on a wall to display the message: 'Self Confidence Produces Fine Results'. At the beginning of the installation, green bananas form the letters of the text, while more ripe yellow bananas make up the background. As they mature and the green turns to yellow, the message fades, to reappear briefly again when the background bananas turn brown while the letters are still yellow. This work provides an example of a directional transformation, where the bananas undergo a one-way, one-time only, change which cannot be reversed.

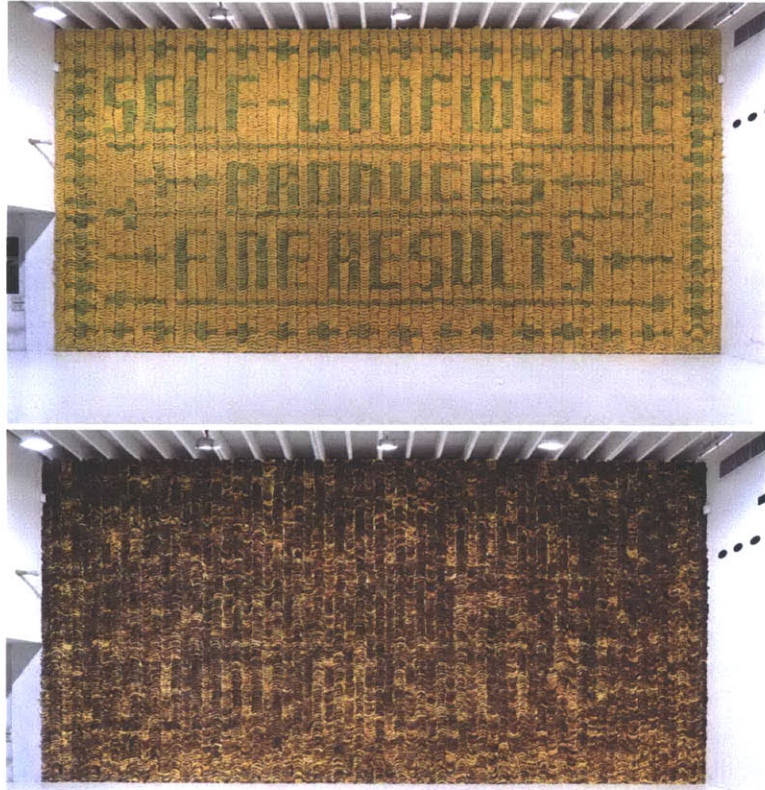


Figure 8. Stefan Sagmeister's Banana Wall (2008): Initial state at the top image and final state underneath.

### 3.5.3 Bidirectional

A bidirectional material transformation builds upon the directional one by treating the material transformation as a reversible process. In this case, material properties change according to an environmental or user controlled stimulus in a predetermined way, but revert to their original state once the stimulus is removed.

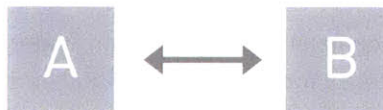


Figure 9. Bidirectional transformation.

Examples of this form of transformation not only include 'smart materials', such as thermochromic inks which undergo a color transformation in the presence of heat, but can also be applied to more traditional materials such as a wood. For example, in HygroScope (Figure 10), Steffan Reichert uses the moisture absorbing properties of wood and related surface expansion to create a skin structure that changes porosity over time in response to changes in the environment. As ambient humidity and moisture change, the wood expands and contracts in a controlled way to curl and open physical apertures. The surface is both structural and a

responsive skin, taking full advantage of the natural properties of the material. This is an example of a bidirectional transformation of a wooden surface that responds to environmental influences without the aid of electrical or mechanical controls.

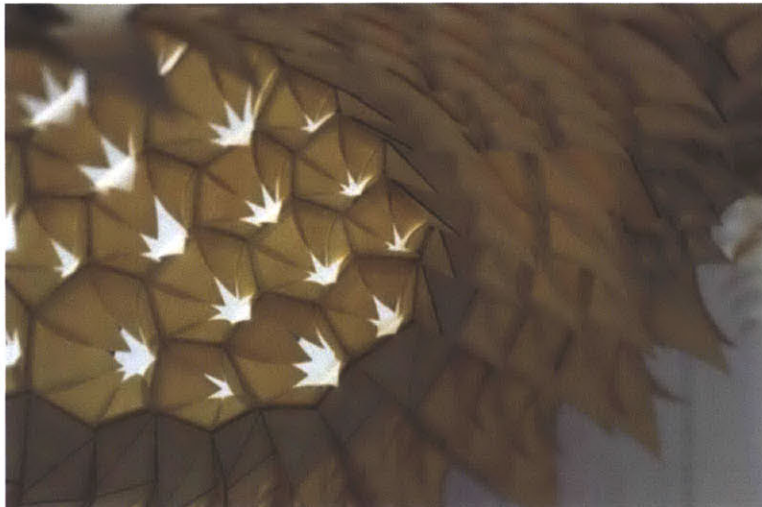


Figure 10. Achim Menges and Steffen Reichert's HygroScope (2012).

Another more common example is a light bulb, whose tungsten filament heats and glows to emit light with the flow of electricity. By flipping a switch and closing a circuit, a user can run an electrical current through the tungsten and cause a light to turn on. Opening the circuit removes the electrical stimulus, cooling down the tungsten filament and returning it to its non-emissive dark state.

### 3.5.4 Programmable

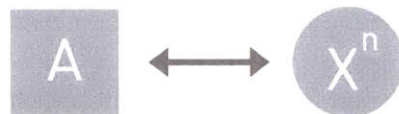


Figure 11. Programmable transformation.

In a programmable form of material transformation, materials are imbued with transitional states, can store information, and sense their environmental or use conditions, akin to a state machine. The role of the material programmer in this case is to select these states, how they are connected to each other, and what kind of external inputs will trigger transitions across states. Differently from a static, directional or bidirectional transformations, the material in this case does not respond to input in a linear and reversible fashion but can engage more complex responses. In order to achieve this, programmable materials also require the discretization of functional material units, which can be assembled together into complex assemblies, to perform roles such as power distribution, processing, input and output.

Daniel Rozin's Wooden Mirror (Figure 13) provides an interesting example of a programmable wooden surface which acts like a physical mirror. It is built from an array of wooden blocks distributed onto a grid, which can be angled to modify how light is reflected. Concealed at the center of the mirror is a camera which records images of viewers and passersby which are then displayed back by reorienting the wooden blocks. Similar to Steffen Reichert's HygroScope (Figure 12), all that the viewer sees and experiences is a wooden surface composed of an array of actuated wooden blocks or pixels; however, due to their programmability, they give rise to very different kinds of material and surface behavior and engender a very different kind of engagement and interaction.

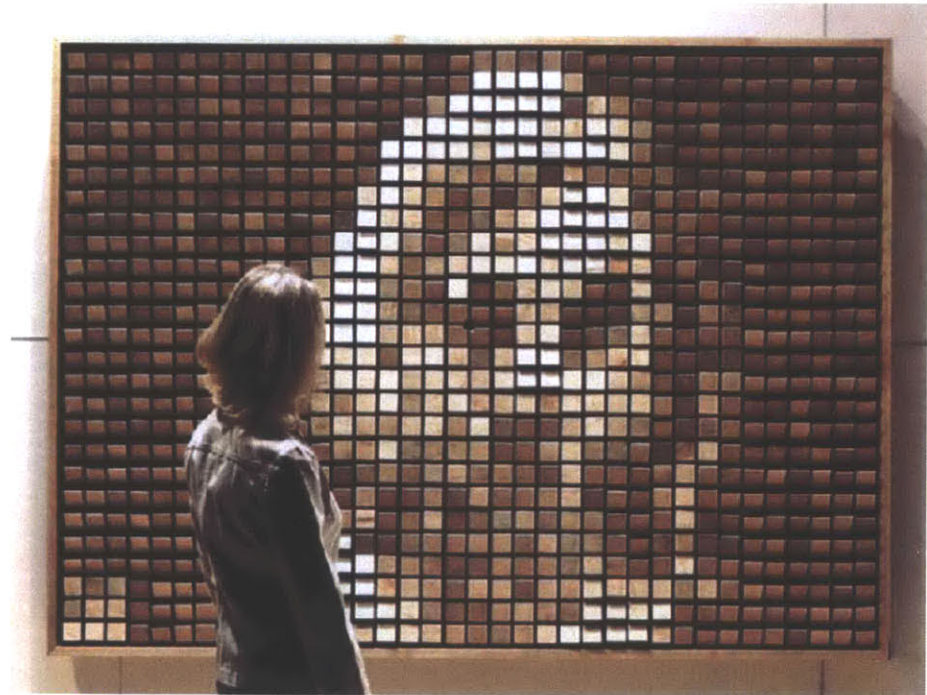


Figure 12. Daniel Rozin's Wooden Mirror (1999).

Another relevant example is Loop.ph's Sonumbra de Vincy (Figure 13), a parasol made from a lacework of electroluminescent wires. Similar to a tungsten filament which emits light with a current flow, each fiber in Sonumbra de Vincy lights up with the flow of electricity; however in this case the work is composed of computer, wires, and a power distribution infrastructure which allows for the programming of much complex behaviors which respond in real-time to people's presence. A particularly interesting artifact of this process is that the addressable animation of each fiber also reveals the lacework structure of the electroluminescent textile.

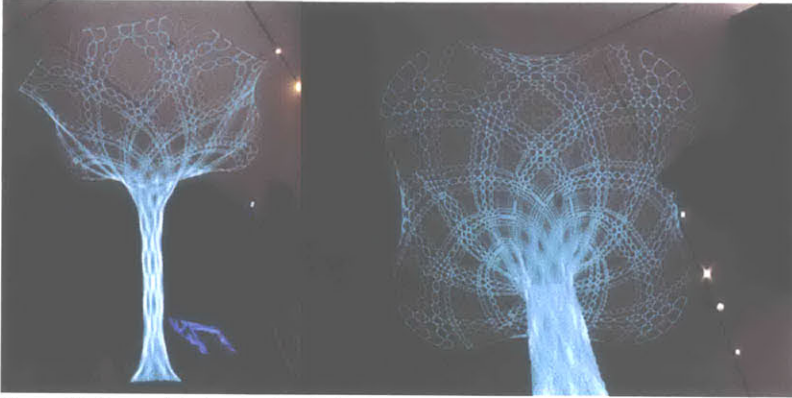


Figure 13. Loop.ph's Sonumbra de Vincy (2006).

The vast majority of the surfaces discussed in this thesis fall within this programmability category, where a composite is created from a complex assembly of functional materials, such as motors, electroluminescent wires, computers, or sensors, and can assume different configurations and behaviors in response to different stimuli.

### 3.5.5 Reprogrammable

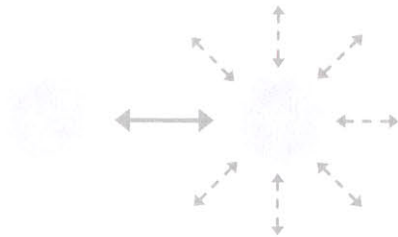


Figure 14. Reprogrammable transformation.

Reprogrammable materials are probably the least explored form of transformation and are characterized by a material being capable of changing its internal state configuration in response to a stimulus. The material in this case can modify its own “program” – variables, structure or composition – which then determine its new set of behaviors.

This form of programmability is akin to the functioning of biological organisms, which through inputs from their environment undergo a physical transformation over their lifetime. As they develop, their composition changes, altering their “program” and their responses, leading to entirely new kinds of behaviors not predictable from the outset of the organisms’ lives.

Another example is the real-time programming of shape-memory alloy (Figure 15). A shape-memory alloy is an alloy which can be heat treated at high temperatures to ‘remember’ a specific physical shape, which is then recalled when the material undergoes a much smaller temperature change. By causing a shape memory alloy

strand to change its shape through heating, it is possible to also reprogram the memorized shape, since the input and the reprogramming stimulus are fundamentally the same. For example, during the development of Shutters, described in more detail in Chapter 6, a heating and cooling cycle had to be chosen to minimize this reprogrammability effect which otherwise would have reconfigured the molecular structure of the material and its actuation behavior to a new unpredictable state.



Figure 15. Shape-memory alloy ribbon.

This section seeks to bridge a parallel between the programmability of computers and materials, highlighting how the act of physicality crafting an object is similar to that of software programming, progressing through a continuum of material and behavior complexity, which starts at static things and ends with fully reprogrammable material assemblies. As we approach the day when computation will become seamlessly embedded in our physical world, distinctions between states, variables and structures in both materials and software will increasingly fade into the background, becoming an important part of a designer's toolset. Most importantly, this juxtaposition is crucial if we seek to create computational devices that can intrinsically support the versatility of computers and the rich physical qualities of materials we encounter in our surroundings. The following sections describe some considerations for creating programmable material units and building them into surfaces which do just that.

### 3.6 Materializing Interaction

The challenge of developing programmable surfaces can be broken down into a two part problem. The first one deals with the **local** challenges of creating and controlling material units which can sense changes in their environment (input) and act as actuators by dynamically changing their properties (output). The

second one deals with the **global** challenges of aggregating these material units into larger surfaces and orchestrating their behaviors so they can operate in unison as a single substrate.

### 3.6.1 Programmable Materials

In order for computers to be seamlessly embedded into our environments, it is crucial that they preserve their capacity to leverage input, output, power storage, communication and processing, while simultaneously conveying a wide range of material properties that can engage our intuition about the behavior and affordances of the material world. 'Smart materials' and their composites are strategically positioned to fulfill this desire by transforming input stimuli into controlled materials responses, while presenting a wide range of material properties and behaviors. Nonetheless, the term 'smart material' is somewhat misleading and, with little regard for how materials are made, used or behave, it tends to encompass a wide range of technologies which are neither 'smart' per se, nor related to one another (Addington & Schodek, 2004) (Ritter, 2006).

To complicate matters, most materials, smart or not, are capable of changing their properties due to different input stimuli, but remain largely unexplored for these dynamic properties. A fitting example is Steffen Reichert's HygroScope Structure, mentioned earlier, which takes advantage of wood's natural capacity to expand and shrink to use it as an actuator. Under these circumstances, how can we identify the material properties which are suitable for the design of interactive systems? Three material characteristics are of particular importance for human-computer interaction and can help us sketch an answer to this question:

**computational control, scale shift, and reversibility/repeatability.**

#### Computational Control

In order to interface with the world of bits, materials need to respond to stimuli that can be computationally controlled. This process can happen directly, as in the case of electronically controlled thermoelectric junctions, or indirectly through a secondary process, as in the case of thermochromic inks activated through the resistive heating of an external element.

#### Scale Shift

To support meaningful interactions, material changes need to operate at a scale in which stimulus and response can be perceived by our senses and acted upon by our bodies and tools. In most cases, this simply means the amplification of the natural material responses we already encounter in the physical world, so they can be brought to a scale where people can interact with them. Even though wood can



change shape in response to humidity levels, the time scale in which it changes removes the possibility of a fluid dialogue with a user.

### Reversibility/Repeatability

Although these are essentially two separate properties, they occur together. Reversibility is the capacity of a material to change to a new state and return to its original condition, and repeatability is its capacity to repeat the transformation process numerous times without considerable performance decay. Without reversibility and repeatability we are bound to static and directional forms of programming, excluding the more complex forms of behaviors that can emerge from bidirectional, programmable and reprogrammable materials.

Although these properties are in no way exclusive and are most likely to find counterexamples which contradict this categorization, they can help us narrow down the scope of relevant technologies.

Programmable Materials are understood here as materials and composites that can leverage input and output capabilities, and which under different stimuli are capable of altering their own properties or transform energy from one form to another. The focus in this case is placed on transformations – transformation of the material itself or the energy applied to it – and the material’s ability to support sensing, actuation, power distribution and communication (to users, other materials or its control infrastructure). The following table illustrates these transformations by comparing the relationship between input stimulus and output response in different materials.

<i>Response</i> <i>Stimulus</i>	Electrical	Magnetic	Optical	Thermal	Mechanical	Chemical
Electrical			Electroluminescent Wires	Resistive Inks	Piezoelectric, Electrostrictive, ER Fluids, Dielectric Elastomers	
Magnetic			Magneto-optic		Ferrofluid	
Optical	Photoconductor		Photochromic Dyes			
Thermal	Peltier Junction		Thermochromic Inks		Shape Memory Alloys	
Mechanical	Piezoelectric, Electrostrictive	Magnetostrictive	Mechanochromic		Negative Poisson Ratio	
Chemical						

Stimulus-response matrix for selected materials  
(ER – electro-rheological; MR – magneto-rheological)  
Source: modified from Textiles Future

Once new programmable material units are created, we are then faced with the challenge of assembling their local transformations into larger material aggregates with global behaviors. The following section describes different strategies for the control and coordination of material units.

### 3.6.2 Programmable Surfaces

The challenge of controlling material units distributed within a large surface aggregate is a well known problem in the development of amorphous computing. In Harold Abelson words: “how can pre-specified, coherent behavior be engineered from the cooperation of vast numbers of unreliable parts interconnected in unknown, irregular, and time-varying ways” (Abelson et al., 2000). Based on where the material logic circuitry is found and how units communicate with each other, this thesis addresses this problem by dividing programmable material units into three control classes: **autonomous**, **dependent** and **hybrid**.

#### Autonomous Control

An autonomous material unit is one which is self-contained and has the required power, logic, input and output hardware necessary to perform its transformations independent of the larger material network where it resides.

Six-Forty by Four-Eighty, presented in chapter 7, is an example of such an autonomous system, where each light pixel is outfitted with a custom PCB, a microcontroller, battery, LEDs and a capacitive antenna for touch sensing and data transmission. Because each pixel can operate on its own, the surface behavior emerges from their individual responses to input and how people rearrange them in space. Due to its autonomous nature, this type of material architecture is less prone to failures, since the omission of one physical pixel does not prevent others from continuing to operate. However, one downside of this material architecture is its redundancy, which increases material and fabrication costs.

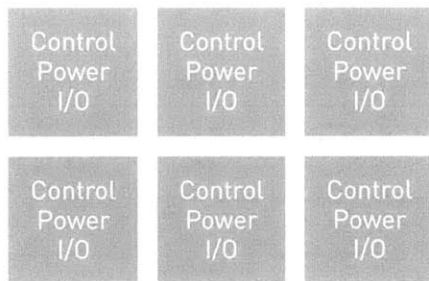


Figure 16. Autonomous material units.

#### Dependent Control

A dependent material unit, on the other hand, is one which is completely inert outside of its material aggregate. In order to sense input or perform any kind of output, it requires power, logic or some external level of coordination which is shared with the whole substrate.

Shutters, discussed in more detail in chapter 6, is an example of such a network, where each shape-changing fabric shutter is controlled through a time-division multiplexing power scheme which determines its behavior. Outside of this network, the material loses its ability to change and its functional role. While in Shutters, time-division multiplexing is used solely for output, a similar strategy can be used to gather input from an array of distributed sensors, such as the one used in the capacitive sensing electrodes of a computer trackpad.

Being more efficient than the autonomous material architecture described earlier and allowing for denser material aggregates, this approach also presents some disadvantages. If a power failure or connection is severed in the network, its effect can cascade down and affect much larger areas of the substrate.

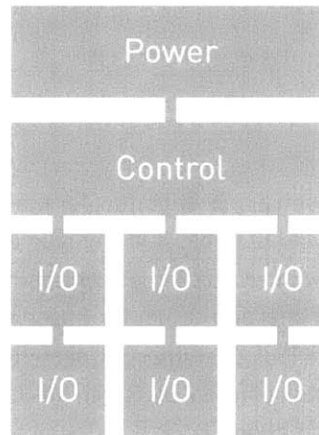


Figure 17. Dependent control.

### Hybrid Control

A hybrid material unit is one which is capable of performing some or all of its functionalities on its own but is still dependent on its material network for power or information.

In order to allow Six-Forty by Four-Eighty to display images or animations, each physical pixel is located in space by an external computer and camera which then transmit this location or color information back to the pixels over infrared, orchestrating their coordinated behavior. Each pixel on-board logic parses the network data and handles the transitions between frames according to its own predetermined local behavior.

A hybrid control infrastructure does not necessarily imply a need for external logic. Siftables and Sound Mites are examples of physical computing units which can identify their physical neighbors through an infrared based lattice communication

and cooperate to achieve a variety of global behaviors (Merrill, 2009) (Bouchard, 2007).

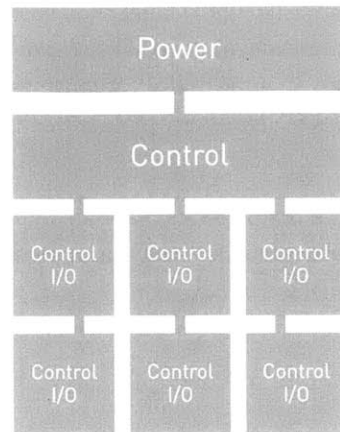


Figure 18. Hybrid control.

### 3.7 Conclusion

In this chapter, I have proposed a new definition for materials and surfaces which takes in consideration their situatedness and engagement with people; I have also looked at the ways in which materials can be programmed with properties and behaviors, positioning traditional and computer-based material practices under a single lens; and finally, I have looked at the control techniques through which the localized behavior of individual material units can be coordinated to give rise to global, surface level transformations.

In the following chapter, I provide a survey and taxonomy of the range of programmable material properties available to designers and the ways in which these properties can be physically arranged to form programmable surfaces.

# 4 Taxonomy

## 4.1 Introduction

In the previous chapter, I presented new definitions for materials and surfaces, taking into account not only the context in which they are created, but also how they are experienced. This discussion provided a foundation for an understanding of how materials can undergo different kinds of transformations and be imbued with dynamic, programmable behaviors.

This chapter continues this thread by diving in further and trying to understand what exactly are the nature and range of these programmable properties. This discussion is presented through a taxonomy which classifies, at one level, the dynamic material properties available to designers and, at another, how these local changes scaffold to form surfaces with global dynamic behaviors. Rather than providing an exhaustive list of materials' physical properties, the focus is placed on programmable properties which can be perceived by our senses, and can eventually lead to the design of richer and more engaging interactive systems. This taxonomy is then applied to discuss examples of prior work in the field, revealing their similarities, capabilities and limitations.

## 4.2 Why a Taxonomy?

Material libraries traditionally section and group material samples based on properties such as composition, manufacturing processes or origin. While this classification scheme provides a valuable tool for allowing designers to understand how things are made or how their mechanical properties will affect the use and lifetime of a product, they ignore the fact that materials provide a rich and high bandwidth communication channel between the physical world and ourselves.

The taxonomy described in this chapter is motivated by the fact that designers still lack a material categorization system that supports their focus on the creation of human experiences. In order to fulfill this gap, I have attempted to describe material and surface properties based on how their transformations (and programmability) can engage our senses. Rather than providing a set of prescriptive parameters, its goal is to formulate a vocabulary and language which can be used to describe and analyze previous works, hoping to help designers

identify unexplored design opportunities and draw inspiration for the development of future work.

## 4.3 Approach

### 4.3.1 Material Unit and Surface Distribution

The distinction between materials and surfaces presented in this chapter draws a technical and conceptual parallel with pixels and display matrices, in an attempt to characterize the properties of the smallest units of programmable material, while isolating them from their aggregate properties. Programmable materials are treated here as material units: the fundamental physical units of change that can be perceived by our senses; while surfaces provide the infrastructural properties through which these units coalesce onto a single medium, as illustrated in Figure 1.

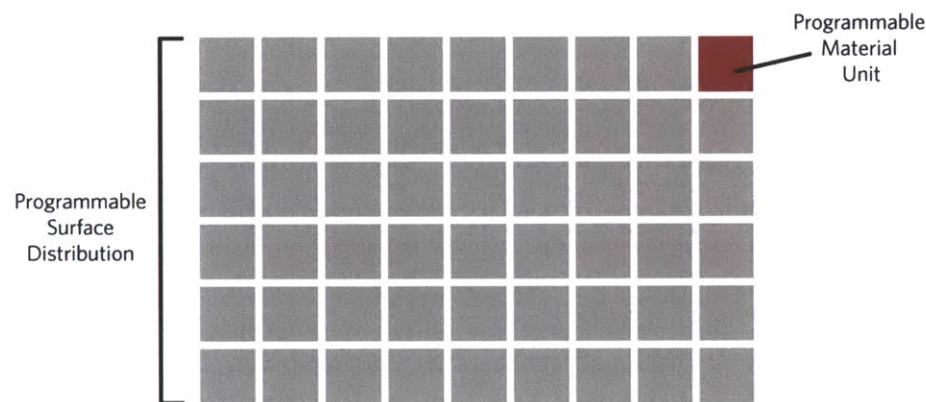


Figure 1. Material unit and surface distribution distinction.

### 4.3.2 Focus on Senses

The senses are our source of knowledge about the physical world. Together, they form a group of parallel and highly interdependent communication channels with very unique characteristics. According to how we detect and respond to external stimuli, the human sensory system can be divided into four main modalities: photoreception (i.e., electromagnetic radiation perceived by our eyes); mechanoreception (i.e., touch, vibration and sound); thermoreception (i.e. the temperature differences between our bodies and external objects); and chemoreception (i.e. the detection of molecules that form our sense of smell and taste). Some of these channels require a direct contact with external materials, such as when touching an object or placing food in our mouths; others requires a transmission medium to carry information between an external object and our senses, such as sound waves propagating through the air; and some can take place without a diffusion medium, such as light perception or heat radiation.

Mapping and classifying material properties according to their effect on our sensory inputs is not an easy task. Material perception operates for the most part across several sensory channels and our interpretation of what we experience is a highly synaesthetic process which integrates the senses in complex ways which are not yet fully understood (Bacci & Melcher, 2011). For instance, the vibrating cone of a speaker can be perceived concurrently through touch and vision but at different degrees of spatial and temporal resolution, while taste perception is highly influenced by smells, vision, color, textures, etc (Delwiche, 2004).

The palette of material and surface properties outlined in this chapter is informed by our sensory capabilities in so far as they provide perceptual boundaries for material transformations, such as bandwidth and resolution, while excluding material changes which are not directly perceivable, such as a light polarization or magnetism.

Based on how material properties can be mapped to our sensory capabilities, the programmable transformations that materials undergo can be divided into four main categories: **spatial**, **optical**, **thermal** and **chemical** exchanges, as illustrated in Figure 2.

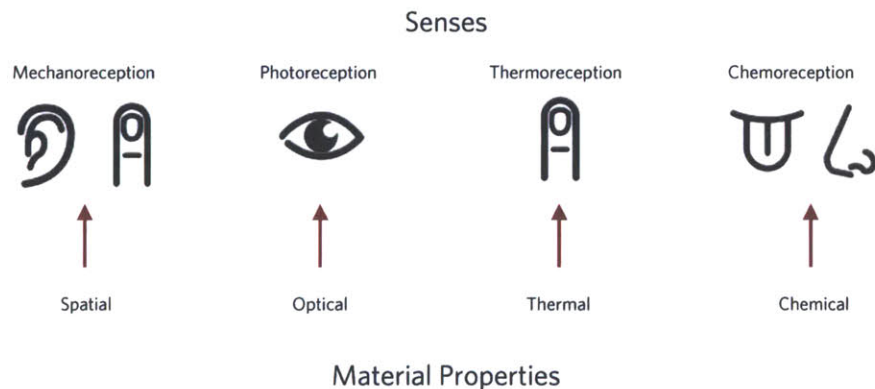


Figure 2. Material properties and their corresponding sensory channels.

## 4.4 Programmable Material Units

### 4.4.1 Spatial

Form is the most fundamental property of a material unit and a prerequisite from which other properties derive. It encompasses at a basic level whether or not a material is present at a certain location in three-dimensional space and as a result how its geometry affects its properties.

Similar to how forms are manipulated in CAD, material units can partition space into three-dimensional physical voxels and be programmatically controlled to

dynamically change their **translation**, **rotation** and **scale** properties (Figure 3). However, differently from the virtual abstractions of CAD, material pixels have mass, density, physical permanency and provide a certain degree of physical resistance to touch and other objects. Due to this physical nature, form transformations can engage our senses directly through mechanoreception or indirectly by affecting how a surface modulates light and sound or the topology of where chemical interactions take place.

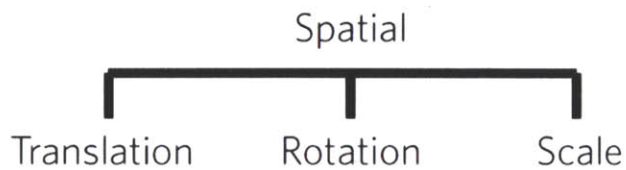


Figure 3. Spatial transformations.

### Translation

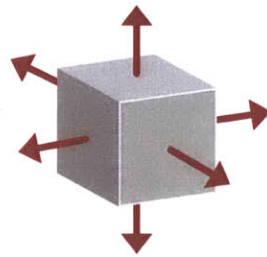


Figure 4. Translation axes.

Translation transformations are those performed by moving a material pixel in X, Y or Z directions in a cartesian space. These changes can take place within a local pixel boundary, with no effect on other pixels, and retaining the surface's overall lattice structure, or they can break away from the "grid" and affect the global distribution and topology of the whole surface by modifying its relation with adjacent pixels.

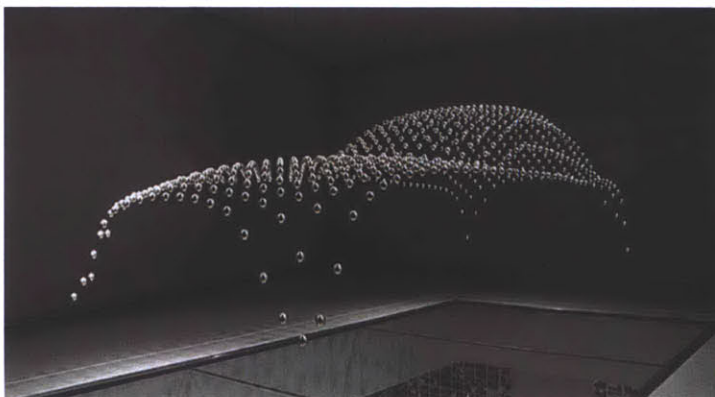


Figure 5. ART+COM Kinetic Sculpture (2008).



ART+COM's Kinetic Sculpture (Figure 5) is an example of material units, in this case metal spheres, which are programmed to translate vertically and generate dynamic patterns and physical representations of BMW's cars (ART+COM, 2012). These patterns take advantage of the closure phenomenon of Gestalt Principles, where in spite of perceiving gaps and holes in a shape or line, the viewer completes the shape by filling in the missing information (Livingstone, 2008).

## Rotation

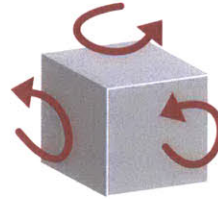


Figure 6. Rotation axes.

Rotation transformations are those performed by changing the angular position of a material unit in relation to an axis of constraint. They are equivalent to the Euler angles  $\alpha$ ,  $\beta$  and  $\gamma$  used to describe the rotation of a rigid body, or the more common aircraft principle angles roll, pitch and yaw.

Daniel Rozin's Circles Mirror is an example of programmable surface which uses this principle (Figure 7). Each unit is made from a disk printed with a color pattern which can roll in relation to its center axis to display different images. Since the pixels are slightly overlapped by each other, only a section of the circle is visible to the viewer at a time (Rozin, 2005).

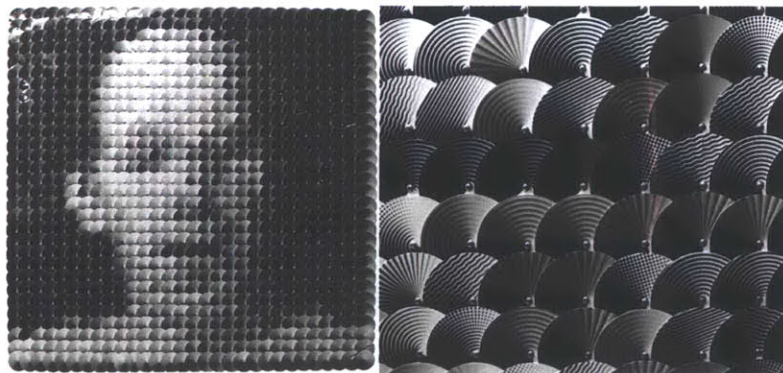


Figure 7. Daniel Rozin's Circle Mirror (2005). Left: view from afar where it is possible to identify a human face; Right: detail of patterned discs.

## Scale

Scale transformations are those performed by changing the size of a unit's dimensions in X, Y and Z. A single dimensional change would lead to the material

unit changing its overall proportions and shape, while a combined transformation in the three dimensions would change its size without modifying its overall shape.



Figure 8. Scale transformation in one axis.

An example of this type of transformation is Daniel Leithinger's Relief (Figure 9), which is composed of a series of actuated rods, which can extend vertically to simulate different surface topologies (Leithinger, 2010). Differently from Kinetic Sculpture, where the material pixel translates vertically, in this case the pixel extend its shape to generate a similar effect but with very different aesthetic results.

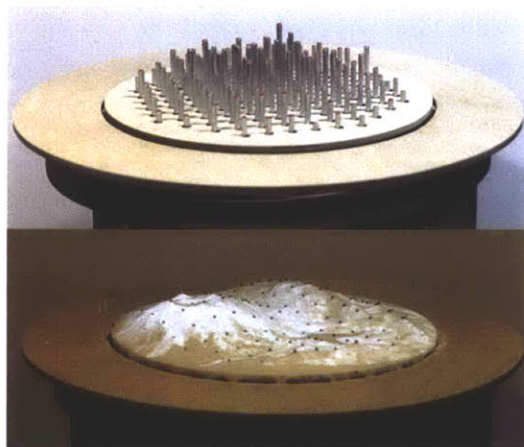


Figure 9. Daniel Leithinger's Relief (Leithinger, 2010).

Another relevant example of a scale transformation can be found in the mylar bags from the installation 'Captured - An Homage to Light and Air' (Figure 10). In this example, a material display is composed from an array of plastic bags distributed in a lattice which can be inflated and deflated with a computer controlled air pump, causing them to increase and decrease in size (Db, 2011).

Due to a material's physical persistence, scale changes also result in combined compressions and elongations in the material. When integrated into a surface where units are physically bound to each other, single axis scale changes can be parallelized to cause a surface to curve and deform into any shape. Chapter 6 presents a more detailed description of how compression and elongations can be combined to create shape-changing surfaces that preserve their homeomorphic equivalence as exemplified by Surfex, Shutters and Sprout I/O.



Figure 10. Nils and Sven Völker's *Captured - An Homage to Light and Air* (2011).

### General Properties

The fundamental form transformations (translation, rotation and scale) can also be characterized by four specific properties which play an important role in their ability to render and communicate information.

- **Amplitude** is the degree to which a material unit can change its form in order for it to be perceivable. A form-changing material display made to be seen requires a different amplitude (based on its distance from an observer) than a haptic display which could operate down to a micrometer and still be sensed by a human hand.
- **Velocity** is the speed which a material unit can transition from two different states, fundamentally affecting its refresh rate. A transformation velocity is generally non-linear (due to the need to accelerate and decelerate a material mass) and affect both the transition between states and also how long a unit needs to remain in a state before it can change again. Shape-memory alloys for instance can perform a fairly rapid shape change through resistive heating, but might require a slow return change due to passive ambient cooling. Another important distinction to make here are material units that display different states by being either in motion (at varying velocities) or static. The Cyclone Display (Figure 11) is an example which uses a combination of rotating discs and a strobe light to create different light patterns (Ochiai, 2011).
- **Refresh Rate** is derived from a unit's transformation velocity and is characterized by a similar dichotomy across different sensory channels. While a 60 Hz refresh rate suffices for creating a visual display, mechanoreception for hearing could support up to 20 KHz.

- **Stiffness** is a somewhat passive property characterized not by a unit changing shape, but by resisting deformation. By retaining or modulating its form under an applied pressure, a material unit can provide a rich palette of haptic feedback and communicate through touch perception.



Figure 11. The Cyclone Display, by Yoichi Ochiai and Hiromu Takai (2011).

#### 4.4.2 Optical

The light properties of a material are those that affect its interaction with the electromagnetic spectrum, and in particular the visible part of the spectrum, encompassing wavelengths between 390 and 750 nm that reach our eyes. In addition to photoreception, radiation outside of this range in the infrared band can be also perceived through thermoreception by causing temperature changes on a person's skin and operate under the same principles.

A material pixel can modulate its interaction with light in four fundamental and highly interconnected ways: emission, reflection, transmission and absorption.

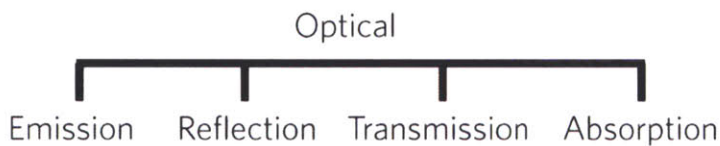


Figure 12. Optical transformations.

#### Emission

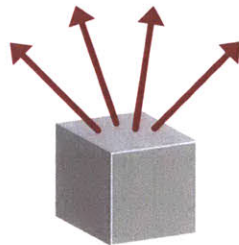


Figure 13. Light emission.

Emission is probably the most ubiquitous technique used in dynamic displays today and is controlled by changing the amount of visible radiation that emanates from a material. Due to its pervasiveness and continuous development in light-emitting technology, such as LEDs, OLEDs, and electroluminescent materials, it also provides a fine degree of control over resolution, wavelength and refresh rate of a display.

Six-Forty by Four-Eighty, described in more detail in chapter 7, is an example of a material display composed of an array of material units which can be rearranged in space and can modulate their emitted luminance and wavelength with a tricolor light-emitting diode (Figure 14).

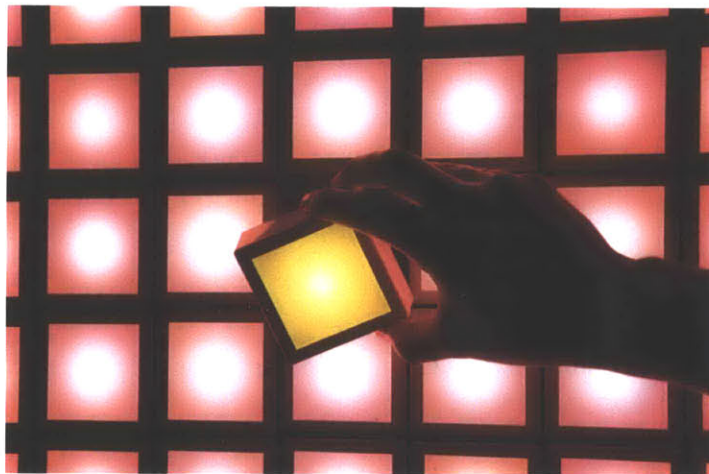


Figure 14. Detail of Six-Forty by Four-Eighty light emitting material pixel.



Figure 15. rAndom International's You Fade To Light (2009).

Another interesting example is rAndom International's You Fade To Light (Figure 15): a rectangular array of OLED panels which can transition from emitting a

uniform diffused light to reflecting its ambient illumination, acting both as a mirror and a traditional light emitting display (rAndom International, 2009).

## Reflection

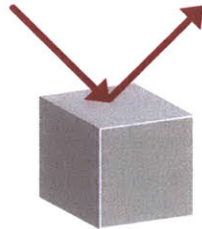


Figure 16. Light reflection.

Reflection is a change in direction on the light's wavefront at the material interface and is normally controlled by regulating transmission and absorption, or by mechanically rotating or deforming a material unit to change its angle of reflection. Angular control of reflection can also be used to reflect certain wavelengths while not affecting others, providing a technique for creating color changes in a material.

Digital mirror arrays (Figure 17) used in DLP projectors operate by rapidly controlling the rotation of an array of micro mirror tiles, so that the light originating at a light bulb can either be reflected towards a lens to be seen, or be reflected towards an internal cavity where it is absorbed.

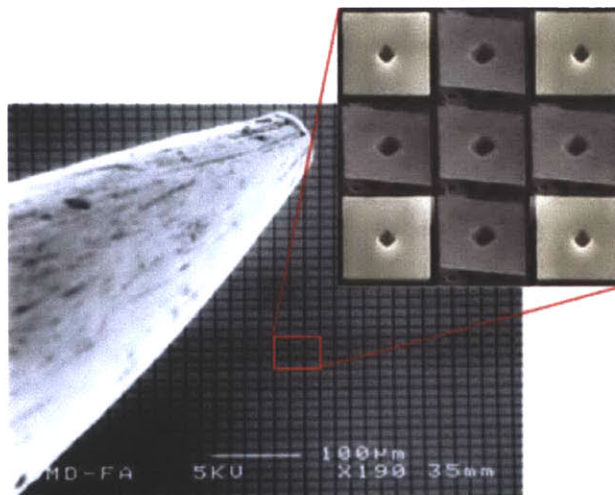


Figure 17. Detail of micro-mirror array.

Another relevant example is Troika's installation Shoal (Figure 18) which uses a wavelength specific reflection to control color changes. Each material pixel in this installation is made from a fish-shaped dichroic glass piece, which is mounted to a rotating metal rod. Dichroic materials can reflect certain wavelengths, while absorbing others depending on the light's angle of incidence. When the glass

pieces rotate, they not only change our perception of their size, but they also transition through a color palette due to the dichroic effect (Troika, 2010).

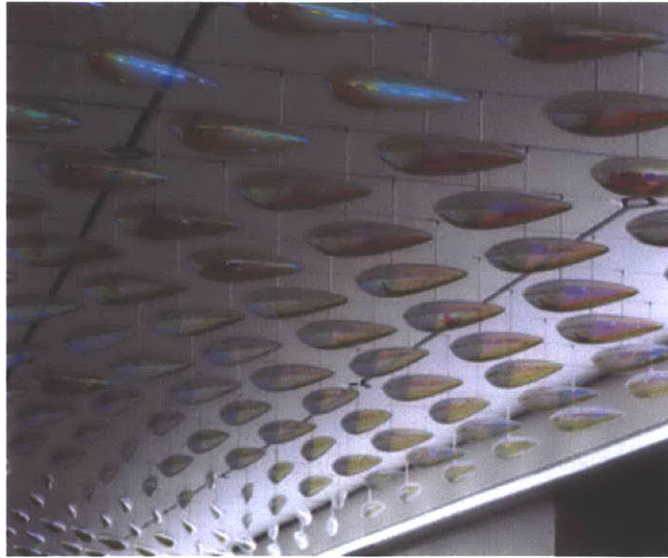


Figure 18. Troika's Shoal (2010).

## Transmission

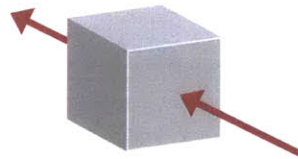


Figure 19. Light transmission.

Transmission is a change in the fraction of incident light within a specific wavelength band that passes through a material. By regulating transmission, it is possible to control a material's transparency. Light emitting displays such as LCDs operate through a combination of transmission control and emission. A backlight provides illumination, while a liquid crystal grid positioned in front of it acts as a mask, changing the transparency of its pixels to regulate what colors and images are visible.

Dan Good et al. eCloud (Figure 20) is an example of an installation which uses an array of suspended particle glass sheets, which can control their light scattering properties under an electrical stimulus. By switching states, the glass sheets can become transparent or an opaque white (Good, 2010).



Figure 20. Dan Good et al., eCloud (2010). Photo by Spencer Lowell.

Patterned by Nature (Figure 21) is a similar example which uses an array of liquid crystal panels, which by switching their degree of polarization can control their opacity. Differently from eCloud, the material units in this case transition from an opaque black to a translucent transmissive state (Sosolimited et al., 2012).

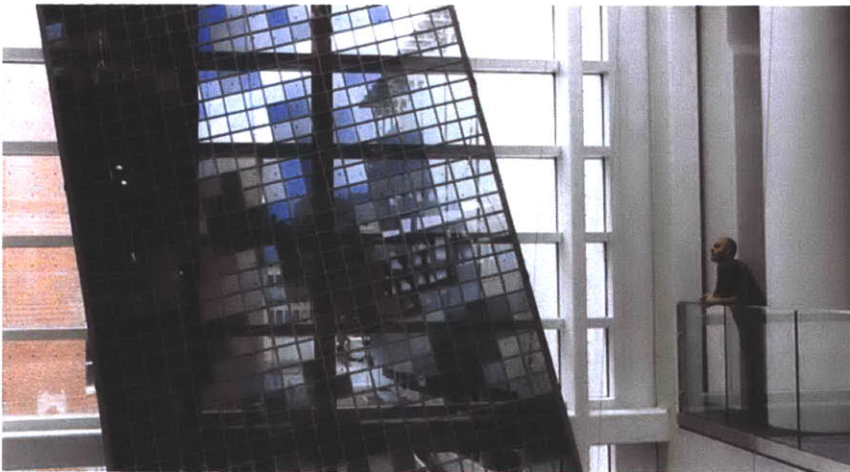


Figure 21. Patterned by Nature (2012), by Sosolimited, Plebian Design, Patten Studio and Bill Washbaugh.

Finally, light transmission is also affected by refraction and diffraction. In refraction, a change in phase velocity affects the angular direction of a wave when it passes from one medium to another with different refractive indexes and cause objects to look distorted or broken in space. In diffraction, light waves, passing through a small aperture or object, interfere with each other amplifying or attenuating certain frequencies, and creating different colors or patterns. Diffraction is one of the underlying processes behind iridescence which gives



certain animals a hue changing quality depending on the angle from which they are observed.

## Absorption

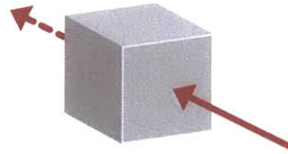


Figure 22. Light absorption.

Absorption is a property of how much light is absorbed by a material. By controlling what wavelength is absorbed and to what degree it is possible to create material displays that have visual qualities similar to those of printed materials.

A relevant example is the technology developed by e-ink, where suspended black and white pigments within a transparent micro-capsule are electrically charged to move to the surface of a substrate, modifying its visual appearance between white and black. In this case, the white appearance is a direct result of ambient light being reflected and scattered by the display, rather than being emitted, while the black is result of ambient light being absorbed.



Figure 23. Detail image of e-ink display.

## General Properties

The fundamental light interaction properties of materials (emission, reflection, transmission and absorption) are highly interconnected and operate in tandem, since for instance a reduction in light transmission can be a result of changes in reflection and absorption. The outcome of these interactions and particularities of our visual system determine the eventual color or luminance we see on an object. Additionally, these properties can be further characterized by:

- **Scattering** is a property of how much a light wavefront deviates from a straight trajectory. In specular, or unscattered reflections, the angle of incidence equals that of reflection rendering materials with a glittering, mirror-like appearance. On the other hand, a diffused scatter, which is the primary light that makes objects visible to us, is a result of a incident light being reflected at many angles, giving materials an evenly distributed luminance.
- **Luminosity** is a measurement of brightness and how strong or weak a light source or reflection is.
- **Wavelengths** determine the colors we see. By modulating how materials interact with different wavelengths through emission, reflection, absorption and transmission we can transform them from one color to another. Thermochromic ink (Figure 24) is an example of a material which at different temperatures can absorb or reflect different wavelengths of light.

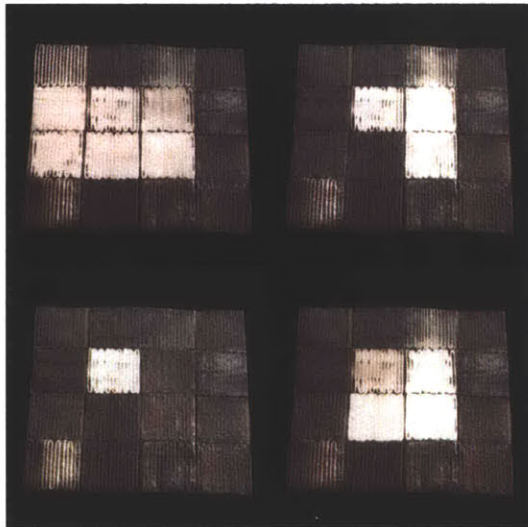


Figure 24. Addressable textile display made from resistive threads and thermochromic ink, by XS Labs (2005).

#### 4.4.3 Thermal

Temperature is a result of thermal disequilibrium between a material and our bodies, leading to the perception of a material being hot or cold. Heat flows from objects of higher temperature to those of lower temperature when a conductive (touch), convective (air or fluid flow) or radiative (IR or microwave) connection is established between them, and by manipulating these connections it is possible to program different thermal material experiences.

Thermal  
|  
Temperature  
Differential

Figure 25. Thermal transformations.

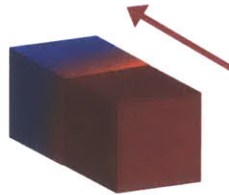


Figure 26. Thermal exchange.

According to Jones and Berris, the ability of humans to discriminate changes in temperature depend on many factors, such as: the site of skin simulated; the amplitude of the temperature change; the rate at which temperature changes; and the temperature of the skin (Jones & Berris, 2002). One of the primary roles of our thermal system is to regulate exchanges happening at the surface of the skin, so that a constant core body temperature can be maintained. This results in poor spatial acuity and good spatial summation — a unique characteristic among our sensory modalities —, where a small temperature change over a large surface area is equivalent to a large temperature change concentrated onto a small area. Jones et al. characterization of thermoception as a communication channel places temperature range at 20 °C (between 22 - 42 °C), heating resolution at 0.001°C, cooling resolution at 0.002°C, temporal transient resolution during cooling at 20°C/s, and temporal transient resolution during warming at 10°C/s, making these the fundamental desired properties of a thermal material unit. Finally, it is important to note that thermal receptors in the skin are not thermometers, and our ability to recognize and distinguish materials such as wood, metal or glass by their temperature is mostly a result of a material's thermal conductance and heat capacity, rather than its temperature (Ino, 1993).

While thermal displays are not particularly common as haptic output devices, a number of techniques have been used to create thermal units, such as resistive heating elements (Jones & Berris, 2002), infrared lamps (Dionisio, 1997), and thermoelectric junctions (Ino, 1993). Thermoesthesia (Figure 27) is an example of a thermal display composed of an array of thermoelectric junctions distributed on a orthogonal lattice under a projection screen. Through an overlaid projection and hand tracking, it allows users to manipulate images of ice crystal growth while perceiving different temperature transients.

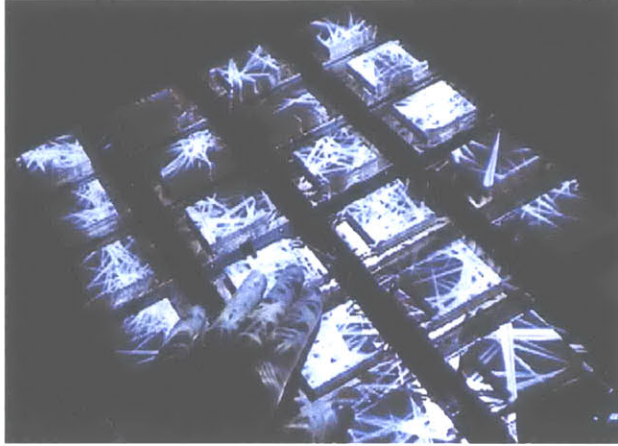


Figure 27. Thermoesthesia, by Kumiko Kushiya.

#### 4.4.4 Chemical

Chemoreception is the process through which we respond to chemical stimuli from our external environments and is primarily divided into the senses of taste and smell. Being the least understood of our sensory modalities, we still lack appropriate techniques to properly characterize and programmatically control these chemical interactions. Additionally, gustation and olfaction are highly intertwined senses, making it difficult to delineate their properties and address one without affecting the other.

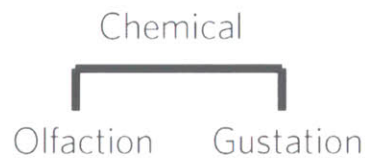


Figure 28. Chemical transformations.

#### Olfaction

Olfaction, or the sense of smell, is our sensory channel responsible for the detection of airborne chemicals generated outside of our bodies and capable of reaching our nasal cavity. Differently from vision, which is restricted to four kinds of receptors — red, green and blue cones, and rods —, our sense of smell develops from a stimulus triggering a thousand different kinds of receptors in our nose. Due to the absence of primary scents — equivalent to the primary colors — from which a whole range of smells can be derived, the computerized production of scents requires a machine containing thousands of different scent samples or needs to restrict its display ability to a small, manageable set of scents.



Figure 29. Olfactory transformation.

As a communication channel, scent provides several limitations in comparison with other senses: it is limited in bandwidth and inappropriate for rapidly changing information, since scents can't be rapidly diffused and be removed from air; hard to categorize due to wide range of smells we can perceive; and difficult to provide on demand. In order to overcome these limitations, material units attempting to convey information through scent should do so based on the qualities, rather than the quantities of scents, and focus on "slow-moving, medium-duration information or information for which an aggregate representation is slow changing" (Kaye, 2004).

Currently, there are only a few methods for creating material units capable of dynamically delivering scent into the air: (1) spraying a chemical with a source of compressed air, such as actuated aerosol cans or perfume bottles; (2) evaporation of volatile chemicals, which can be aided by a heat source or fan as in the use of scented oils and wax; (3) projection of scented toroidal vortices through an air cannon (Nakaizumi, 2006); and (4) inkjet printing capable of producing a jet of scented droplets (Sugimoto, 2010).

In spite of the challenges of creating a scent display, several attempts have been made at having better control of scent delivery and diffusion. Scents of Space (Figure 30) by Haque Design + Research is an example of a scent installation where fragrances are localized within three-dimensional space without dispersion through the use of actuated fragrance dispensers and by carefully controlling airflow (Haque: Design Research, 2012).



Figure 30. Haque's Scents of Space.

SpotScents (Figure 31) on the other hand is an example of a technique which uses combined vortex canons to carry and more precisely position a scent in space. In this case, two toroidal vortices are launched towards the user's nose, but collide in mid-air breaking their ring and diffusing a fragrance within a more specific region in space (Nakaizumi, 2006).



Figure 31. SpotScents air cannon.

## Gustation

Gustation, or the sense of taste, is our sensory channel responsible for the detection of chemicals reaching our oral cavity and taste buds concentrated on the upper surface of the tongue. As a sensory channel, taste is comprised of five distinct sensations: sweetness, sourness, bitterness, saltiness and umami; and is highly integrated with our sense of smell, temperature, color, texture, sound and irritation or pain, such as those caused by chili peppers, analgesics or onions (Delwiche, 2003).



Figure 32. Gustatory transformation.

These multi-modal sensations develop through complex interactions making it difficult to characterize and synthesize taste experiences based solely on the combination of the basic tastes. (Narumi, 2010). Nonetheless, research in this area has sought to explore this sensory integration by simulating taste experiences through the manipulation of visual, olfactive and haptic stimuli. One noteworthy

example is Hiro Iwata's Food Simulator (Figure 33), a haptic interface which attempts to simulate taste experience by integrating biting force feedback, chemical stimulus injected through a micro pump, and mastication sounds played through a bone vibration speaker (Iwata, 2004).

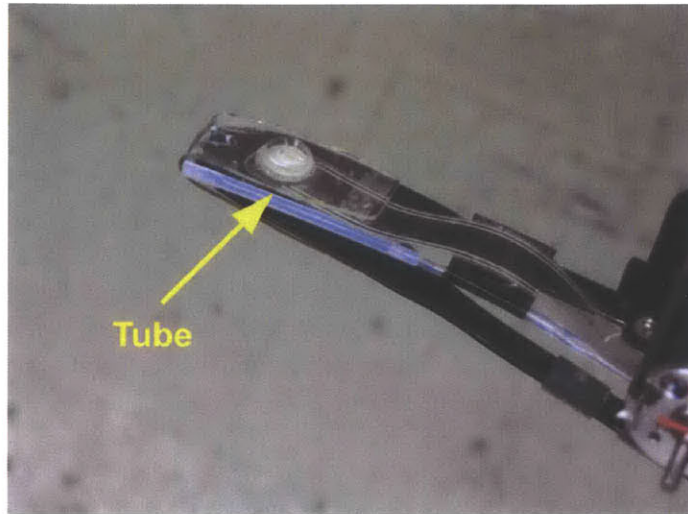


Figure 33. Material unit used in Food Simulator.

## 4.5 Programmable Surface Distributions

Once we develop material units which can computationally stimulate a wide range of sensorial stimuli, it is important to study the ways in which they can be aggregated into surfaces. This section outlines the fundamental ways in which material units can be physically distributed to form surfaces.

Distribution in the context of this thesis refers to the position, arrangement and recurrence of material units over a continuous surface. The choice of distribution can be a result not only of the form of a material unit, which lends itself to certain patterning or packing arrangements, but also technical constraints resulting from its fabrication and deployment. To study the main ways in which material units can be distributed for the creation of a programmable surface, we can draw insights from both mathematical classifications of tiling patterns as well as mosaic techniques developed over hundreds of years.

According to their symmetry or lack thereof, material units can be distributed on a surface in **periodic** or **aperiodic** patterns, which can be additionally subdivided into: **lattice**, **radial**, or **multiple scale** patterns for periodic distributions; and **stochastic**, **hybrid** or **dynamic** for aperiodic ones.

## 4.5.1 Periodic

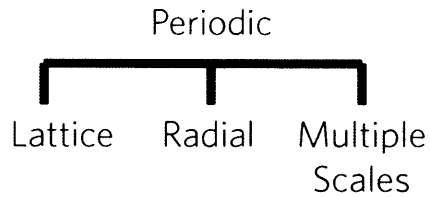


Figure 34. Periodic distribution types.

### Lattice

There are three basic categories of symmetry groups based on increasing levels of complexity: Frieze Groups, Wallpaper Groups, and Space Groups. All deal with the isometric repetition of a single module (respectively categorizing symmetry in one, two and three dimensions) and are based on the four basic operations of movement, traditionally broken down into: reflection, translation, rotation and glide reflection.

In the context of this thesis, reflection is more appropriately defined as yaw; rotation as roll; and glide reflection as a combination of both translation and yaw operations. Since the focus of this thesis is primarily placed on the properties of surfaces, I will exclude any discussion of Space Groups.

Frieze Groups describe designs that are repetitive in only one direction, on a two-dimensional plane. Using the four movement operations listed above, we can create seven unique symmetry types within this category, as illustrated in figure 35.

Wallpaper Groups, on the other hand, retain a given pattern in more than one direction, on a two-dimensional plane. Using the movement operations listed earlier, we can create seventeen unique symmetry types within this category, as illustrated in figure 36.

It is important to note that within the aforementioned symmetry groups material units can also be arranged within five distinct lattice types: parallelogrammatic, rectangular, rhombic, square and hexagonal. For instance, an example of material units with a hexagonal distribution is Daniel Rozin's Shiny Balls Mirror (Figure 37) (Rozin, 2003).



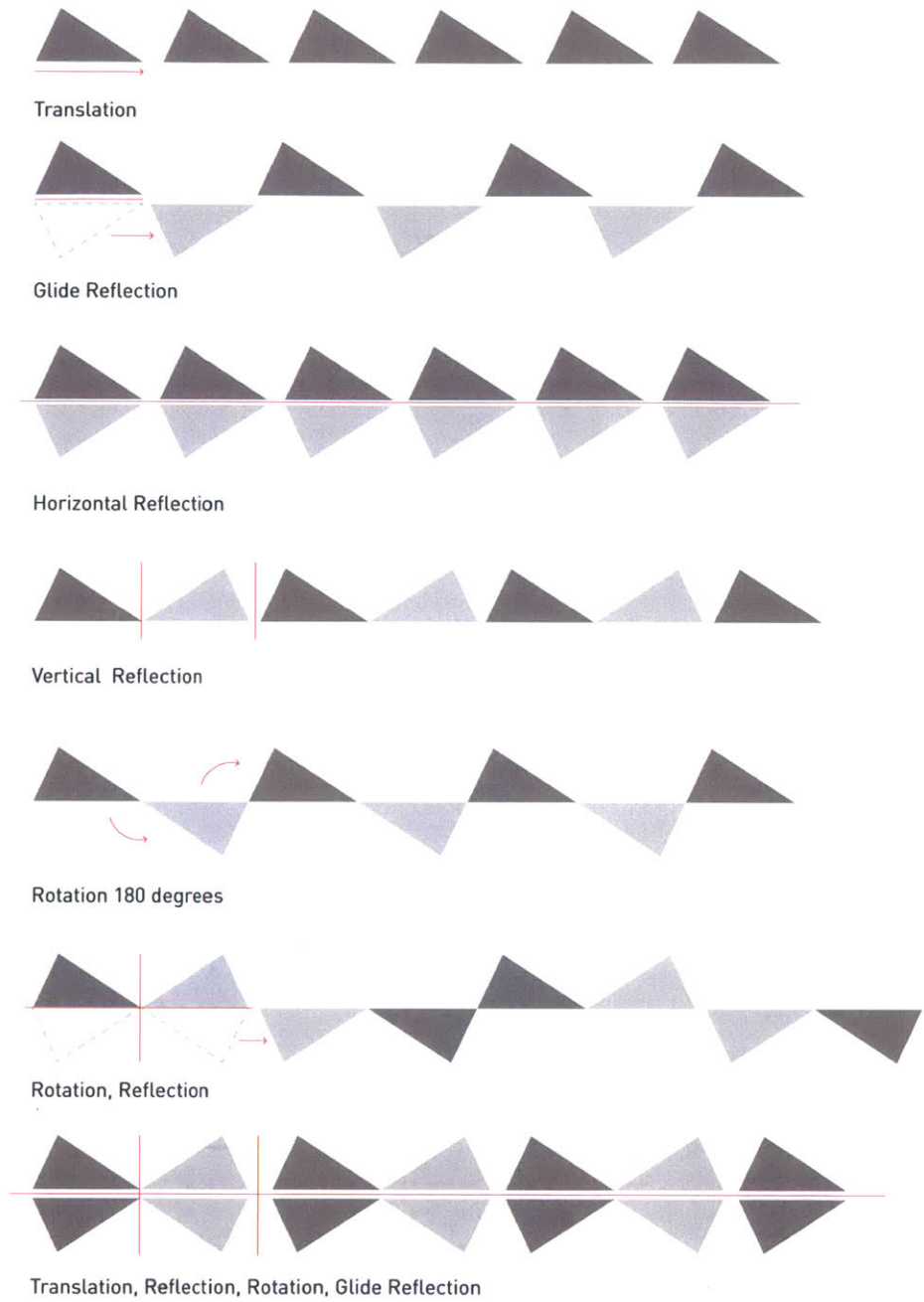
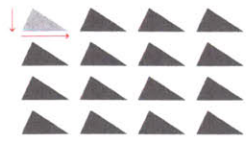


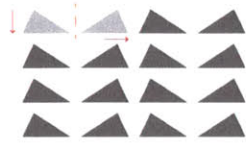
Figure 35. Frieze Groups.

# 17 WALLPAPER GROUPS

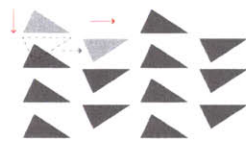
FOUR TYPES OF TRANSFORMATION  
 translation  
 rotation [60°/90°/120°/180°]  
 reflection  
 glide reflection



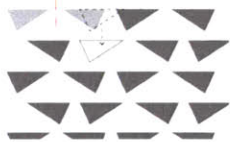
Translations only, along any two axes [p1]



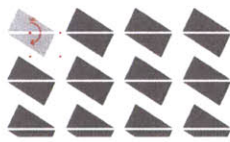
Reflection, perpendicular to one axis of translation, and parallel to the other [pm]



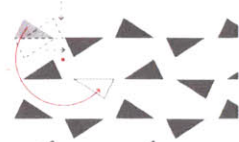
Glide Reflection, perpendicular to one axis of translation, and parallel to the other [pg]



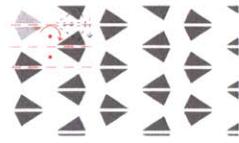
Reflection and Glide reflection [cm]



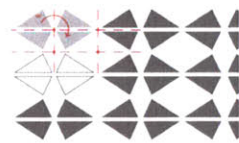
Rotation [180°] at four centers [p2]



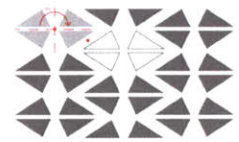
Rotation [180°] and Glide Reflection [pgg]



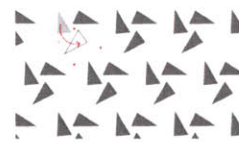
Reflections, Glide Reflection and Rotation [180°] [pmg]



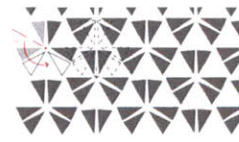
Reflection, with perpendicular axes, and Rotation [180°] where axes intersect [pmm]



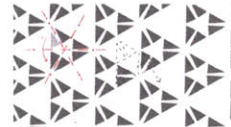
Reflection, with perpendicular axes, and Rotation [180°] [cmm]



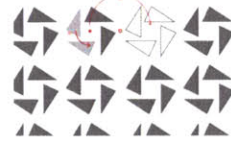
Rotation [120°] at three centers [p3]



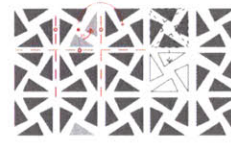
Reflections along a 60° axis, Rotation [120°], Glide Reflection [p3m1]



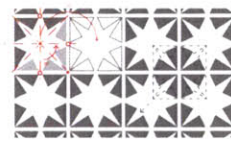
Reflection [at 60° intervals] and Rotation [120°] and Glide Reflection [p3m1]



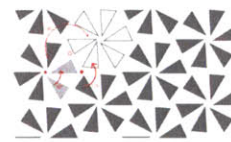
Rotation [90°, 180°] [p4]



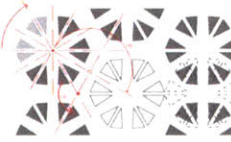
Reflection, Rotation [90°, 180°] and Glide Reflection [p4g]



Reflection [at 45° intervals], Rotation [90°, 180°] and Glide Reflection [p4m]



Rotations [60°, 120°, 180°] [p6]



Reflection, Rotation [60°, 120°, 180°] and Glide Reflection [p6m]

Figure 36. Wallpaper Groups.

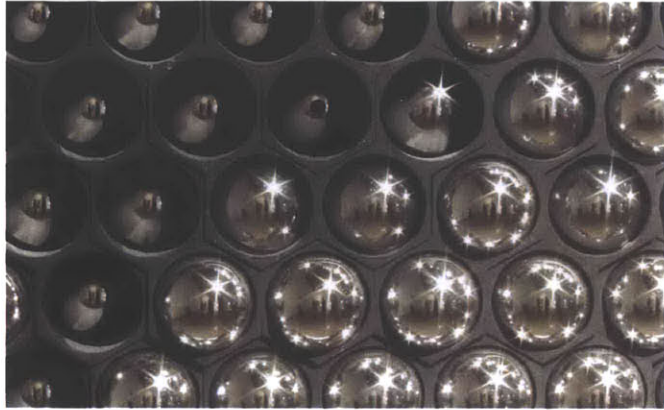


Figure 37. Detail of Daniel Rozin's Shiny Balls Mirror.

### Radial

In addition to these fundamental lattices types, it is possible to also arrange material units within a polar coordinate system with symmetry taking place over a radial or spiral distribution. An example of a radially distributed surface is United Visual Artists' Focus (Figure 38), which is composed of an array of light-emitting pixels arranged in concentric circles emanating from a center point (United Visual Artists, 2010). While a lattice distribution retains the same level of density and symmetry throughout a complete surface, a radial distribution carries a much different unit arrangement on its center than it does at its edges.



Figure 38. United Visual Artists' Focus (2010).

### Multiple Scales

Distribution symmetry can also take place across several scales, such as in fractal patterns (Figure 40), where for instance a triangular arrangement can propagate into ever larger triangular arrangements, or in combination, where particular local material organizations are inserted into a larger differing organization strategy. A static example of this is for instance planks of wood with parallel running grains being arranged into a rhombic lattice grid (Figure 39).

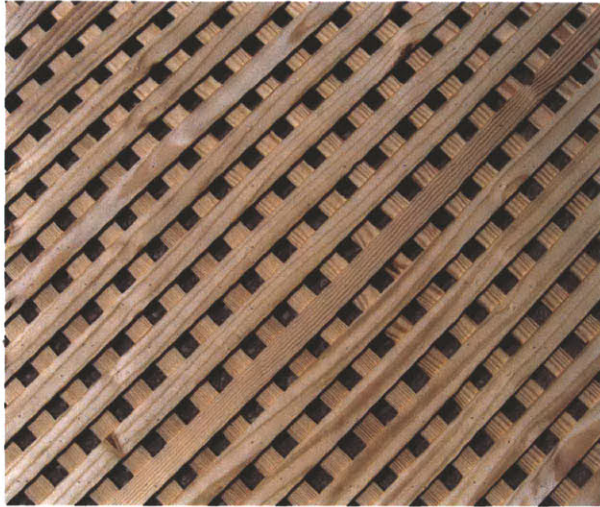


Figure 39. Combined distribution patterns of a fence.

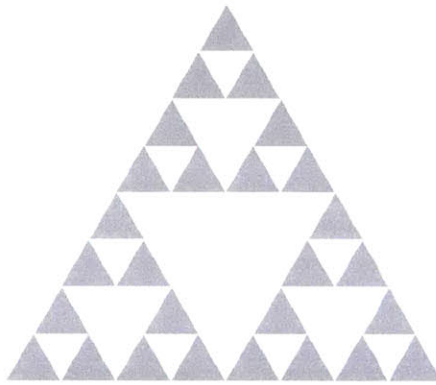


Figure 40. Illustration of a multiple scale, fractal distribution.

#### 4.5.2 Aperiodic

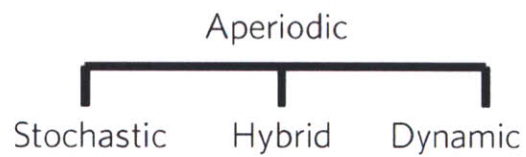


Figure 41. Aperiodic distribution types.

#### Stochastic

Once symmetry is broken, material units can be distributed in stochastic patterns outside of any lattice configuration, such as the pattern created with Six-Forty by Four-Eighty (Figure 42) or Pushpin Computing (Figure 47).

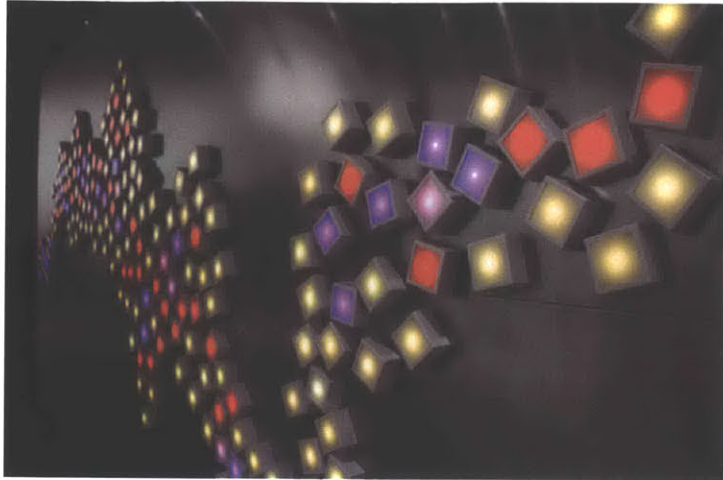


Figure 42. Six-Forty by Four-Eighty material units arranged in an stochastic distribution.

## Hybrid

In addition to the symmetry patterns described so far, materials units can also be aggregated through a combination of several different distribution types in order to achieve a range of aesthetic effects. While examples of these types of hybrid distributions are relatively rare, we can look at Roman mosaics for basic examples of hybrid distribution typologies.

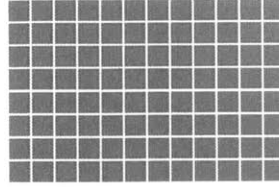
Mosaic is the ancient art of creating a unified image from the assembly of small pieces and provides a historical precedent for the discussion carried so far. Each mosaic piece or tile is called a tessera, and the process of creating a two dimensional plane using the repetition of a geometric shape is called tessellation.

Historic methods used to create images through mosaics can lend insight into useful methods for creating a programmable surface. When designing a mosaic, the size, shape and material of the individual tessera are chosen specifically to create a desired effect. In the pre-planning stage, an artist traditionally breaks down the image into orthogonal lines, diagonal lines and arcs. Depending upon the application (ceiling or floor), and amount of detail across an image, some areas are built on site, and some off-site in the artist's studio. For utilitarian reasons, larger tesserae and simple rectilinear grids are used to fill large areas of uniformity, while smaller tesserae and an underdrawing of non-rectilinear guide lines are followed to create more detailed parts of an image.

Due to the needs of different methods of application, requiring more and less detail, more and less order, artists have developed a system of mosaic techniques, called Opus, which describe the ways in which tesserae can be distributed in two-dimensional space and provides some insight for a possible range of hybrid surface distributions. Of particular relevance are the following techniques:

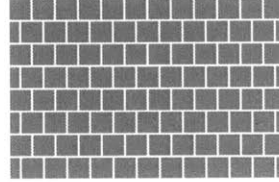
**Opus regulatum**

A grid of quadratic tesserae aligned vertically and horizontally.



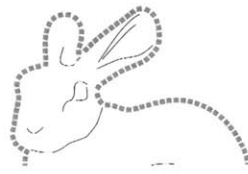
**Opus tessallatum**

Large tesserae used in vertical or horizontal rows.



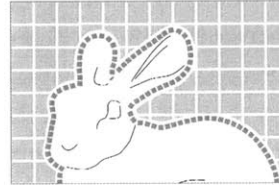
**Opus vermiculatum**

Smaller tesserae used to achieve finer details, in addition to one or more parallel lines following the edge of a shape.



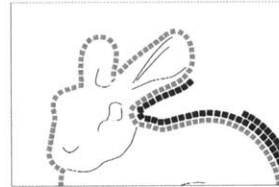
**Opus classicum**

A combination of vermiculatum, tessallatum and regulatum patterns.



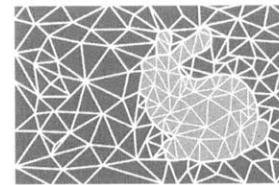
**Opus museum**

A vermiculatum pattern that extends throughout the background of an image.



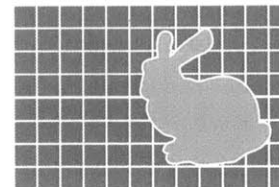
**Opus palladianum**

No perceivable rows and irregularly shaped tesserae.



**Opus sectile**

A major shape is formed by a single tessera.



**Opus circumactum**

When tesserae are laid in overlapping semicircles or fan shapes.

**Micromosaic** General use of very small tesserae for rendering color gradients and fine details.

### Dynamic

While so far I have only described surface distributions which are static, it is also possible for materials units to dynamically alter their location and overall distribution within a surface. An example of a dynamic distribution is Disney Research's Display Swarm. In this case, each material unit is mounted on robotic wheels and can move in X and Y directions allowing the display to render different physical configurations as needed (Alonso-Mora et al., 2011) (Figure 43).

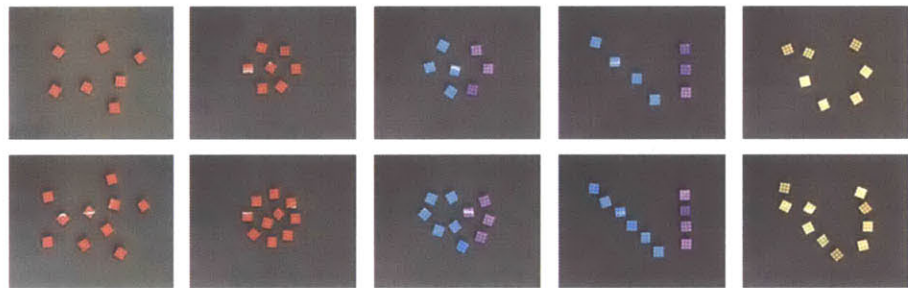


Figure 43. Disney Research's multi-robot pattern formation (Alonso-Mora et al., 2011).

### 4.5.3 General Properties

In addition to their distribution patterns, programmable surfaces are also characterized by the following properties:

- **Density**, traditionally referred to as DPI (dots-per-inch), is the number of material units per surface area.
- **Continuity**, closely related to density, refers to the interstitial space in between material units. Different kinds of continuity can be a result of unit geometry (since some unit forms can be arranged into a closed packed grid while others cannot), technical constraints, as well as aesthetic choice.
- **Transparency** is a sub-property of continuity. In a programmable surface such as Shutters, the space in between spatial units is filled with felt — the same material from which its actuated flaps are made —, while in the MiSPHERE display developed by Barco (Figure 44), the space in between optical units is open to allow viewers to see through the screen.

- **Form** is the overall shape of a programmable surface which can be distributed in one, two and three-dimensions and different form-factors. Some examples include rectangular surfaces, such as those found in computer and television screens, circular ones such as those used in United Visual Artists' Focus, or amorphous ones such as Six-Forty by Four-Eighty.
- **Hybrid Units** refers to the mixed use of material units both in their form, type of transformation but also the sensorial stimulus they provide.



Figure 44. Barco's MiSPHERE display used by U2.

## 4.6 Prior Work

Following this discussion of the primary properties of both programmable material units and their distribution, I will present a couple of examples of how these can be applied to describe programmable surfaces.

### Aegis Hyposurface

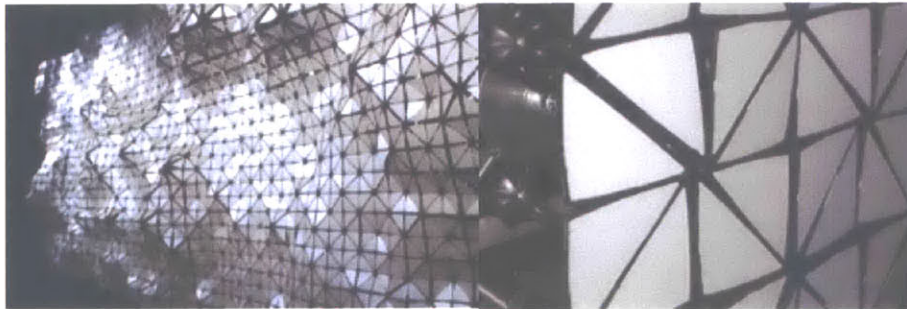


Figure 45. Aegis Hyposurface by dEcoi Architects.

A striking example of a programmable surface is dEcoi Architects' Aegis Hyposurface (Figure 45), a kinetic wall-sized surface constructed out of interconnected metallic plates and actuated by an array of pneumatic pistons,



which can display evolving patterns or text at a high refresh rate (Goulthorpe, 2000).

Material units in Aegis Hyposurface undergo a Z-axis translation — a spatial transformation — and are distributed in a periodic lattice arrangement, as detailed in the taxonomy tree in figure 46.

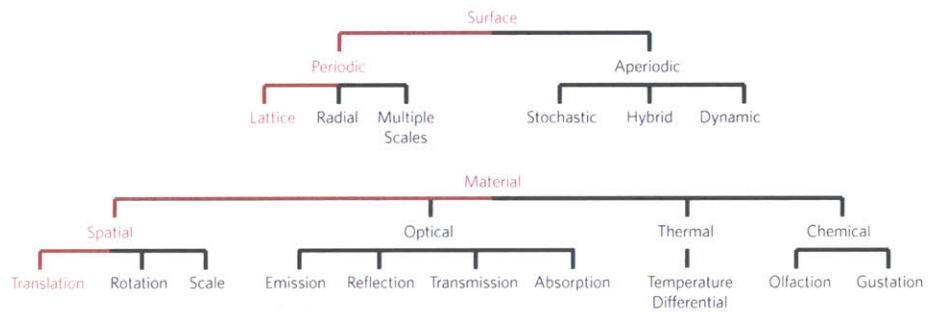


Figure 46. Taxonomy classification for Aegis Hyposurface.

### Pushpin Computing



Figure 47. Pushpin Computing

Pushpin Computing (Figure 47), developed by Josh Lifton et al., is a hardware and software platform composed of an array of physical light emitting pixels (Lifton et al., 2005).

Differently from Aegis Hyposurface, material units in Pushpin Computing can be categorized as undergoing primarily emission — an optical transformation — and as a platform for experimenting with sensor node localization strategy, Pushpin's distribution is a aperiodic and stochastic (Figure 48).

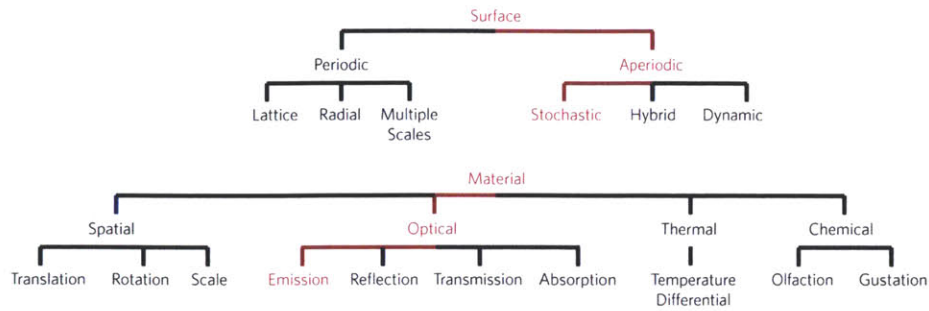


Figure 48. Taxonomy classification for Pushpin Computing.

## 4.7 Conclusion

In this chapter, I have outlined a taxonomy for classifying the general properties of both material units and surface distributions, elucidating how they can be combined to create a host of programmable surfaces which engage the full breadth of our sensory apparatus. In the following chapters, I present a series of design probes and installations I have developed, which implement some of these ideas and discuss some of the affordances, trade-offs as well as technical and aesthetic limitations of programmable materials and surfaces.

# 5 Design Probes

## 5.1 Introduction

In the previous chapter, I presented a taxonomy that reveals the fundamental programmable material properties available to designers. In this chapter, I discuss in further detail my composite design approach which combines the rich qualities of traditional materials such as paper, textiles and food with electronics, sensors and actuators. This material-based design approach is exemplified through a series of experiments and prototypes that both reveal some of the technical challenges designers face but also shows how the taxonomy described earlier can be used to distinguish these works and reveal new design opportunities.

## 5.2 Composite Approach

Designers seeking to use materials for both their dynamic properties and physical affordances can take advantage of a composite design approach by integrating into a single material unit, previously distinct and incongruous properties. Composite materials are engineered combinations made from two or more constituent materials with significantly different physical or chemical properties. These materials remain separate and distinct on a macroscopic level within a finished structure, but together create unique properties.

### 5.2.1 Static Composites for Performance

Traditionally composites are made from fibers embedded in a matrix or substrate and are designed to achieve specific performance goals, such as higher stiffness, strength or low density. Reinforced concrete is a good example in which reinforcement bars ("rebars") or fibers are incorporated to strengthen concrete, a material that would otherwise be brittle. Typical concrete mixes have high resistance to compressive stresses, but any appreciable tension (e.g. due to bending) breaks the microscopic rigid lattice resulting in cracking and separation. If a material with high strength in tension, such as steel, is placed in concrete, the composite material becomes capable of resisting compression as well as bending and other direct tensile actions. A reinforced concrete section, where the concrete resists the compression and steel resists the tension, can be made into almost any shape and size, opening new design possibilities for engineers and architects.

### 5.2.2 Programmable Composites for Interaction

The same approach that aims to improve concrete's performance can also be used to give new interaction possibilities to a host of materials which would normally only be considered for their static properties. Materials come in every form imaginable, such as powders, liquids, fibers, films etc, and can therefore be combined through different fabrication techniques, such as sewing, weaving, casting, silk screening, papermaking, etc. This synergy between material property and fabrication technique inevitably leads to their dynamic behavior as well as visual and tactile qualities.

Ultimately, rather than focusing on ubiquitous computing approaches that employ sensors and actuators as discrete add-on components, these composites allow computation and interaction to be seamlessly embedded into materials themselves opening new possibilities for the deployment of computation into the environment.

The main challenges in creating programmable composites are three-fold: (1) finding the appropriate material combinations; (2) developing the fabrication techniques for putting them together in a way that takes advantage of their properties; and finally (3) interfacing them to the logic circuitry that can control their behavior. In my work, I have sought to develop a series of compositing techniques which combine the dynamic behaviors of property-changing materials with the physical affordances of traditional materials, such as textiles, paper or glass, through a range of fabrication techniques.

## 5.3 Textiles

My first design explorations and research in this area were inspired by the electronic textiles work pioneered by Rehmi Post et al. (Post et al., 2000). Seeking to create wearable computers which are more appropriate for the shape, movements and interactions we undergo with our bodies, I worked at XS Labs in Montreal, Canada on the development of a series of techniques for fabricating sensors, actuators and circuit boards that preserve the softness and pliability of textiles (Berzowska, 2005) (Berzowska and Coelho, 2005).

This work was characterized by a composite design approach that combines the properties of traditional craft techniques, such weaving, knitting and beading, with the electrical properties of conductive fibers, inks and materials, such as thermochromic inks or shape-memory alloys. Challenging the role of textiles in architecture and fashion, these technologies were deployed through a series of conceptual garments and wall hung textiles, including shape-changing dresses, subtractive color textile displays, and body worn touch sensors. PurePlay, Kukkia

and Vilkas are examples of three garments based on the development of unique programmable composites.

### 5.3.1 PurePlay



Figure 1. Pureplay on a mannequin (left), peltier junction integrated into custom pockets surrounding the neckline (center); and detail of a peltier junction (right).

PurePlay is a tunic decorated with a dynamically changing color element along its neckline (Figure 1) (Berzowska, 2005). Functioning as a simple non-emissive animated display, the tunic's neckline is instrumented with an array of peltier junctions overlaid with thermochromic ink, which changes color with a change in temperature. This combination creates a textile materials unit that overlaps both thermal and optical transformation properties (Figure 2).

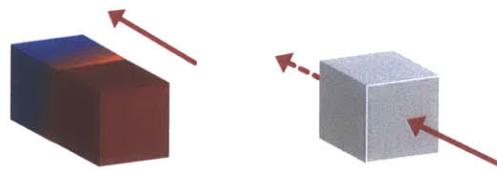


Figure 2. Material unit based on a combination of thermal differential and optical absorption.

Peltier junctions are thermoelectric devices capable of converting electrical energy into a temperature gradient. They are constructed from an array of two semiconductors connected by metallic conductors and arranged between two ceramic plates. Electrons in the two materials have different potential energies and, to move from one to the other, they absorb heat on one side of the ceramic plate, and release it at the other. By inverting a peltier junction's current, it is possible to quickly switch it from a heating to a cooling state, and vice-versa, allowing for a finer electronic control of the textile's temperature.

This combination of thermoelectric heating and thermochromic color change allows for an interesting actuation interplay, where the wearer physically perceives the tunic's thermal changes, while an external viewer can only perceive them through the thermochromic optical changes.

### 5.3.2 Kukkia and Vilkas



Figure 3. Kukkia's are animated to open and close (left) while Vilkas' hemline translates vertically (right).

Kukkia and Vilkas are two animated dresses that move or change shape over time, using a combination of felt, shape memory alloy, and control electronics. A shape-memory alloy (SMA) is an alloy made of nickel and titanium, that, once treated to acquire a specific shape, has the ability to indefinitely remember its geometry. In the following chapter, I discuss the properties of SMAs in more detail. (Berzowska and Coelho, 2005).

The Kukkia dress is decorated with three animated flowers that frame the neckline. Each flower opens and closes over (on average) a 15 second interval (Figure 3). The flowers are constructed out of felt and silk petals that provide relative rigidity and conceal the SMA wire stitched onto the back. When heated, the wire shrinks and pulls the petals together, closing the flower. As it cools down, the rigidity of the felt counteracts the shape of the wire, allowing the flower to open.

Vilkas, on the other hand, is a dress with a kinetic hemline that rises over a 30 second interval to reveal the knee and lower thigh (Figure 3). It is constructed of heavy hand-made felt with a very light yellow cotton element that contracts through the use of hand-stitched wires. Once heated, the SMA easily pulls the cloth together, creating a wrinkling effect. This movement is slowly countered by gravity and the weight of the felt.

In these examples, the material units transform spatially through scale changes. In Kukkia these changes are radially distributed to form a flower, while in Vilkas they are arranged on a one-dimensional lattice along the hemline.



Figure 4. Material unit based on scale transformations.

To develop the kinetic mechanisms in these dresses, it was necessary to explore several custom shaped SMA wires and their integration with textile techniques such as knitting, weaving, hand stitching, and embroidery. After experimenting with the different methods, it became evident that two methods, (1) felting SMA wire directly into wool and (2) hand-stitching SMA onto felt, were superior to knitting or weaving techniques. Overall weight was an issue, as we had to consider thickness (strength) of SMA wire, resistance of the wire (which determines the power needed to produce heat), and the weight of the material to be moved or distorted.

Felting is one of the earliest forms of textile processing. It renders wool windproof and water-resistant, as well as fire-resistant insofar as it will not start a flame and it extinguishes itself. Due to the resistive heating technique used to actuate the SMA, felt turned out to be the ideal material for the design of these composites: Felt is fire-resistant; It is thicker than most woven fabrics, so we could stitch conductive threads on both sides of the textile, effectively insulating one side from the other; and a wire or conductive thread can be completely embedded into felt, creating a seamless soft circuit that is insulated from the outside and from the wearer's skin. Mechanically, felt has the rigidity and thickness necessary to house strings of SMA and conductive threads, and it also offers enough physical resilience and rigidity to slowly force an SMA coil to straighten, so as to counteract the motion of the SMA.

Continuing to pursue this approach, I explored traditional fabrication techniques outside of the world of textiles, looking at how different material affordances could support new physical computing substrates.

## 5.4 Pulp-Based Computing

By applying similar compositing techniques to paper, I have developed Pulp-Based Computing: electronic circuits built out of paper which leverage interaction affordances such as folding, ripping or crumpling (Coelho et al., 2007).

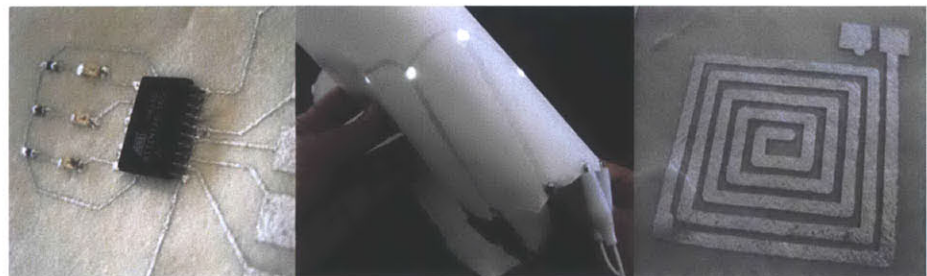


Figure 5. Pulp-Based computing examples: AVR microcontroller with LEDs and silkscreened programming header before inclusion (left); LEDs embedded in a pliable sheet (center); and silkscreened paper speaker (right).

Whereas industrial papermaking processes are highly mechanized and produce large quantities of paper, its handmade alternatives are laborious and time consuming activities. However, handmade paper allows for an inclusion process, where a physical object can be permanently embedded in between two individual paper sheets which are then compressed, drained and set to dry. By silk screening and encapsulating electrically active inks in between sheets, it is possible to create an electronic paper "sandwich" which is resilient and inseparable from its embedded object (Figure 5). Rather than simply depositing ink on a sheet's surface, which is prone to chipping and breaking, this process encapsulates the ink particles in-between wet paper sheets. When the sheets dry and shrink, they compress the inks, keeping them protected from external stresses. The result are sensors and actuators that are more resilient, reliable and electrically insulated from the outside.

Through this encapsulation technique, we have developed several distinct underlying technologies, which combined can provide a framework for the development of a paper-based computing platform.

### **Embedded Off-The-Shelf Components**

The first technique consists of embedding off-the-shelf sensors, actuators and integrated circuits into paper sheets. We have specifically experimented with piezo-microphones, surface mount LEDs, vibrating motors, photovoltaic cells and bend sensors. This approach takes advantage of existing hardware interfaces which are already optimized to account for electric variations, such as long term drift, hysteresis or non-linearity, and, since the components are electrically independent from the paper substrate, they suffer no relevant interference.

### **Bend Sensor**

We have also developed a paper sheet that can sense deflection in two dimensions (x,y) by infusing carbon resistive ink in between two layers of paper. Instead of silk screening resistive ink on top of a dry sheet of paper, we printed it on a pressed wet sheet and covered it with a second layer, forming one single double-layered sheet. In the case of a book, this approach allows us to measure variations in resistance and detect when pages are being flipped without additional electronic components that could interfere with the textural and visual qualities of the book. Moreover, it prevents the resistive ink from chipping or cracking upon stress, which would dramatically reduce the sensor's lifespan.

### **Speakers and Collocated I/O**

The same silkscreening and inclusion technique was used to print spirals of conductive ink on the surface of paper sheets. By oscillating a current flow through



this spiral, it's possible to create a controlled magnetic field which can vibrate the paper fast enough for it to produce an array of audible frequencies. Sound quality from a paper speaker is somewhat limited; but this restriction might not hinder applications where a broad frequency range is not a priority, such as interactive postcards or wallpapers that can provide relevant information to users. The same speaker spiral can concurrently function as an antenna for touch and proximity sensing when its capacitance is compared against RC variations caused by the interference of an external stimulus, such as a human hand. By intercalating sensing with actuation, the paper sheet becomes a true collocated input and output substrate. Additionally, by combining matrices of conductive and resistive inks, it is possible to detect touch on paper two-dimensionally, in a similar fashion to how the antenna design of a laptop's touchpad works.

### **Kinetic Paper**

We also experimented with an SMA and paper composite. When current is applied to small strands of SMA embedded into paper, a sheet can physically deform and bend to acquire new shapes, or relax and return to its default shape. Future applications for this technology are numerous, ranging from self assembling boxes to customizable wall dividers and tangibles interfaces that can adapt to use and context.

### **Interface and Logic**

Finally, to unite all of these elements into a cohesive interactive system, we printed complete circuit boards and electrical buses with conductive ink. We also embedded conductive threads into paper, which present the same electrical profile as wires, but can withstand greater physical stress without permanent damage. Finally, microcontrollers, which need to be in-circuit programmed, were embedded and attached to an external hardware programmer through connecting pads left exposed on the outside surface of the paper.

The final design probe described in this chapter address chemical transformations, the least explored properties of programmable materials.

## **5.5 Cornucopia**

Food is one of the fundamental ingredients of life. We cannot go a day without it before experiencing discomfort and the kinds of food we eat and how we eat them are closely intertwined with our cultural practices, physical environments and personal health. Nonetheless, we have been cooking progressively less. While digital media has transformed every facet of society, the fundamental technologies we encounter in the kitchen today provide only incremental improvements to the

tools we have been using for hundreds of years and don't take advantage of the programmability we find in other design disciplines.

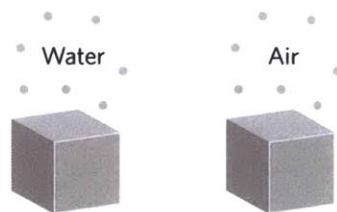


Figure 6. Gustation and olfaction transformations are the least explored programmable material properties.

In order to bring our cooking technologies to the digital age, Amit Zoran and I have developed prototypes and concept designs that examine how digital fabrication technologies and food can be combined (Zoran and Coelho, 2011). The designs we have conceived address the three fundamental processes that lie at the heart of cooking, namely the mixing of ingredients; the physical and chemical transformation of these ingredients into new compounds; and finally their modeling into aesthetically pleasing and delectable textures and shapes (Figure 7). Our hope is that these concepts and prototypes provide a glimpse at the new aesthetic and cultural possibilities, which can be brought forth by a new, digital gastronomy, while rethinking how programming can be used to manipulate olfaction and gustation.



Figure 7. Digital fabricator concept design. A food-based FDM machine.  
Rendering by Amit Zoran.

In addition to concept designs such as the Digital Fabricator (Figure 7), I have also developed the the Digital Chocolatier: a prototype for a machine that allows users to quickly design, assemble and taste different chocolate candies (Figure 8). This machine is composed of three primary elements: a carousel of ingredients, a

thermoelectric deposition cup and a user interface. Through a graphical user interface, users can select and combine the ingredients housed in the different carousel containers to create customized candies. The carousel rotates to extrude these ingredients into the thermoelectric cup that rapidly cools and hardens the chocolate, making it ready for consumption. The interface also makes it possible to save and rate favorite recipes for later use.



Figure 8. Digital chocolatier prototype (top) and interface that allows users to design custom chocolate candies (bottom).

Far from simply bringing the production of processed food to the home, the Digital Gastronomy concepts and machines described here attempt to imagine how the most advanced food technologies and techniques can be used to retain the freshness of ingredients, increase the potential for personal creative expression and develop a new and tighter connection between food production and our digital lives. We believe technologies such as these cannot only expand the material palette available to cooks today, but can also do it in a networked, collaborative

and accessible fashion, akin to the digital design and fabrication revolution that is well under way in industrial design and architecture.

## 5.6 Conclusion

In this chapter, I have discussed my programmable composite design approach and have exemplified through a series of experiments, prototypes and concept designs. In the following chapter, this design approach is further examined through three design probes, Surflex, Sprout I/O and Shutters, which explore the design of shape-changing materials units and surfaces.

# 6 Shape-Changing Surfaces

## 6.1 Introduction

Through a process of design and iteration, we continuously saturate the world with new forms and painstakingly improve on the ones which fail to meet our expectations. Nevertheless, the ability of objects to physically transform themselves is still in its infancy and remains in the realm of myths and storytelling.

Today's state of the art technology for form transformation can be found in the special effects and parametric design tools of computer animation. In these virtual spaces, surfaces can be created, destroyed and transformed to tell stories or solve dynamic engineering and design problems, while remaining impervious to the constraints of matter. However, in spite of their enormous flexibility, virtual forms still lack the sensorial engagement we encounter when directly interfacing with the physical world.

In this chapter, I present a foundation for the design of shape-changing programmable surfaces that are based on spatial material units distributed in lattice arrangements. I provide a survey of shape changing materials and their dynamic properties, define the concept of soft mechanics, and describe a soft mechanical alphabet which provides the kinetic foundation for the design of three design probes: Surfex, Sprout I/O, and Shutters. These probes explore how individual *soft mechanical elements* undergo spatial transformations and can be combined to create large-scale transformable surfaces, which can alter their topology, texture, and permeability. I conclude by providing application themes for shape changing materials in human-computer interaction and directions for future work.

Before looking at the future of shape change, it pays off to briefly look back at the past and understand how the kinetic materials we use today have come to be the way they are.

## 6.2 The Mechanisms of Shape Change

Mechanical systems have been around since at least Archimedes' times and in spite of having evolved considerably up to now, benefiting from revolutions in

materials, power and miniaturization, the machines we use today are still very similar to their predecessors. And there is a good reason for this: the capabilities of machines are inherently constrained by the materials from which we build them.

In the 18th century, the Swedish engineer Christopher Polhem invented a mechanical alphabet, which consisted of a large collection of mechanical devices. Polhem believed that with just five vowels—the lever, the wedge, the screw, the pulley and the winch—and more than 70 consonants he could construct every conceivable machine. He went on to identify and fully describe the entire mechanical design space of his day and his work had a strong and direct impact on the training of engineers which is still influential (Strandh, 1988). Nonetheless, Polhem's machines helped perpetuate an inherent limitation: they were designed to be primarily constructed from materials such as wood or steel, where material rigidity and strength are desirable qualities. Building upon the ancient simple machines, these designs were predicated on the assumption that their mechanical elements are rigid, and that variations on their flexibility and shape hinders functionality by adding unnecessary friction or stress where they are not desired. Materials were seen by Polhem as static substrates from which to build complex systems, rather than dynamic and responsive elements, which could change their properties on demand and adapt to ever changing design requirements. On the other hand, form and its ability to change in nature are the result of a harmonious orchestration between elements with disparate and changing physical properties. As observed by D'Arcy Thompson, the human body is neither hard nor soft, but a combination of muscles, bones, tendons and ligaments which make up the complete load-bearing actuation structure that allows us to walk, resist the pull of gravity, or write this document (Thompson, 1992).

This material restriction is no longer relevant today but continues to inherently constrain alternative design possibilities, where, for instance, a mechanical element could change the elasticity, shape or conductivity of its alloys to respond with a more adequate behavior to its changing environment. In the following section, we have gathered a short compendium of the unique properties of shape changing materials, hoping to shine some light on the new opportunities they offer for the design of mechanical systems.

### 6.3 Shape Changing Materials

Shape changing materials are materials that undergo a mechanical deformation under the influence of direct or indirect electrical stimuli. They are by nature dynamic, in addition to the static properties that we find in other conventional polymers or alloys. While materials science literature is replete with examples of shape changing materials, which promise one day to revolutionize the way we build things, most of these materials are in early stages of development and only a few are sufficiently mature today to be reliably implemented.

## Survey of shape changing materials

The comparative table below serves two primary purposes: to give designers a starting point and overview of what material capabilities are available today; and, most importantly, to generalize, compare and extrapolate the core relevant properties which can help guide the selection and use of these materials. This table is in no way comprehensive. I have purposefully chosen to list the more common and accessible materials. Also, I have omitted from this list materials that are pH or light controlled, and whose mechanical properties cannot be triggered by a direct or indirect electrical stimulus, due to the difficulty of interfacing them with the control electronics necessary for computer controlled applications.

Material	Direct or indirect electrical stimulus	Keeps shape when stimulus is removed	Displacement	Number of 'memory' states	Force
Shape Memory Alloy	heat	no	large	1 (or 2)	high
Magnetic Shape Memory Alloy (Ni <sub>2</sub> MnGa)	magnetism	no	large	2	high
Shape Memory Polymer	heat	yes	large	1	weak
Piezoelectric Ceramic	electric	no	small	2	high
Dielectric EAP (e.g. Dielectric Elastomers (DEs))	electric	yes	large	2	high
Ionic EAP (e.g. Ionic Polymer Metallic Composite (IPMC))	electric	no	large	2	high
Magnetostrictive (Terfenol-D)	magnetism	no	large	2	high
Electrostrictive (Lead Magnesium Niobate (PMN))	electric field	no	small	2	small
Thermoplastic	heat	yes	large	1	weak

## Properties of shape changing materials

In order to clarify how material properties can limit, constrain and generally affect the design and behavior of shape changing objects, I list and compare in this section the properties of shape changing materials which are most relevant to designers today. It is important to note that these properties are intrinsically connected to each other. In order to design a material that maximizes a specific

quality, it is crucial to understand how it might affect the performance of other properties.

- **Deformation Strength and Power Requirement:** These properties are inversely proportional and play an important role in limiting things such as size or mobility, much like in the design of traditional actuators. For instance, shape memory alloy (SMA) wires drawn in large diameters are incredibly strong, but their power requirements increase considerably as their size goes up, making their untethered use impractical. Power requirements also play a role in determining how the material should be interfaced to electronic circuitry and controlled.
- **Speed and Resolution:** These properties determine the frequency and precision with which a material can be controlled. Materials with a linear response, such as piezoelectric films, can be controlled with fine precision and be used in microscopes or small linear actuators, while electrostrictive materials are fast, but non-linear, making it harder to control finer movements with precision.
- **Number of Memory Shapes:** The number of active memory shapes determines how many physical configurations a material can take and if it requires a counter-actuator to return to its original shape. Certain electroactive polymers (EAP), for instance, have two deformation shapes and can be controlled to cycle from one to the other, while an SMA only has a single usable shape memory and requires an external actuator to return to its original shape.
- **Transition Quality:** Materials that transition from a malleable to a rigid memory state, such as SMAs, are capable of actuating other materials without requiring any external force. However, materials that transition from a stiff to a malleable memory state, such as shape memory polymers (SMP), become too weak when active to exert any relevant force on other materials.
- **Trainability:** The capacity to give a shape changing material new memorized shapes after it has been fabricated. SMAs can be trained numerous times, while SMPs can only be trained when they are originally cast.
- **Reversibility:** The capacity of the material to fully recover from the shape memory transitions without considerable decay. This is closely related to the concept of fatigue, where a material can progressively wear over time



until it loses its shape changing properties. For instance, SMAs can repeat their memory cycles numerous times, but under considerable stress they eventually start gaining a new memory shape and 'forget' the previous one.

- **Input Stimulus:** The nature of stimulus required to trigger the shape change, such as a voltage potential, pH change or heat. This also deeply influences the power efficiency as well as the infrastructure needed to electronically actuate the material or measure its degree of transformation.
- **Bi-Directionality:** The capacity of the material to change shape under a stimulus but also to generate that same stimulus when physically deformed. This is an important property, especially in the design of interactive systems where it might be interesting to sense touch and gather feedback on how a user modifies or offers resistance to shape change. Several materials are capable of doing this, such as piezoelectric ceramics which can be used as vibration sensors or power harvesting devices and SMAs which increase temperature when physically deformed.
- **Environment Compatibility:** The material's capacity to operate in the same environment as their application. For most cases, this means dry environments at ambient temperature, however, some ionic EAPs, need to be immersed in an aqueous media containing ions, such as saline solution, blood, urine, plasma or a cell culture medium, which makes them ideal for medical applications but impractical for use in everyday situations.
- **Consistency:** A material's physical state (whether it is a solid or liquid) plays a role in the kinds of application it enables and infrastructure required for using it. Liquid shape-changing materials for instance, such as ferrofluids and magnetorheological fluids, need to be encapsulated inside other solid structures that can prevent them from leaking or coming in contact with other substances.

### Shape memory alloys

Due to their market presence, many years of practical use, and strong shape memory effect, SMAs, and Nitinol in particular, are currently the most versatile of the shape changing materials and have been used for the development of the design probes described in this paper. Alternative materials would have required different control electronics, but the overall electromechanical infrastructure used in their application would have remained the same.

SMAs are thermomechanical alloys that, once treated to acquire a specific shape, have the ability to indefinitely recover from large strains without permanent

deformation and remember their original geometry. After undergoing a physical deformation, an SMA wire can be heated through resistive heating to its final transformation temperature ( $A_f$ ) and regain its original shape.

The shape-memory effect (SME) which gives SMA their unique transformational capability is in fact a dual process which combines a transition to a memorized physical form with a transition from a malleable to a rigid state. At ambient temperature SMAs, in their martensite phase, are malleable and can be bent into various shapes, and when heated, to their austenite phase, they become rigid and remember their memorized shape. The diagram below (Figure 1) illustrates this relationship:

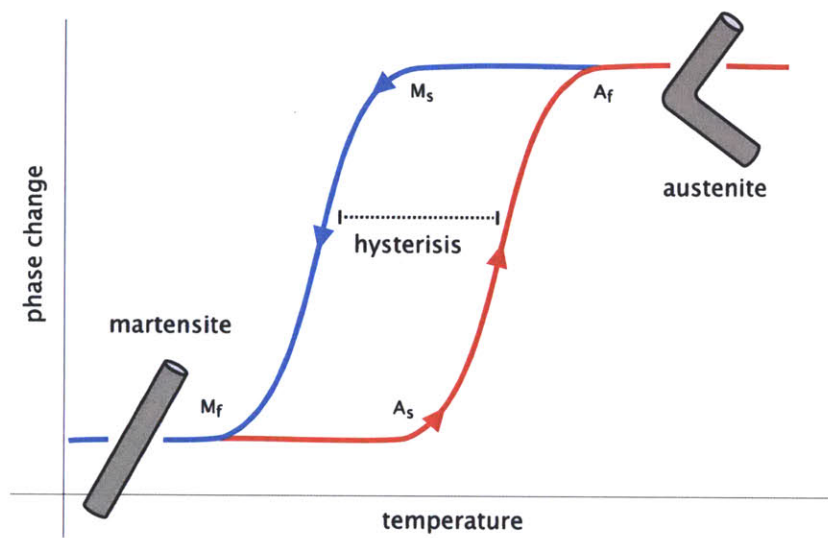


Figure 1. In its martensite state, the SMA is malleable and can be easily deformed by an applied force; however, when heated, the SMA transitions to its austenite phase, becoming stiff and remembering its 'memorized' shape.

SMAs, however, are not for all applications, and it is important to take into account the forces, displacements, temperature conditions, and cycle rates required of a particular actuator. The advantages of SMAs become more pronounced as the size of the application decreases, since there are few actuating mechanisms which produce more work per unit volume than SMAs. Moreover, SMAs present several form factors and can be used as thin films, single-wire linear actuators or be embedded into composites, where its active memory can operate in tandem with the passive memory of materials such as silicone and polyurethane foam. In the following sections, I focus on the underlying principles that allow shape memory and elasticity changes to support the design of shape changing surfaces for HCI.

## 6.4 Soft Mechanics

The term soft mechanics refers to systems based on the use of shape changing materials and their composites, which generate kinesis and physical transformation via transitions through different memory and elasticity states.

Contrary to the machines popularized by Polhem, this ability allows us to look at mechanical systems in a new light, where kinesis and transformation happen through changes in material properties, rather than changes in how different mechanical elements, such as gears or joints, come together. Soft mechanics is a powerful design approach, opening up novel possibilities for the construction of biomimetic robots (Trimmer et al., 2006) that can be squeezed flat to reach inaccessible places and then regain their shape, or for adaptive furniture (Fan & Schodek, 2007) or wearables where softness and malleability are more appropriate affordances for human interaction (Berzowska & Coelho, 2005).

For designers at large, this shift brings about new challenges, but also the potential to overcome stasis and some of the traditional assumptions we make about mechanical systems, in exchange for a more holistic approach where elements can assume different roles according to their received stimulus. For instance, structural components which rely on external actuators for movement can now become the actuators themselves, and conceptual distinctions between structure and membrane are made irrelevant by surfaces which can transition from providing structural support to enveloping a space or object.

In a similar fashion to how Polhem extrapolated a mechanical alphabet from the simple machines from Ancient times, fully transformable surfaces can be derived from the two basic ways through which real, physical materials deform: compressions and elongations. These changes in scale can take place in any three-axis configuration and can be combined to create complex forms.

In the following figures, I sketch a soft mechanical alphabet for form transformation. They show several variations of how compression and elongation lines can be combined to build simple shape changing elements.

### 6.4.1 Individual Soft Mechanical Transformations

In the first set of examples, compressions and elongations operate independently of each other to enlarge and shrink a cube.

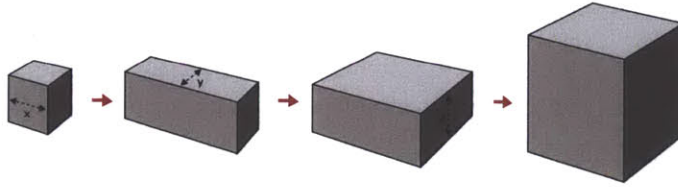


Figure 2. The cube in this image undergoes a scale transformation by consecutively elongating in one, two and three dimensions.

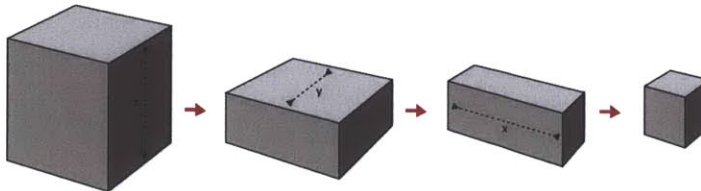


Figure 3. In this case, the reverse transformation process occurs through compressions in one, two and three dimensions.

### 6.4.2 Paired Soft Mechanical Transformations

In this set of examples, compressions and elongations act together to bend a surface into different configurations. The number of paired transformations, their angle of orientation and placement determine the overall transformation effect.

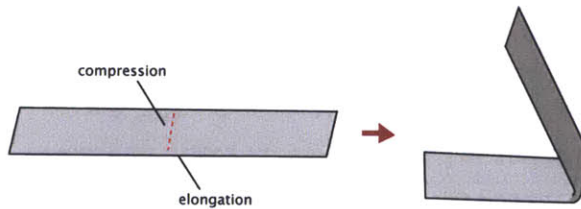


Figure 4. A single orthogonal line of a paired elongation and compression makes the surface bend.

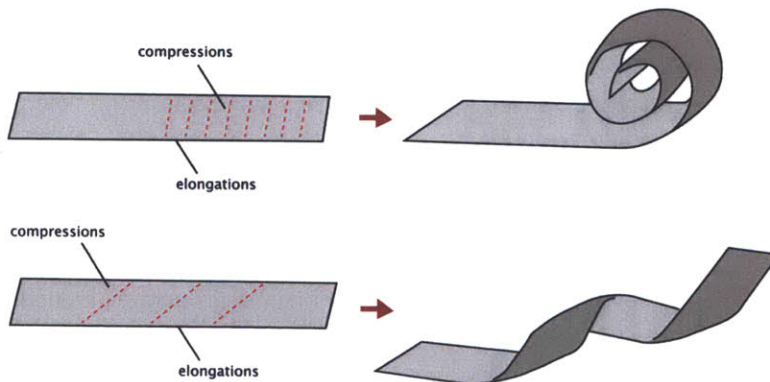


Figure 5. A series of parallel orthogonal lines of elongation and compression make the surface curl (top). Parallel diagonal lines give the surface a helical shape (bottom).

But how exactly can these simple soft mechanical elements be combined to create shape changing interfaces? In the following section, I discuss how surfaces can physically transform from one shape into another. The inherent topological limitations in their transformations provide the constraints behind the design of Surfex, Sprout I/O, and Shutters.

### 6.5 Shape Changing Surfaces

At a basic level, surfaces are very simple and only have four distinct shapes: flat, convex, concave, and saddle-shaped (Figure 6). At a convex point, a surface curves like an egg, at a concave point it curves like the inside of an egg and at a saddle point it curves like a horse's saddle providing a smooth transition between convex and concave regions. The simple compression and elongation transformations described in the soft mechanical alphabet can be combined to create each of the four surface types and these surfaces as consequence can then be tiled together to create any physical form and transform it, as long as topological equivalences are preserved.

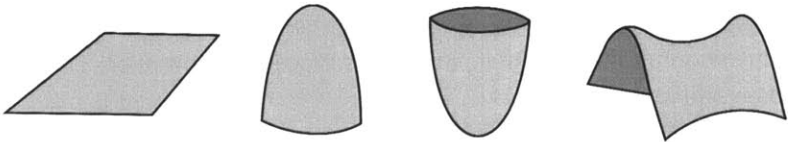


Figure 6. Surfaces shapes: flat, convex, concave and saddle-shaped.

In mathematics, surfaces capable of transforming into one another are considered to be homeomorphic or topologically equivalent. Two spaces are topologically equivalent if they can be continuously stretched and deformed into another without cutting or joining distinct parts. A common example is the topological equivalence of a donut and a mug. A sufficiently pliable doughnut could be reshaped to the form of a coffee cup by creating a dimple and progressively enlarging it, while shrinking the hole into a handle, without the need for cutting or joining (Figure 7). Homeomorphism places a considerable limit on the number of possible transformations a surface can support, but it also reveals the physical constraints we encounter when designing transformable surfaces without having to resort to constructive or destructive processes, such as punching holes or stitching surfaces together.

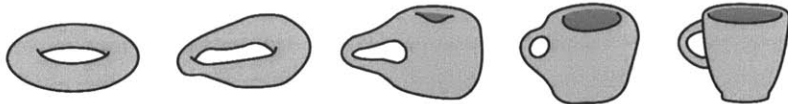


Figure 7. A pliable doughnut can be reshaped into a cup in a homemorphic transformation (Lynn, 1999).

In the digital realm, these limitations do not exist and a surface is generally regarded as a two-dimensional programmatic field: an "immaterial and pliable

two-dimensional datum with no depth or internal structure" (Taylor, 2003). Digital surfaces are unconcerned by gravity, construction, and traditional distinctions between surface and structure. In the physical world things are quite different and physical surfaces are constrained by their topological and material limitations, as well as external forces such as gravity and user control.

It is not difficult to imagine a future where designers will be able to create three-dimensional transformable surfaces by digitally drawing their initial and final states. Specialized morphing software will then pick the simplest compression and elongation elements required for building a single surface capable of physically transforming between the two states. However, due to material and homeomorphic constraints, there might still be limitations on what transformations might become possible. The design of Surfex, Sprout I/O, and Shutters are partially motivated by these constraints and the possibilities leveraged by different transformation types.

## 6.6 Topology, Texture and Permeability

According to how we perceive and interact with surfaces, and taking into account the homeomorphic limitations of materials, surface transformations can be divided into three separate types:

- **Topological transformations**, where the complete surface has a modifiable curvature and a combination of compression and elongation lines can give it any continuous shape.
- **Textural transformations**, where small shape changes at the surface boundary can give a surface new visual and tactile properties, without affecting its overall shape.
- **Permeable transformations**, where the porosity of a surface can be controlled to regulate its transparency and the exchanges between two spaces, ultimately breaking its homeomorphism.

These distinctions are relevant here in so far as they hint at how different transformations can support or hinder new interaction possibilities. For instance, Surfex proposes a material architecture in which a surface can adopt any topology by combining compression and elongations in the principal directions, much alike NURB-based digital surfaces. However, its design is limited by the fact that it cannot break its homeomorphic continuity. Sprout I/O, on the other hand, focuses on changing the tactile and visual qualities of the surface through a shape changing texture, rather than its overall topology. The lines of compression and elongation in this case are not on the surface itself, but on small protrusions

coming out of it. Finally, Shutters breaks the surface continuity by using small controllable perforations to modulate the permeability between two spaces.

### 6.6.1 Surflex: Topology

Surflex is a transformable and programmable physical surface for the design and visualization of digital forms. It combines active and passive shape memory materials, specifically SMAs and foam, to create a surface that can be electronically controlled to deform and gain new shapes without the need for external actuators (Figure 8).



Figure 8. Surflex's surface deformation in three steps.

### Dynamic output forms

Today designers have a variety of additive and subtractive fabrication techniques available to them, such as laser sintering or CNC milling, to visualize and physically create virtual objects at high resolutions. While these fabrication processes can support almost an unlimited control over the fabrication of digital forms, once objects are materialized they lose their digital and computational possibilities. They cannot be easily modified to accommodate revisions or reuse of materials and, most importantly, physical changes in a printed model are not directly updated in its virtual correlate.

Researchers have sought to address this issue by creating kinetic surfaces and interfaces for physically manipulating and visualizing digital information. Aegis Hyposurface (Goulthorpe, 2000) and Lumen (Poupyrev, Nashida & Okabe, 2007) are examples of two surfaces that use an array of pistons and linear actuators to display kinetic and three-dimensional images. In spite of the possibilities they offer, these technologies are inherently limited by the fact that they mimic surface deformations with an array of linear actuators mounted on an external plane, rather than embedding the actuation in the moving surface itself. This choice limits the shapes and angles of curvature they can create to a small set of topological transformations making it impossible, for instance, to wrap the surface around objects and bodies. Surflex is unique in that the hardware necessary to make the surface change shape is embedded in the surface, rather than being attached to a separate structure. Additionally, Surflex uses the changes in the physical properties of its materials to generate kinesis and deformations in three dimensions.

## Engineering Surfex

Surflex is constructed from 1" foam which can return to its original shape after being compressed. This substrate is pierced by 4 assemblies of 2 printed circuit boards (PCBs) each, which are connected to each other through 8 SMA springs arranged on an x,y grid.

In computer-aided design, three-dimensional surfaces are made from a combination of splines oriented in opposing U and V directions and their curvature is manipulated by pulling and tilting the splines' control vertices. In order to build a physical spline-based curve, these control vertices cannot float autonomously and need to be located on the surface itself. To address this problem, Surfex uses an array of SMA strands arranged in opposing U and V directions which act as soft mechanics compression elements that pull the surface's vertices together (in this case small circuit boards attached to the surface itself). When the SMA cools down to the ambient temperature and reaches its 'malleable' state, the foam becomes stronger than the SMA and forces the composite back to the foam's original shape. Acting as soft mechanics elongation elements, the foam uses its passive shape memory to counteract the SMAs actuation (Figure 9).

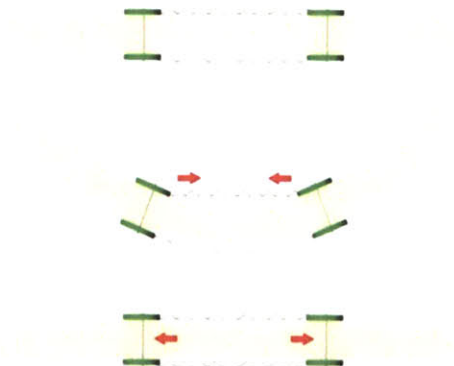


Figure 9. Surfex deformation diagram.

By combining horizontal (x) and vertical (y) compressions, it is possible to bend the foam composite into any shape in the z-plane, which allows for a range of surface deformations as broad as the ones we find in virtual surfaces.

Due to its topological configuration, Surfex is limited to homeomorphic shape changes and could not create perforations on its surface or stitch any of its edges together. However, actuating two parallel SMA strands compresses the foam without making it bend, which could allow other uncompressed parts of the surface to bulge out and protrude.



## Application

A Surfex-like material technology could be used for instance into two different kinds of applications: the real-time computer modeling of objects and programmable acoustics.

As an alternative to subtractive or additive 3D rapid fabrication processes, Surfex could be used as a tool for displaying computational models in real time. Designers could make their models in a CAD program and have that design instantly sent to a tabletop Surfex, which could reconfigure itself to represent any curve or shape, at different scales and degrees of resolution. Another possibility is modeling at a room-size scale, where a large Surfex could serve as walls to a room and quickly update to reflect different space arrangements or acoustic profiles. Walls could not only be updated overtime to reflect changes in its usage but they could even be 'played' in a similar way to how a musician plays an instrument.

### 6.6.2 Sprout I/O: Texture

Sprout I/O is a textural interface for tactile and visual communication composed of an array of soft and kinetic textile strands which can sense touch and move to display images and animations. Rather than modifying a surface's overall topology, shape change in this case is used to generate dynamic surface properties at an object's physical boundary with the external world (Coelho & Maes, 2008).

#### Dynamic texture

Surface properties, such as texture, can play an important role in how users perceive objects' affordances and interact with the information they convey. Small shape deformations on a surface can not only modify how surfaces feel to the touch, but also modulate light reflectance, color, and give us audio and visual feedback of how objects react when in contact with one another. Additionally, since texture plays a crucial role in how the surface qualities of an object are perceived, it can also enhance or counteract the overall perception of form.

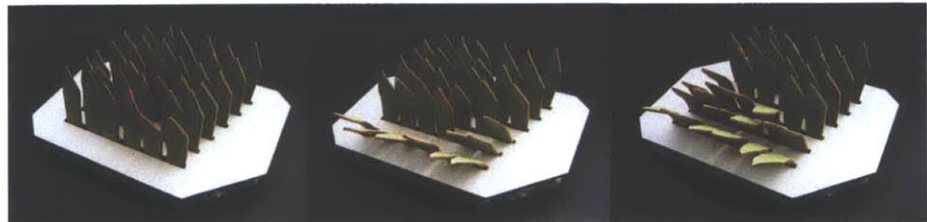


Figure 10. Sprout I/O animation steps.

Although there seems to be no definitive agreement in the visual perception literature about the specific properties of a texture pattern that are most effective

at conveying three-dimensional shapes, it is generally accepted that the shape of a smooth curve or slanted plane can be conveyed much more effectively when the surface is textured rather than left plain (Interrante, Fuchs & Pizer, 1997). Through techniques such as cross hatching, artists have repeatedly emphasized the importance of texture and stroke direction in line drawings bringing particular attention to how our perception of forms can be significantly altered by the direction of the lines used to represent them. In fact, researchers have found that a shape can be more easily identified when overlaid by a pattern with a strong directional component and when the texture is oriented in the direction of maximum normal curvature, also known as the first principal direction (Interrante, Fuchs & Pizer, 1997).

Dynamic texture has been used as a compelling alternative to current display technologies. Hayes Raffle's Super Cilia Skin, for instance, is a texturally enhanced table top membrane that couples tactile/kinesthetic input with tactile and visual output, by moving small felt tipped rods controlled by an array of electromagnets (Raffle, Ishii & Tichenor, 2004). While systems such as this enable a rich set of interaction scenarios, their level of kinesis and material affordances are limited. In Sprout I/O, actuation is part of the material itself, rather than depending on an external mechanism such as an electromagnet.

## Engineering Sprout I/O

Sprout I/O is composed of a grid of 36 textile strands (6 rows and 6 columns) that resemble grass blades (Figure 10). Each strand is made of a fabric and SMA composite and can bend in two directions (backward and forward). In this case a paired soft mechanics line of compression and elongation is located midway through a strand. When the strands are aligned up straight, the surface feels rough to the touch, and when they curve down it feels smoother. Since the two faces of a strand are made of different color fabrics, their motion can transition the surface from a dark green to a light green color.

To create a strand that could move in two directions, I 'bond sewed' a complex SMA shape onto both sides of a felt strand. To guarantee that shear between the different composite laminates would not hinder actuation, a stretchy fabric was used as the external substrate. By controlling the current running through each side of the SMA strand and localizing heat, it is possible to cause an orthogonal bend on the felt, as well as control its angle, speed and direction. While the SMA gives two-directional movement to this composite, the fabric provides structure, as well as visual and tactile quality.

## Coincident kinetic I/O

Another engineering challenge was to develop a strand that could change shape in response to touch, providing user input in Sprout I/O. To accomplish this, I used the SMA as an electrode for capacitive sensing, combining its resistive heating circuit with a relaxation oscillator and switching between sensing and actuation modes with a microcontroller.

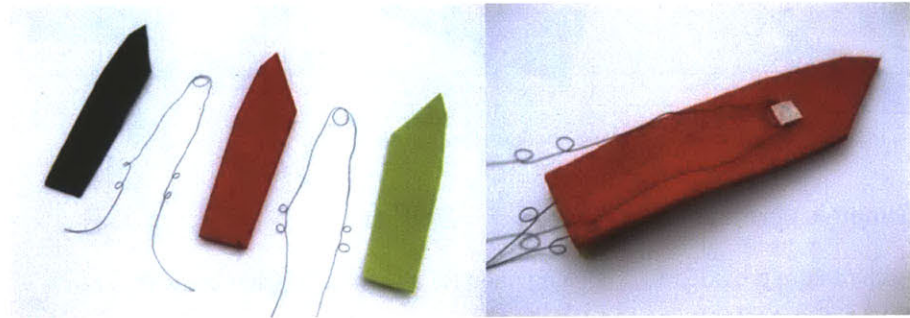


Figure 11. Sprout I/O strand construction details.

## Application scenarios

Apart from functioning as a new kind of soft and non-emissive display, applications for this technology could take many forms. I currently envision a series of different applications: display surfaces for the visually impaired which could take advantage of the textural qualities of different materials; carpets or grass fields for public spaces that could guide people to their destination or closest exit route, as well as displays for advertisement and to provide information about a game or event taking place; a robotic skin that could sense the fine subtleties of touch and respond with goose bumps to create tighter emotional bonds with their owners; and interactive clothing that could record its history of interaction or simply animate to display the mood or personality of its wearer.

### 6.6.3 Shutters: Permeability

Shutters is a curtain composed of a grid of actuated louvers (or shutters), which can be individually controlled to move inwards and outwards, regulating shading, ventilation, and displaying images and animations, either through its physical shape changes or by casting shadows in external surfaces (Figure 12).

While Surflex changes topologically and Sprout I/O changes texturally, Shutters on the other hand, changes permeability—the third type of form transformation. In Shutters I have created perforations in a continuous surface to break its homeomorphism. The resulting apertures are regulated to control the boundary between two distinct spaces, examining how kinetic membranes can be used to blur their physical boundary, rather than just modulate topological relationships.

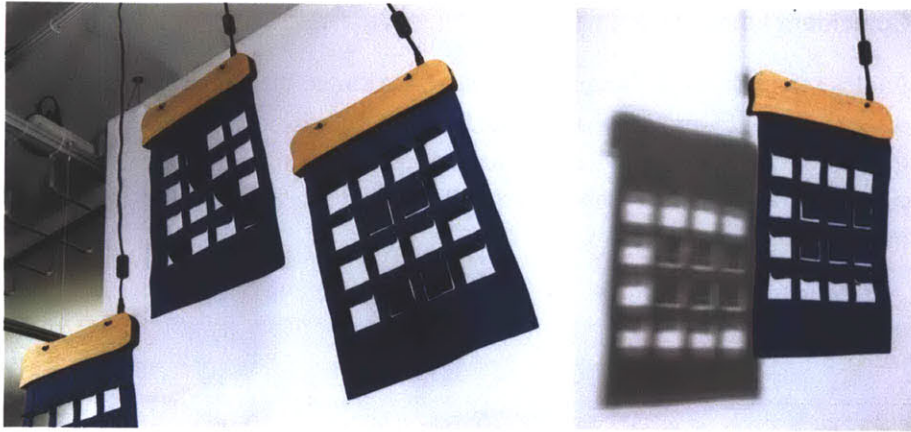


Figure 12. Shutters as a kinetic and shadow display.

### Dynamic permeability

Architecture provides a compelling need for a permeable membrane that can physically transform itself to simultaneously accommodate multiple conditions and functionalities. Spaces are affected by their exposure to the elements, which vary continuously, and 'one size fits all' louver approaches usually turn out to be inefficient or inadequate for individually regulating ventilation flow, daylight intake, or visual privacy. Moreover, people's use of space is complex and changes frequently, raising the need for an environmental control system which is equally flexible, and capable of adapting to its users.

Most buildings present some form of adjustable sun-shading element or technique (also referred to from French as *brise-soleil*, or sun-break). These can range from traditional methods, such as lattices, pierced screens or blinds, to more elaborate smart membranes that can filter out lighting and control ventilation at varying degrees with preprogrammed computerized behaviors.

The façade of L'Institut du Monde Arabe (Paris, 1987), designed by the architect Jean Nouvel, is an example of a structure carrying several motorized apertures that act as a *brise-soleil* to control the light entering the building according to weather conditions and season. In spite of their functionality and striking design, these façade panels are noisy, tend to break easily and do not provide a very scalable solution that can be easily integrated into other buildings or replaced when they fail. Most importantly, they are fully automated, not allowing residents in the building to have a high granularity of control over their own space.

Using a shape changing material to control its apertures, Shutters improves upon previous façade systems by creating living environments and work spaces that are more controllable and adaptable, while also providing information to its users in a subtle and nonintrusive way.

## Engineering Shutters

Shutters is primarily built from a natural wool felt sheet, laser cut to create a grid of 16 louvers (4 rows and 4 columns). Each louver can be individually controlled to move inwards and outwards regulating their aperture within a 180 degree shape change. Similar to Sprout I/O, the soft mechanics lines of compression and elongation are placed midway through a louver causing them to deform orthogonally to Shutters' surface and creating its regulated apertures. Shutters is constructed out of fabric so as to be flexible and easy to manipulate, while still embodying the conventional functionalities of external façade elements.

The actuation mechanism in Shutters is also similar to that of Sprout I/O, where SMA strands are embedded within the fabric substrate and electrically heated by multiplexing specific rows and columns, similar to the design of a conventional LED display. However, 'pixels' in a kinetic display cannot 'jump' from one state to another; they need to transition from being open to being closed, and vice-versa. This way, gradient scales can be achieved by addressing the louvers at different modulations or counteracting the movement of a louver by powering the SMA on its opposite side. Moreover, Shutters' 'pixels' are in fact high current resistors and need to be separated from each other with additional diodes with high voltage bias to prevent current distribution over the whole substrate.

## Application

The key to Shutters' functionality is in its ability to have a three-state control of environmental exchanges. When the louvers move outwards they allow for ventilation to pass through but due to their angle, they block daylight. However, when they are bent inwards they allow both ventilation and daylight to come in. Finally, the louvers can rest at a midpoint where they block any exchanges with the outside.

The design of a louver grid is an attempt to improve on traditional shutters to allow for the 'blades' in the same horizontal row to move inwards and outwards, and individually from each other. This flexibility opens the possibility for three important functionalities: (1) precise two-dimensional control of shading, so that the daylight can illuminate different parts of a space and be blocked from others; (2) control of the ventilation between different parts of a space by opening and closing the specific shutters necessary to regulate airflow, and finally; (3) use of Shutters as a soft kinetic and shadow display.

## 6.7 Interaction Model

In this section I look at the different ways in which users can interact with shape changing surfaces and how they can be used as a tool to enrich human-computer interaction.

As far as interaction affordances are concerned, shape change can be described as physical deformations which occur in an object or space and can be perceived and acted upon by a user. Therefore, users can perceive shape changes in four distinct ways: (1) the overall shape changes as in Surflex; (2) the external surface quality changes as in Sprout I/O; (3) homeomorphic changes as in Shutters; and (4) any combination of these changes. These transformations can be perceived directly or, as in the case of Shutters, indirectly through changes to external elements such as wind and light.

In response to a deformation exerted by a user, shape-changing surfaces can develop the following kinds of interaction with a user:

- Objects can gain a new physical shape and the transformation mapping between input and output can be amplified, dampened, modulated, or simply remain the same.
- Objects can respond with force-feedback and counteract the user's deformation.
- Objects do not respond at all, recording the user's action and applying it in some other place or context.
- Objects can constrain and limit the deformation imposed by the user.

Additionally, I have identified three ways in which shape change can be used in human-computer interfaces.

### **Dynamic forms reveal dynamic functions**

As previously discussed, surfaces and form play a great role in how we construct an object's affordances, telling a user how to touch, hold, and use an object or space. But as forms become dynamic they start to reflect dynamic functionalities. One example is Fan and Schodek's shape memory polymer chair (Fan & Schodek, 2007). Another example is Haptic Chameleon, a dial for navigating video content that can change shape to communicate different functionalities to a user. A

circular dial advances the video continuously (frame-by-frame) while a rectangular-shaped dial advances it scene-by-scene (Michelitsch et al., 2004).

### **Dynamic forms as a physical representation for dynamic data**

Another scenario is the use of form transformation as a representation for dynamic data. Shape changing interfaces can communicate information by: (1) acquiring new forms which in themselves carry some kind of meaning; (2) using motion as a way to communicate change; and (3) providing force-feedback to a user.

These methods can be used to communicate the current state of an object or some external information completely unrelated to the form and context of the object. Lumen, described earlier, is an example of a display that use kinesis as a way to change shape and display information. Lumen can communicate data to a user visually or through tactile feedback (Poupyrev, Nashida & Okabe, 2007).

### **Dynamic forms guide and limit dynamic physical interactions**

Physical constraints are sometimes pointed out as being a drawback of tangible interfaces when compared to the more versatile graphical UIs (Michelitsch, 2004). However, these constraints can help a user learn an interface or system; they can be catered to support specific tasks or goals; and physical limitations in shape and movement can portray limitations in digital data. Topobo is an example of a construction toy which uses motion, kinetic memory and the constraints and relationships of its parts to teach children about balance, relative motion and coordination (Raffle, Parkes & Ishii, 2004).

These scenarios are not comprehensive. They are used here to give examples of how, in spite of their tangibility and inherent limitations, transformable physical forms present great advantages over their digital counterparts or similar physically static equivalents.

## **6.8 Future Directions**

Shape change is not a new topic in design, but it remains largely unexplored in human-computer interaction due to technical challenges and the relative lack of information regarding its value. To conclude this chapter, I outline some possible directions for future research.

## Shape change parametric design

As shape changing materials improve, the need to simulate their transformational properties will only increase. Current parametric design tools allow for the creation of complex three-dimensional forms, which can adapt in response to changing conditions and parameters, or provide multiple design variations based on a set of defined rules.

Future design tools will need to extend this potential for adaptability and support the design of physically transformable surfaces. Designers will require tools to automate the selection of the soft mechanical elements necessary to generate a transformation between multiple forms.

## Morphable interfaces

A promising application domain for shape changing surfaces is the design of physical interfaces that can physically change to accommodate different users, uses, and contexts. When compared to the versatility of graphical user interfaces, one of the drawbacks for tangible user interfaces is their physical limitations and the fact that they are rarely generalizable or scalable. However, as computer interfaces become fully capable of changing shape and reconfiguring themselves the dichotomy between graphical and tangible user interfaces will become increasingly obsolete and these limitations could be overcome. With advances in shape changing materials, tangible interfaces could dynamically morph to accommodate contextual information, body language, gestures, and user interests perhaps mimicking the way that animal forms are the evolutionary result of forces such as gravity or surface tension.

## 6.9 Conclusion

In this chapter, I have presented the design principles for the creation of shape-changing programmable surfaces. This exposition progresses from the specific material properties of shape-memory alloys towards the development of more complex transformable surfaces, embodied in the implementation of three distinct surface prototypes. In the following chapter, I look at Six-Forty by Four-Eighty and the use of light as a material for the development of programmable surfaces.



# 7 Amorphous Display

## 7.1 Introduction

Light is an intangible physical phenomenon which plays a critical role in how we perceive and define the properties and boundaries of our surroundings. Surface variations in color, luminosity and scatter, and their relation to other surfaces, informs us about the depth, scale, movements and material composition of the physical world; and most importantly, the careful manipulation of light provides a powerful medium for emotional and symbolic representation.

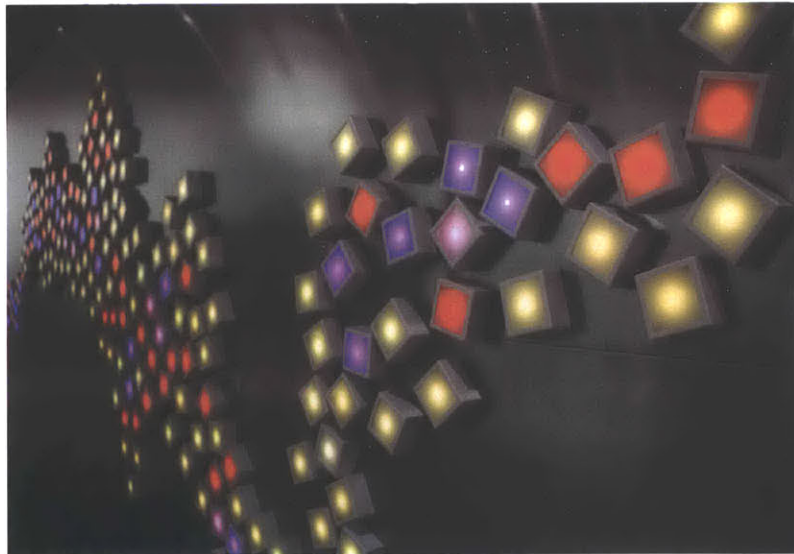


Figure 1. Six-Forty by Four-Eighty installation. Optical emission material units, which are stochastically distributed.

For millennia, we have developed increasingly advanced techniques for precisely and efficiently distributing and controlling light in our spaces. Nonetheless, light still remains far from being a tangible material substrate that can be easily overlaid onto our surfaces. In order to examine the illumination and information capabilities of a tangible light material, I have developed Six-Forty by Four-Eighty: an installation composed of autonomous, light-emitting physical pixels.

While in the previous chapter we have looked at the spatial transformations of programmable materials distributed on a lattice, this chapter focus on the optical properties of an stochastic distribution. I discuss related work, the design principles and motivations behind the development of Six-Forty by Four-Eighty, potential applications for reconfigurable illumination and displays, and how a particulate light source affords new interaction modalities. The deployment of Six-Forty by Four-Eighty in varied exhibition contexts provides final insights into its capabilities and design trade-offs.

## 7.2 Design Goals

Six-Forty by Four-Eighty was created to technically and conceptually explore light as a material that can provide both functional illumination and information. As an intangible phenomenon, light is fundamentally independent of its material embodiment and new form factors for programmable light surfaces open new opportunities for manipulating our spaces and interfacing with computer mediated information.

### 7.2.1 Illumination

Light fundamentally dictates how we parse and experience the physical world. As a building material, strategic use of light can shape people's perception of depth, the relationship between foreground and background and the volumetric characteristics of form (Seitinger, 2010).

Before the electric lightbulb, illumination was either provided by nature — sunlight or moonlight — or by our ability to harness flame. This imposed a particular set of constraints on architects and designers seeking to use light for both its practical illumination purposes and also for its dramatic effects. For instance, advancements in building techniques such as the vaulted arch and flying buttresses allowed for the thinning of walls and greater flexibility in the placement of windows and openings. This freedom allowed architects to deliberately use natural light to illuminate and draw attention to certain objects and spaces. A noteworthy example is Hagia Sophia's clerestory which gives its dome the appearance of floating in space. With the advancement of techniques for controlling and delivering light, windows were supplemented with complex network systems. At the onset of the Industrial Revolution, the need for longer work shifts, that could extend beyond the limits of natural daylight, required factories to be outfitted with complex networks of pipelines, gasometers and valves that could provide gaslight illumination (Seitinger, 2010). These technologies were then later replaced by electrical wires, switches and the generators we find in most buildings today.

Over the last century the form factor of our light sources and our ability to control them has increased dramatically, as evidenced by the multifaceted range of

alternatives, such as fluorescent light bulbs, light-emitting diodes, or electroluminescent panels. However, in spite of its importance in shaping our experience of the material world, our interface to these light sources is still highly decoupled from its material instantiation and inherent properties. Light switches on a wall are used to control light sources on a ceiling with obscure physical mappings. Motion sensors can trigger lights based on people's presence within a space but cannot accommodate flexible work schedules and the complex uses of shared spaces.

As we advance our ability to create light sources with different form factors and capabilities, this is bound to change. Six-Forty by Four-Eighty was designed to function as a light particulate whose affordances resemble those of materials such as bricks or tiles, which can be arranged to create surfaces at will. This particular form of physical instantiation allows Six-Forty by Four-Eighty pixels to be physically rearranged and sculpted, while also preserving the remote and aggregate forms controls we find in computer and television displays.

## 7.2.2 Communicative

Aside from its indirect role in communication by modifying how we see and engage with the physical world, light can also be directly manipulated to convey information.

The use of light as an information medium can be traced back to Ancient times. In the twelfth century BCE, the Greeks used fire beacons strategically placed on mountain tops to relay to short messages, which could be observed from watchtowers twenty miles away. The transmission of information, in this case, required considerable planning, labor and dedicated resources, and its meaning had to be determined a priori, being condensed into a single binary choice: fire or not (Gleick, 2011).



Figure 2. Pixel Pour 2.0, by Kelly Goeller.

With the development of the cathode ray tube and its use in television, electrically-controlled, structured light became one of the primary forms of asynchronous human communication at a distance, having a profound cultural impact. Computers later embraced this technology as its primary mode of output and this partitioning of light space into a rigid, pixelated grid has remained our de facto standard for interfacing with bits, pervading throughout all forms of visual representation (Figure 2).

At its most primitive level, a single point source such as an LED can provide with only one color 24 easily identifiable messages by modulating its intensity and rate of change (Figure 3) (Harrison, 2012). Traditionally used as a way to indicate intangible and invisible events in a device, a point source is characterized by being sequential and non-persistent (similar to audio, speech and haptics), where a viewer is required to remember how it has changed.

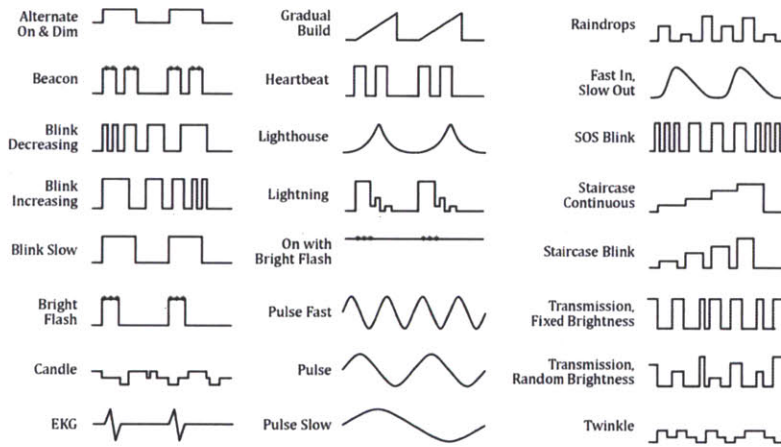


Figure 3. 24 proof-of-concept light behaviors (Harrison, 2012).

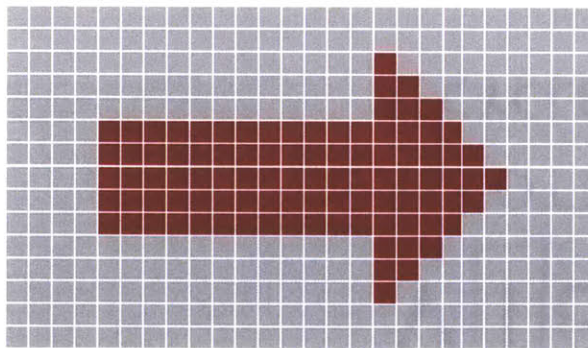


Figure 4. In this illustration of a rectangular display, only the red pixels forming the arrow provide information, while the grey pixels could be easily discarded.

At the other extreme, multiple point sources such as those found in an LCD, CRT or PDP do not require information to be displayed sequentially and allows a viewer

to scan a grid of lights in search for information. Conventional displays provide high information density, but are inflexible in terms of their resolution, scale and shape. Additionally, their uniform pixel distribution bears no relation to the actual spatial distribution required by the information itself (Figure 4).

Six-Forty by Four-Eighty is an attempt to implement a display that is not bound by a grid and where pixels can be added or condensed as needed, depending on the kinds of information displayed. If you need more resolution, you just pack pixels tighter together and if you need more information, you use more pixels.

### 7.3 Related Work

Six-Forty by Four-Eighty was originally developed as an installation to be exhibited at Design Miami's 2010 fair in Basel, Switzerland. Commissioned as a piece that could allow viewers to experience and reflect on the the future of industrial design, it sought to provide a first glimpse at the aesthetic and interactive possibilities at the convergence of visual displays and programmable matter.

Originally coined by Toffoli and Margolus, the term programmable matter describes a "three-dimensional, uniformly textured, fine-grained computer medium" (Toffoli & Margolus, 1990) (Sun, 2012). Its first hardware implementation was CAM-8, a computer workstation designed to perform simulations of dendritic growth, fluid dynamics of lattice-gas models, and image processing techniques, among others. Over the years, programmable matter research has expanded to include the development of interconnected robotic modules (Murata, 2002), shape-changing surfaces that can fold into distinct shapes (Hawkes, 2010), and materials engineering.

In human-computer interaction research, the dream of turning pixels and computers into tangible, graspable artifacts is far from new and has continuously sought new implementation techniques as technology advances. In this section, I introduce a few noteworthy works which have provided both conceptual and technical inspiration for the design of Six-Forty by Four-Eighty.

An early example of material pixels is John Frazer's Universal Constructor, an assembly of stackable physical pixels which can communicate with each other on a lattice and be used to model interactive environments and structures (Frazer, 1995). In a similar vein, Kelly Heaton's Physical Pixel Project focuses on the convergence of physical sculpting and computer animation by developing light orbs and cubes that are networked and respond to touch (Heaton, 2000).

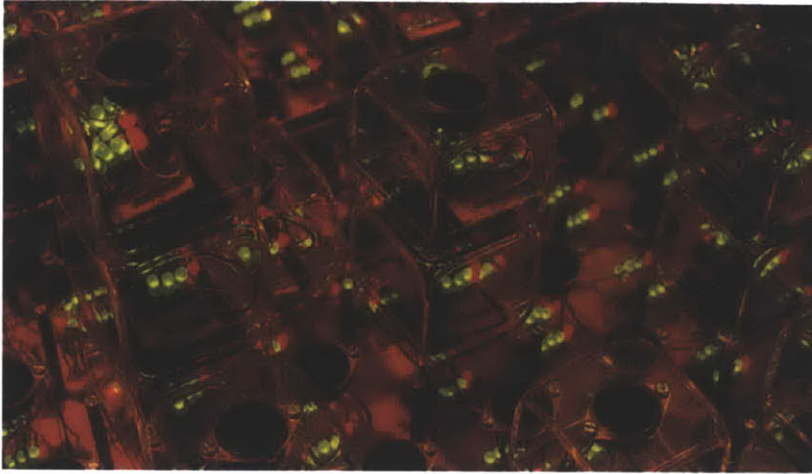


Figure 5. John Frazer's Universal Constructor.

As far as a global surface behavior develops from the aggregation of several light pixels, Six-Forty by Four-Eighty was also inspired by Pushpin Computing, Urban Pixels and Siftables. Pushpin Computing, developed by Josh Lifton, is a hardware and software platform used for the research and development of algorithms for distributed sensor networks (Lifton et al., 2005). Each material pixel, or "pushpin", sensor node is a self-contained computer which uses a series of different expansion modules, including acoustic and light sensors which allow pixels to localize themselves through time-of-flight measurements.



Figure 6. Pushpin Computing.

Susanne Seitinger's Urban Pixels has brought these ideas to the scale of the city and implemented wireless, solar-powered lighting units that influence how we experience the city as a display (Seitinger, 2010). Due to its scale and implementation strategies, pixel locations are determined a priori and hard-coded into each material pixel and an external computer coordinates global behaviors through a radio channel.



Figure 7. Urban Pixels by Susanne Seitinger, on a building façade.

David Merrill and Jeevan Kalanithi's Siftables is a set of self-contained, interactive electronic tokens that can display visual feedback and can be manipulated gesturally by users as a single, coordinated interface (Merrill, 2009). Siftable tokens are outfitted with infrared transceivers for lateral localization and are connected to a host computer which determines how their physical proximity and connections affect their behavior.



Figure 8. Siftables tiles.

During the design of Six-Forty by Four-Eighty, we have chosen to focus on what we believe are two fundamental properties of future, interactive programmable

matter: (1) that physical materials can concomitantly operate at global and local scales depending on the spatial proximity, perspective, and level of physical engagement of the user; and (2) that due to its physicality, it is important for the user's body to play a role in how computation metaphors cross differing levels of perspective and engagement.

In order to implement a physical 'copy-and-paste' capability, we built upon two different works, namely: the Personal Area Network project developed by Thomas Zimmerman, wherein handshakes are used to transmit data between two users (Zimmerman, 1995); and Jay Silver's Drawdio, in which people can draw resistive networks with a paintbrush, and by touching different parts of such a drawing one can modulate a sound output (Silver, 2009).

Finally, this work has also drawn inspiration from the work of visual artist and photographer Vik Muniz, who composes images from unorthodox materials. Muniz provides viewers with an experience wherein the work presents a subject when viewed from far away, but reverts to its materiality when viewed up close, interlacing a deeper connection between the represented subject and the medium chosen to represent it (Muniz, 2005).



Figure 9. Action Photo I (after Hans Namuth) from the series Pictures of Chocolate (1997-98) by Vik Muniz.

## 7.4 Optical Material Unit Technology

The challenge of developing a programmable light surface starts at the creation of a single material unit. In Six-Forty by Four-Eighty, units are self-contained and autonomous physical objects, whose form references the rectangular field of color most people associate with a "pixel" while their behavior evokes materiality. Different from "virtual pixels", these material units can be grabbed, moved and re-



arranged in space; when touched, their colors change and are transmitted to other units through our bodies; and a remote control can directly change the frequency and sharpness with which the light changes.

This section describes the industrial design, hardware and software behind a single pixel and is followed a subsequent section describing the infrastructure necessary for their global, aggregate behavior.

### 7.4.1 Industrial Design

The industrial design principles behind Six-Forty by Four-Eighty were elicited from the necessity to create a piece that conceptually communicates to an audience the latent possibilities of physical computing, while providing a new material embodiment for light emission.

#### Form

Six-Forty by Four-Eighty is composed of 220 material pixels, made from custom electronics enclosed by an ABS and polycarbonate 3" x 3" x 1.5" box. Its front facing surface is covered by a special light diffuser and ITO (indium tin oxide) glass composite for data transmission and body communication. Internally pixels are outfitted with a lithium polymer rechargeable battery, rare earth magnets so it can be attached to ferrous surfaces, a spring loaded pin for ground coupling, and a custom-designed circuit board responsible for its interactive behavior and functionality.

The form and dimensions of the pixels were chosen to fulfill a set of requirements: First, it was important that they be easily graspable by a person, so they can be moved and rearranged in different physical configurations. Second, the height of a pixel was determined experimentally to provide the correct distance between the diffuser-ITO composite and the RGB LED which provides its illumination. Third, its corners are filleted to be inviting to touch, and a flat base provides stability when placed on a ferrous surface. Fourth, the cube shape was chosen to allow for close packing in a square lattice distribution (*opus regulatum*), referencing the orthogonal grid of a computer display.

Different pixel form factors, which could afford different distribution arrangements were also explored. For instance, a circular shape was chosen to afford a hexagonal lattice distribution, closer to the pixel form-factor found in CRT displays (Figure 10). The choice of lattice distribution plays an important role in how displays are capable of rendering images. LCD screens with square lattice distributions are capable of displaying horizontal and vertical lines without a need for antialiasing, but render diagonal lines with a fuzzier appearance (Figure 11).

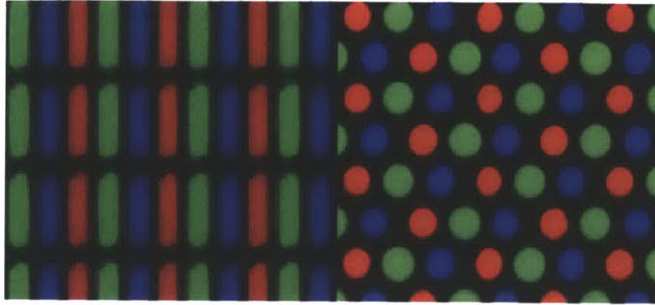


Figure 10. Close-up image of rectangular LCD subpixels (left) and circular CRT subpixels (right).

Hexagonally distributed displays, on the other hand, are ideal for displaying diagonal lines and either a vertical or horizontal row, but never both, since one of them will require a higher degree of anti-aliasing interpolation.

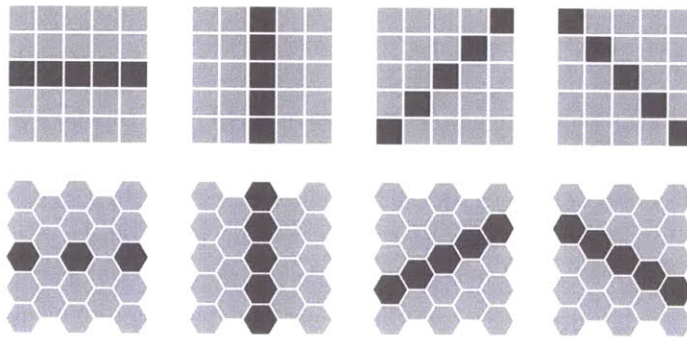


Figure 11. Vertical, horizontal and diagonal lines rendered through square and hexagonal pixels.

### Enclosure Fabrication

The pixel enclosure is divided into two parts: a top part which provides a cover for the electronics and surface for people to grab and move the pixels; and a bottom part which houses the electronics and primary components. They were designed for rapid injection molding which was performed by Protomold with aluminum molds, ideal for low-volume productions.

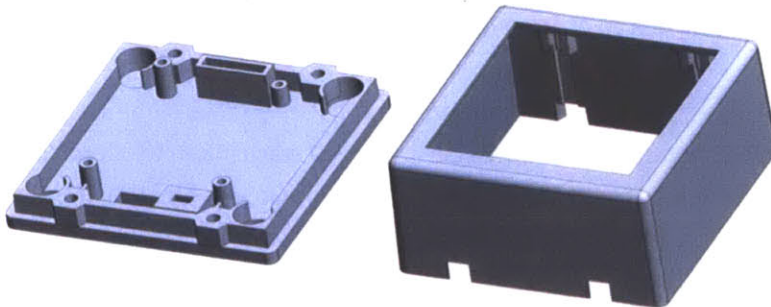


Figure 12. Bottom enclosure (left) and top enclosure (right).

The chosen finish for the enclosure is a SCI-PI, which removes toolmarks from the part while providing a semi-gloss look. The material is a combination of a white ABS and polycarbonate polymer created by Bayer and called Bayblend T65-000000 (Bright White 4% (UN0005) ABS/PC), providing a balanced compromise between cost, part rigidity and aesthetics.

### Diffuser

The pixel light quality and its ability properly diffuse light was probably one of the most important parts this design to communicate the idea that each material pixel represented a traditional display pixel from an LCD screen. In order to conceal the LED source, we experimented with different kinds of diffusing elements and settled on a flashed opal glass, which creates a soft light cone capable of completely filling the square window of the pixel in dimly lit environments. OLED tiles, such as Philips Lumiblades, could have provided a more ideal light quality, however at the present time a single OLED element is not capable of displaying the primary RGB colors. The diffuser glass was then laminated to a Pilkington TEC 7 conductive glass (a glass infused with ITO while molten). The edges of this glass composite were sealed from dust with a conductive copper strip that was also connected with a wire to the capacitive touch sensing and data transmission circuits located on the bottom enclosure.

### Finite Element Analysis

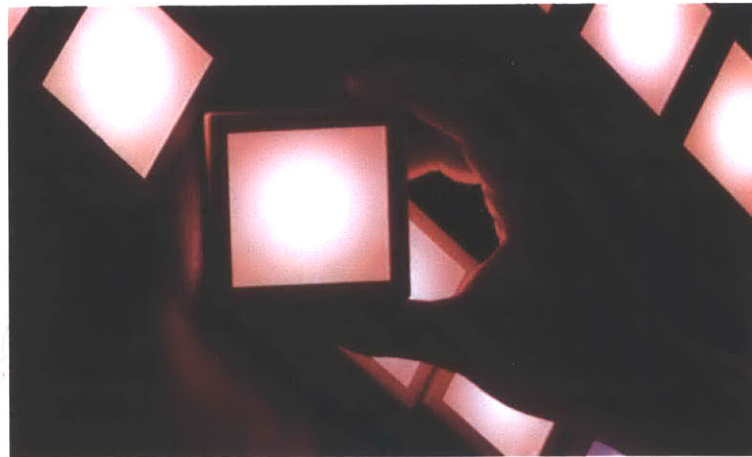


Figure 13. Typical pinch-grip.

When moving the tile, users normally grasp the case in a pinch-grip, where fingers are on one side of the case and the thumb is on the other, without the palm of the hand touching the enclosure. A pinch-grip is generally considered to be weaker than other grip positions and the maximum force applied by this type of grip ranges from 18 to 45 pounds, at a mean of 26.6 pounds (Mathiowetz, 1985).

Six-Forty by Four-Eighty has been exhibited extensively and it was crucial that the enclosure could last through continuous and rough use, as well as consistent dropping which happens when people are moving pixels on a vertical surface. In order to assess potential stress and failure points, I have performed finite-element analysis studies of the final bottom and top enclosure assembly, since their coupling undoubtedly affects the amount of stress and displacement that loads exert on the pixel. The fixture points in this analysis are located where the cases are fastened together by screws through the small perforations in the bottom enclosure. This is the region of the case assembly with most material and more likely to be rigid.

Due to the fact that the bottom enclosure constrains and provides extra rigidity to the top enclosure, the stress and displacement are localized at the top rim of the pixel where the ITO glass is inserted. The displacement in this area is negligible, roughly  $1.89\text{e-}001$  mm (or  $3.78\text{e-}001$  mm total across the case), which would most likely not cause any problems or even be noticeable to a user handling the case, however it is interesting to notice that this has been the only failure point in the enclosure design. The diffuser and ITO glass are glued to the underside of this rim and, out of 220 enclosure assemblies we have built, about 10% of the glasses have broken off after considerable use. This is primarily a result of people pressing the glass to make the pixel change color but also an indication that loads applied during handling might displace and weaken the diffuser and enclosure bond over time.

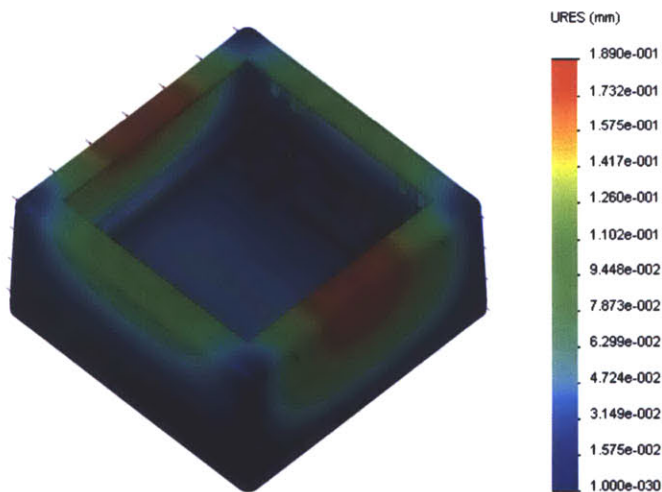


Figure 14. Finite-Element Analysis Simulation.

## Assembly

Excluding electronic components, a pixel is composed of 27 parts, which can be divided into four primary subassemblies: glass composite; top case; bottom case; and electronics; which are assembled through four main stages. Most of its

functional elements are located in the bottom enclosure and electronics, while the top enclosure provides the pixel's form factor and support for the glass composite which acts as a capacitive antenna and light diffuser.

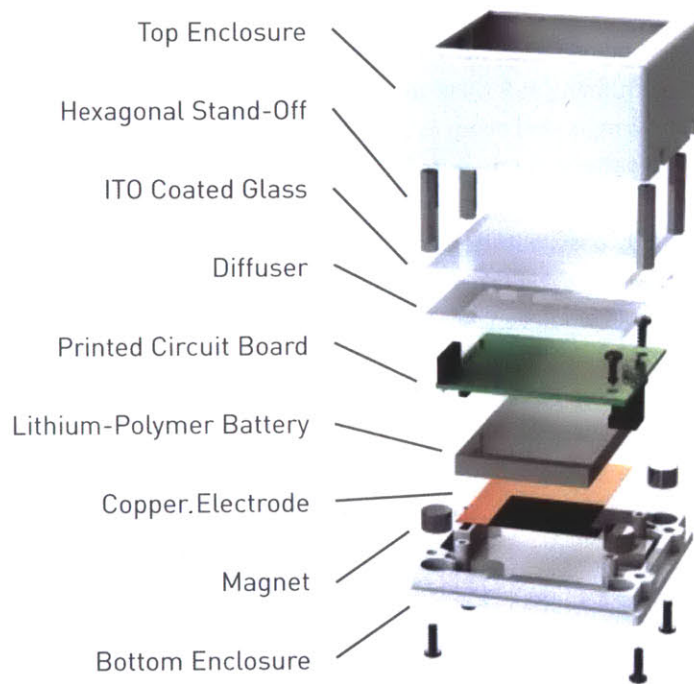


Figure 15. Pixel anatomy.

### Support Surface

Six-Forty by Four-Eighty was designed to be shown on a vertical surface, magnetically attached to a wall or free-standing structure. In addition, the body communication technique implemented requires that the pixels be constantly connected to a ground electrode through a spring-loaded pin protruding from their bottom surface. These requirements, in addition to aesthetic considerations, impose several constraints on the kind of material and fabrication we can use for Six-Forty by Four-Eighty's support surface.

A 430 stainless steel is the only metal alloy that is concurrently, conductive, magnetic and does not rust due to finger prints and prolonged use. Mechanically, it is important that the metal surface be planar, without screws or holes, so that the spring loaded pin is always in contact, and that it does not move or buckle when viewers remove pixels from the wall. The surface of the metal sheet is treated with a #4 horizontal brush, to give it a non-reflective appearance and help conceal specular scratches. In conjunction, the bottom surface of the pixels is also outfitted with four circular silicone rubber feet to help with adhesion and prevent the ABS enclosure from scratching the metal.

## 7.4.2 Electronic Hardware

The electronic hardware for the pixels is composed of several elements: microcontroller, power regulation, RGB LED, infrared communication, and an integrated capacitive sensing and body communication circuit.

The pixel logic and behavior are performed by a AVR ATMEGA328P microcontroller running at 8 MHz and powered by a single 1700 mAh lithium-polymer battery, regulated down to 3.3 Volts by a switching regulator. At full brightness, the battery charge lasts for roughly 5 days and under a firmware sleep mode, it can extend its lifetime to 15 days. Battery charging is performed through a separate charging base, outfitted with an array of 12 MAX1555 integrated circuits. A complete charging cycle takes approximately 4 hours. The charging base is made out of maple wood veneer, in order to resemble a piece of furniture rather than a conventional electronic device, and charging state white LEDs indicate when a pixel is charging.

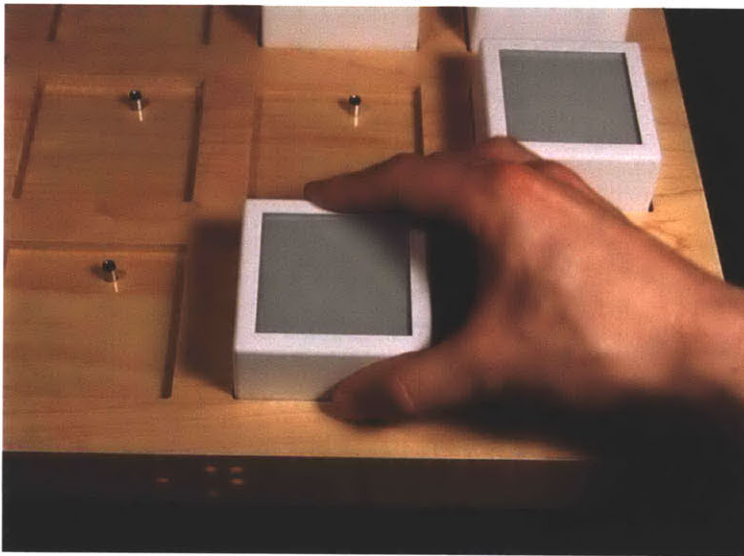


Figure 16. White LED visible through wood veneer indicates battery charge status.

The RGB light emitted by the pixel is generated by a Cree LED located in the center of the board. The choice of LED was based on its wide beam cone and low-power requirements.

Incoming infrared communication is established with a receiver unit which demodulates infrared light on a 38 KHz carrier and an Apple remote control which provides seven distinct messages encoded on a NEC infrared protocol. Running on a hardware interrupt, this communication channel allows users to switch between color palettes, change RGB LED oscillation frequency and smoothness, and put the pixels in a power-saving sleep mode. Outgoing transmissions, on the other hand,

are performed by an infrared LED emitter which can broadcast pixel status information and provide illumination for blob detection, as described in the following section.

A pixel is able to transmit its color state to other pixels through the human-body. To accomplish this, we use the diffuser-ITO composite as an electrode for capacitive touch sensing, data transmission (TX) and reception (RX), providing users with a minimal and simple interface that can handle multiple functionalities. The microcontroller cycles between the three different modes in a time-division multiplexing scheme alternating between sensing and data receiving when a touch is not being detected, and sensing and transmission when touch is detected. In order to operate these three channels through a single electrode, the microcontroller puts its idle ports in high impedance when not in use.

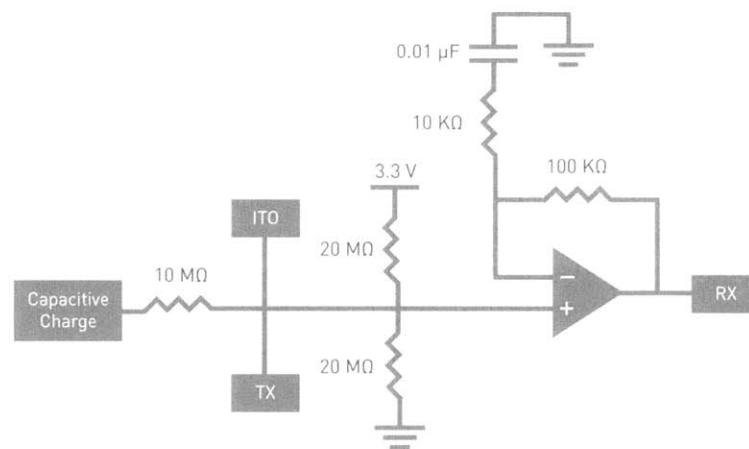


Figure 17. Pixel touch sensing and communication circuit.

The most challenging aspect of this design was to ensure consistent UART data reception that was free of noise and unaffected by the circuit's large stray capacitance. This required the use of a two-step analog amplifier, buffering and a common ground between the tiles shared through a steel back plate and spring-loaded pin located at the bottom of all enclosures. The capacitive sensor was implemented in software through loading mode, where the charge and discharge frequency is controlled through firmware, allowing for the easy calibration of its sensitivity. Similarly, the body communication was implemented with software UART at a 19200 Baud Rate. The communication rate was kept high to facilitate its differentiation from ambient noise.

### 7.4.3 Software

The pixel software was written primarily in C and C++, with support from Wiring and Arduino libraries for low-level functionalities. Its structure is asynchronous, relying on several interrupt handlers to respond to user input and to maintain pixel

state. One interrupt is triggered by a timer every 1/30th of a second and is responsible for capacitive touch sensing, handling incoming and outgoing communications, and updating the display. A second interrupt handles incoming communications from other pixels, and a third decodes incoming infrared remote control communication. Data dependency relations and differing time sensitivity between the code regions is addressed with a system of resource-locking flags.

The capacitive sensing stream and the color transmission channel are both subject to a significant amount of error, which necessitates the use of error-rejection schemes. The choice of these schemes was determined by a desire for speed and responsiveness on the one hand and a desire for accuracy on the other.

The capacitive sensing stream is noisy, subject to drift, and variable with respect to the physical handling of the pixel. These factors are mitigated successfully with an adaptive filtering and calibration algorithm. This algorithm is able to reliably detect touches as brief as 1/15th of a second in all different physical settings and can easily be adapted to detect proximity as well as touch.

The color transmission data stream for body communication is subject to a great deal of analog noise. The standard UART protocol we employ translates that analog noise into digital noise. To mitigate this, a set of permissible bytes was chosen and all other bytes were rejected. Furthermore, a strict syntax was imposed on these bytes to group them into packets. All malformed packets were rejected outright.

## 7.5 Stochastic Distribution Technology

The technologies described so far create the underpinnings of a material pixel that is highly interactive and capable of rendering a broad range of colors and pulsating states; however, they lack the higher-order level of coordination necessary for a programmable light surface to display two-dimensional aggregate images and animations, and most importantly enable new interaction modalities.

Due to the visual and interactive nature of Six-Forty by Four-Eighty, it was important to develop a location system capable of high spatial and temporal accuracy, while being invisible as to not interfere with the user experience and inexpensive for a 220 pixel deployment. To meet these requirements, I have developed an infrared communication and computer vision system for locating pixels in space and providing them with location coordinates and color data.



## 7.5.1 Hardware

The location sensing technique developed for Six-Forty by Four-Eighty consists of two core elements: (1) a base station instrumented with a camera and infrared emitter, connected to tethered computer capable of resolving pixel location; and (2) pixels instrumented with infrared receiver and emitter for two-way communication.

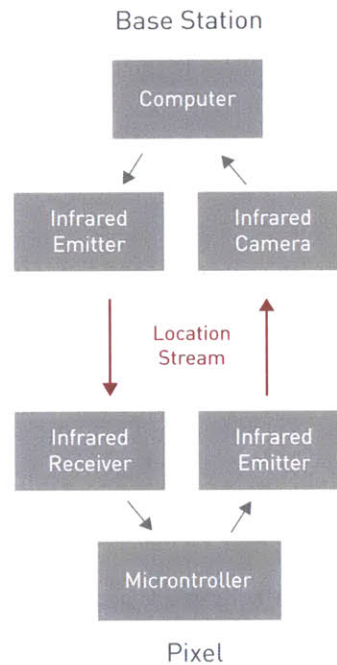


Figure 18. Location sensing infrastructure.

### Base Station

The base station is comprised of a Playstation 3 camera, modified to filter out the visible light spectrum, while allowing any infrared light to pass through. An adjustable lens allows the modification of both the field of view and depth of field observed by the camera. Parallel to the camera, a microcontroller connected to a high luminosity infrared emitter parses incoming UART data and retransmits them over infrared. Both microcontroller and camera are connected over USB to a computer, which runs a custom software for performing a background subtraction routine for locating pixels and manages outgoing communication with the pixels.

### Pixels

The pixels are instrumented with an infrared receiver which demodulates infrared light over a 38 KHz carrier and an emitter which can both transmit modulated light or illuminate the pixel so it can be viewed by the camera. One disadvantage of placing the infrared receiver and transmitter inside of the pixel is that its diffuser attenuates any light transmission. While this requires a stronger infrared emitter at

the base station to reach the pixel's receiver, it actually helps with the vision tracking, since the diffuser creates an evenly distributed infrared square which is easily trackable by the camera and computer vision software.

## 7.5.2 Software

The software is divided into three main components: a Processing **application** which performs a vision based location routine and sends over UART control commands and data to a **transmitting station**; a transmitting station which parses these commands and broadcasts them to the pixels over infrared; and the **receiving pixels** which demodulate, parse and interpret the received infrared information.

In this architecture, pixels are fairly simple elements unaware of their location within the surface aggregate. They are responsible for interpreting received color and infrared data and displaying appropriate transitions between frame targets. The software application on the other hand is responsible for the orchestration of the aggregate behavior, developing complex animations and patterns which are relayed to the physical pixels on a frame-by-frame basis. This places the more computationally intensive processes in the faster, tethered computer and distributes to the pixel simpler computational tasks.

Alternatively, other system architectures are possible for creating programmable light surfaces, bearing different sets of trade-offs. For instance, pixels could be developed without a unique identification code and location data could be relayed to them through a structured or scanning infrared light projection. As complete frame information is then transmitted to the pixels, they would be responsible for matching location and frame information to determine what needs to be displayed according to their position in space. While the chosen architecture for this thesis minimizes the computation requirements for the pixels and simplifies the location sensing hardware, the alternative architecture proposed would not require individually identifiable pixels and would be more resistant to node failures.

### Application

A Processing application is the center component in this system and is responsible for locating pixels in space, allowing users to color or animate them using a graphical user interface (GUI), and outputting a stream of data to ensure that the pixel pulses are properly synchronized.

The location sensing portion of the application works by polling pixel responses over the IR spectrum while performing an OpenCV background subtraction to locate this response. Since the pixels' RGB color is not visible with the infrared camera, frame comparisons can be done over the IR spectrum with no interference from the current animation state and color of the pixels.

This polling scheme works by first sending a command over IR to turn off the infrared channel on all pixels and registering a clear, or "empty", reference frame. It then continues by commanding each pixel to turn its infrared LED on for 30 ms, which is enough time for it to be seen by the camera which registers a new frame. By subtracting both images the application can extract X,Y location information, as well as pixel distance and orientation by looking at the size and shape of the square displayed.

One downside of this polling technique is its relative speed, since it requires at least one camera frame (1/30 s) to locate each pixel, in addition to the time required for background subtraction. In order to address this, I have implemented a binary search algorithm, where every pixel concurrently flashes its identification number 1-255 in a binary fashion (ON for 1 and OFF for 0). After capturing 8 consecutive pulses, the application is capable of locating 255 pixels in space.

Once pixels are located in space, a virtual pixel representation is displayed on the computer screen. These virtual pixels can then be manipulated by a standard graphical user interface, where users can control the pixels illumination as described in the Interaction Model section below. As modifications are made to the virtual pixels, the application keeps them synchronized with their physical counterpart by constantly streaming infrared data.

An infrared packet library has been created to streamline the process of preparing data for transmission, transmitting it, and waiting for a confirmation acknowledgment before sending another packet. Data packets are defined as illustrated below:

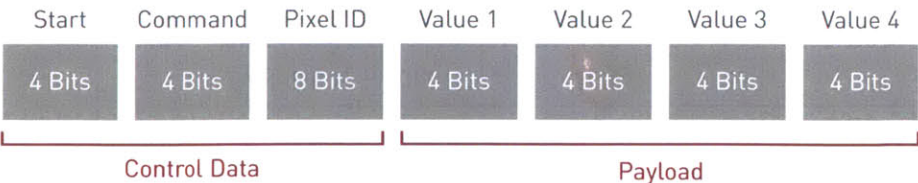


Figure 19. Data packet structure.

This data packet structure reserves 16 bits for control data and 16 bits for payload. The start nibble is responsible for indicating to a pixel that this is the beginning of a new packet to prevent any kind of data corruption caused by external IR

interference. The command nibble on the other hand is responsible for instructing the pixel on how to handle the received message. While a total of sixteen commands are possible, I am currently using only five to describe the nature of the payload — COLOR, IR, IR BINARY, STREAM, SHOW — as described in the Receiving Pixel section below. Pixel ID stores the address of which pixel the message is addressing. A value of 0 indicates that the message is addressed to all pixels. And finally, values 1-4 store information such as RGB colors, location data such as XYZ, and timing information for animations and the binary search. Under this data structure, there is not enough space available to address the RGB LED with a full 8-bit color range; however, colors are not rendered linearly by the RGB LED and a large part of this color space is somewhat redundant, since it is neither perceivable by people nor it is aesthetically interesting. A 4-bit resolution in this case is sufficient for creating 16 different steps for each color channel and create a variety of animation and image patterns.

The transmitting station is responsible for receiving 8-bit sub-packets from the Processing application through a UART link, repacking the stream as a single 32-bit long data packet, broadcasting them over infrared using the Sony IR protocol, and sending an acknowledgment byte back to the application. This guarantees that the time required to send the infrared data is respected by the application, preventing any data loss and synchronizing infrared commands with the vision tracking algorithm.

### Receiving Pixel

In this location sensing architecture, each pixel requires a unique 8-bit identification number so that they can be distinguished from each other. Incoming data is initially parsed for its start nibble, for verifying data integrity, and a pixel ID (0 for addressing all pixels or 1-255 when addressing only one specific pixel). Subsequently, the command nibble is parsed so that the pixel can perform the following functions:

Pixel Commands	Pixel Behavior
COLOR	Color information is directly sent to one or all pixels for immediate display.
IR	Pixels pulse their IR emitter at different intervals as specified by the data packet.
IR BINARY	Pixels start a binary search display pattern.

Pixel Commands	Pixel Behavior
STREAM	RGB Color information and transition pattern is sent to a pixel and is stored for display at a later time.
DISPLAY	Pixel is instructed to display its stored colors at a specific frame rate. This command is primarily used for synchronization purposes so that pixels can start their animation sequences at the exact same time.

In order to execute these different commands, pixels are pre-programmed with frame-to-frame animations so that they can switch from one color to another through linear and non-linear interpolations rendering different animation aesthetic qualities. For instance, pixels can directly blink or slowly transition from one color to another.

## 7.6 Interaction Model

The primary goal of the technology infrastructure described so far is to allow Six-Forty by Four-Eighty to operate at the both the local and global level, concurrently acting as both a material and a surface. In order to bring together these distinct interaction modalities into a cohesive interaction experience, the affordances are broken down into local, global and hybrid behaviors as detailed below.

### 7.6.1 Local

At the local scale, the pixel are designed to be interacted with in exclusively physical ways. First, a person needs to be within arm's reach of the tiles, which facilitates a sense of becoming surrounded by the installation and losing the sense of scale and behavior of the sum arrangement. From this standpoint, the tiles can be grabbed and moved around into different arrangements, and by touching their screens it is possible to make their colors change. Finally, by sequentially touching two pixel-tiles at the same time, it is possible to physically 'copy-and-paste' their colors from one to another. Six-Forty by Four-Eighty's only form of output perceivable by viewers is the light produced by an RGB LED, while input is received by direct touch. At this local scale, pixels act as an interactive particulate and elicit three forms of interaction: physical reconfigurability, individual color control and color cloning.

## Physical Reconfigurability

The pixels are magnetic and can be physically re-arranged or sculpted on a ferrous surface into two-dimensional forms (Figure 20). Physical engagement with the blocks resembles that of material such as wooden or Lego blocks which can be positioned in different configurations for creating abstract patterns, writing text, or drawing more complex forms of representation.

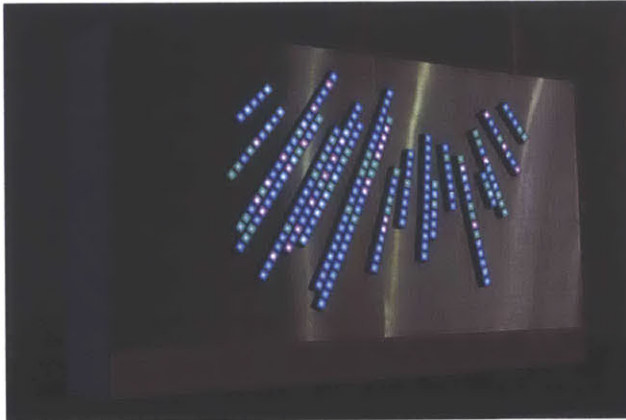


Figure 20. Pixels arranged in a diagonal striped pattern.

## Individual Color Control

Touching the pixels causes them to change color, cycling through two palettes of four pre-determined colors each. This small color selection provides enough diversity to create interesting images while also constraining the overall look of the piece to a harmonious whole. The colors palettes are divided into warm and cold colors, so its possible to work within two very distinct kinds of ambiance (Figure 21). Additionally, color transitions happen through a spring model, which gives viewers the impression of physically deforming a pliable material during touch.



Figure 21. Progressive transition from a warm palette (left) to a cold palette (right).

## Color Cloning

Touching a pixel and holding it, while using another hand to touch other pixels, 'copy-and-pastes' color from one pixel to another establishing a physical link between them. This technique allows people to quickly 'paint' all pixels with a chosen color and also allows people to engage each other in changing the pixels. By holding hands, viewers can 'copy-and-paste' colors across each other's body requiring a new level of experimentation and group coordination (Figure 22).

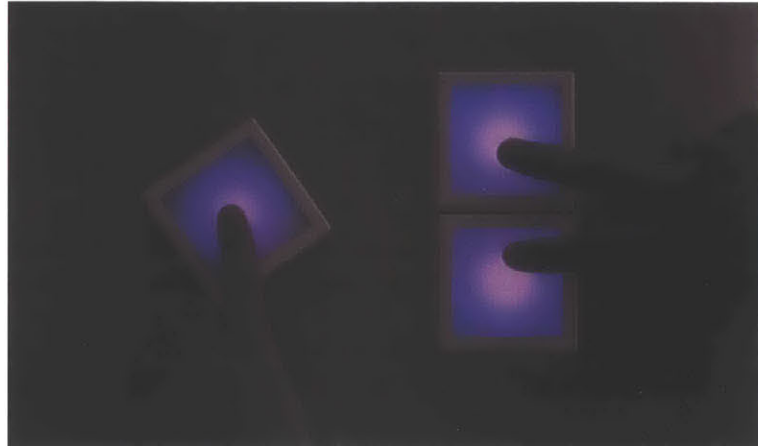


Figure 22. Left pixel transmits a purple color through the viewer's left hand, while the pixels on the right receive the same color through the viewer's right hand.

### 7.6.2 Hybrid

When a user steps back from the local level, taking a more distanced and global perspective of the installation, the intimate physicality melts away. The three-dimensionality of the enclosures disappear into darkness and the viewer sees only floating squares of light animating in unison. The global behavior requires users to control the installation as an aggregate through an infrared remote control or an external animation application. The pixels acting together foster the emergence of behaviors that cannot be perceived when one is standing up close. Additionally, the directionality of the IR beam preserves the sense of direct control but shifts its scope from operating onto a single pixels to acting upon the computational substrate as a whole.

Global behavior interactions take place independent of the ability to locate pixels in space. In between local and global scales, the pixels can continue to be controlled individually, but their response and behavior can be perceived as a surface aggregate. We have observed three interaction models unfold at this hybrid scale: remote control, tessellation and infrared mask.

## Remote Control

The Apple remote control acts as a kind of color and animation wand. It allows viewers to control a pixel's animation by changing the speed and sharpness in which they pulse a certain color and also allows viewers to switch between a warm or a cool color palette and put the pixels in sleep-mode to increase battery life. A transient white pulse indicates when an IR message is received to provide feedback to the viewers. The IR emitted by the remote is spatially limited by its light cone and allows viewers to only affect certain portions of the display depending on how far back they are from the pixels and how the remote is oriented. This limitations allows for global interactions to take place, but also provides some level of spatial control without a higher level of location coordination.

## Tessellation

Another interesting type of hybrid behavior happens when pixels are closely packed. Viewers can run their fingers through several pixels at a time, creating lines similar to a drawing application on a conventional touch screen. In addition, due to the configuration of the color palette, when lines intersect a new color appears forming an additive tessellation pattern similar to the stripe patterns found in woven textiles (Figure 23).

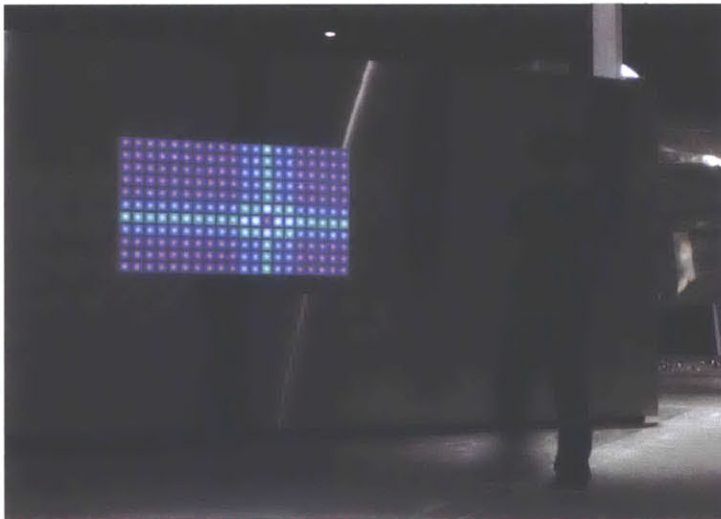


Figure 23. Tessellation pattern.

## Infrared Mask

Finally, in a closed packed configuration, it is possible to partially obstruct the infrared beam from the remote, creating a light mask. This allows viewers to rapidly paint the pixels with low resolution silhouettes of their bodies (Figure 24).



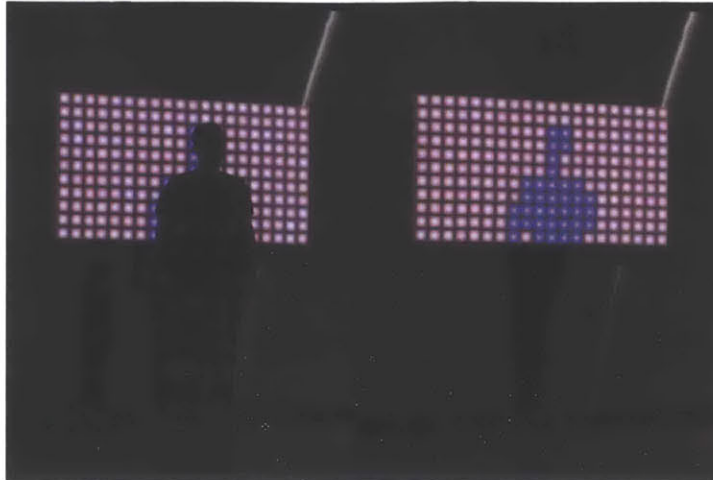


Figure 24. Left: Body preventing pixels from receiving infrared light; Right: Body outline.

### 7.6.3 Global

Finally, location sensing allow pixels to change and modulate their behavior according to their position on a wall or distance from other pixels. I have only begun to explore the interaction possibilities available for an amorphous display medium that can locate itself. The interaction models describe here hint at some of these possibilities.

#### Image Display

Once location sensing is introduced, Six-Forty by Four-Eighty allows for a whole different set of aggregate behaviors. The simplest example is its ability to match its color configuration to that of a source image independent of where pixels are positioned in two-dimensional space (Figure 25). Images can be displayed both in a relative or absolute fashion.

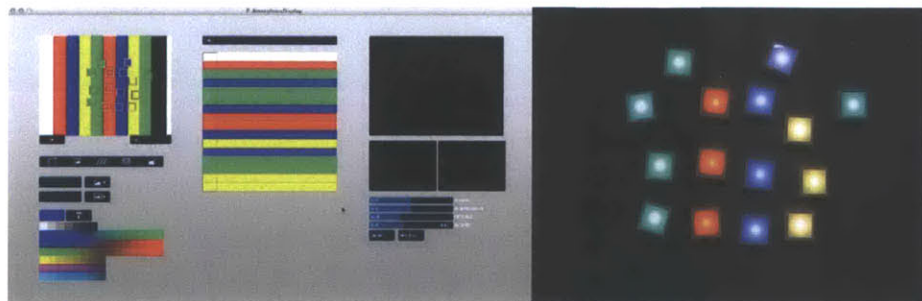


Figure 25. Pixels displaying striped pattern from image source.

## Painting

Similar to matching the pixels to an image, it is also possible to create this image in real-time allowing users to directly paint the pixels through a graphical user interface (Figure 26).

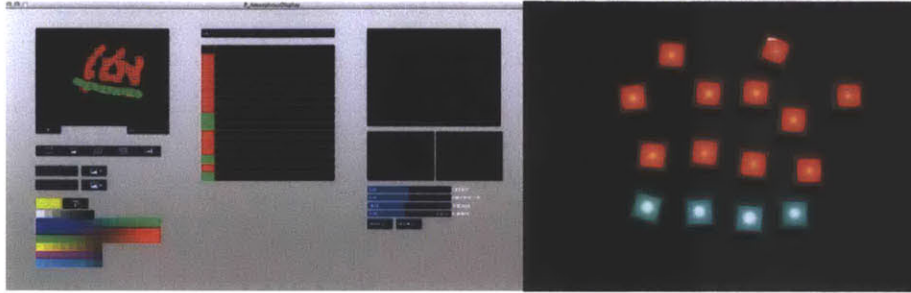


Figure 26. Pixels update in real-time as user colors canvas on graphical user interface.

## Animation Display

An extension of displaying images is the ability to animate them. I have implemented two different techniques to accomplish this. The first one uses the alpha channel from a pre-recorded image to store the period or frequency of animation pulses and provides an easy and integrated way to create animations (Figure 27). The second technique is key-frame timeline interface that allows viewers to use an external control to select pixels and create color animation sequences.

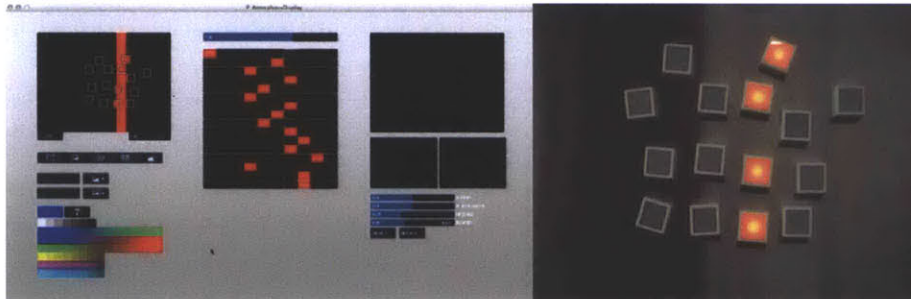


Figure 27. Gradient image used to create a swipe effect.

## 7.7 Reflections

Over the last two years, since Six-Forty by Four-Eighty has been shown in ten countries, and around twenty places, including galleries, museums, conferences, and events, being experienced by approximately 100,000 people. Each exhibition provided viewers with a particular context and set of expectations on how they should engage with the work.

By observing people interact with Six-Forty by Four-Eighty in a wide variety of contexts it has been possible to draw a number of conclusions about both its success and weaknesses. In this section, I describe the kinds of venues where Six-Forty by Four-Eighty has been shown, key environmental conditions around these installations, and my observations on how viewers interpreted the piece's affordances and interaction model.

## 7.7.1 Exhibition History

### Museums

Six-Forty by Four-Eighty was shown in June 2011 at the Corcoran Gallery of Art in Washington DC as an extension of the Washington Color and Light exhibition; in October 2011 at the Cambridge Science Center opening in Cambridge, England; and in November 2010 at the MIT Museum.

The Cambridge Science Center and the MIT Museum are both museums focusing on science and technology development with an educational focus. Visitors at these sites reacted to the work similarly to visitors at the MIT Media Lab and Academic Conferences, detailed below.

Conversely, the Corcoran Gallery of Art is one of the largest privately supported museums in the US, with a primary focus on American art, and presenting a traditional Fine Arts museum setting. At this venue, a 96-pixel sized installation was exhibited on a 3-meter wide steel wall plate. The work was hung on the mezzanine level of their atrium, in conjunction with abstract paintings and sculptures from artists of the Washington Color School, such as Ellsworth Kelly, Kenneth Noland, Martin Puryear, Anne Truitt and Gene Davis. Visitors to the Corcoran were museum-goers from all walks of life, coming to see more traditional works and happening upon Six-Forty by Four-Eighty on their way through the museum.

### Contemporary Art and Design Fairs, Galleries, and Festivals

Within a more contemporary art and design context, Six-Forty by Four-Eighty was first debuted in 2010 at Design Miami/ Basel, in Basel, Switzerland, and was subsequently exhibited at a solo show at the Rifleman Contemporary Art Gallery in London, England, in a group show with Johnson Trading Gallery in New York, as a winner of honorary mention at the 2011 Ars Electronica festival in Linz, Austria, and with the Creators Project, a traveling festival promoting arts and technology, in both New York and San Francisco.

At Design Miami/ Basel, viewers were primarily comprised of art collectors, dealers, critics, artists and designers, who were not particularly familiar with

electronic artifacts that operate outside of the consumer electronics industry. Work shown in this environment is rarely meant to be touched or interacted with; on the contrary, touching is highly discouraged. From our observations, visitors' initial impression was to approach the piece and observe it, completely unaware of its interactive possibilities. After observing others interact with the pixels or being instructed to do so, a visceral connection started to develop. First, visitors tried to grasp the full extent of pixel's functionality, gaining control of its behavior and color, similar to how we observe and physically explore a new material we have not encountered before. After this exploration stage was overcome, then the piece became a tool for co-creation, and visitors used it to create their own designs and arrangements, continuously transitioning between the local and global interaction levels.

This first moment of estrangement did not happen at other galleries and festivals, since visitors had either come specifically to see Six-Forty by Four-Eighty or were expecting an interactive work requiring a certain degree of action for a response and behavior to unfold.

### Academic Environments

Since its creation in 2010, a 48-pixel sized installation of Six-Forty by Four-Eighty has been on display outside of the Fluid Interfaces group space at the MIT Media Lab (building E14). Additionally, we have exhibited Six-Forty by Four-Eighty at the 5th International Conference on Tangible, Embedded, and Embodied Interaction (TEI'11) in Madeira, Portugal, and as a video at Conference on Human Factors in Computing Systems (CHI'11) in Vancouver, Canada.

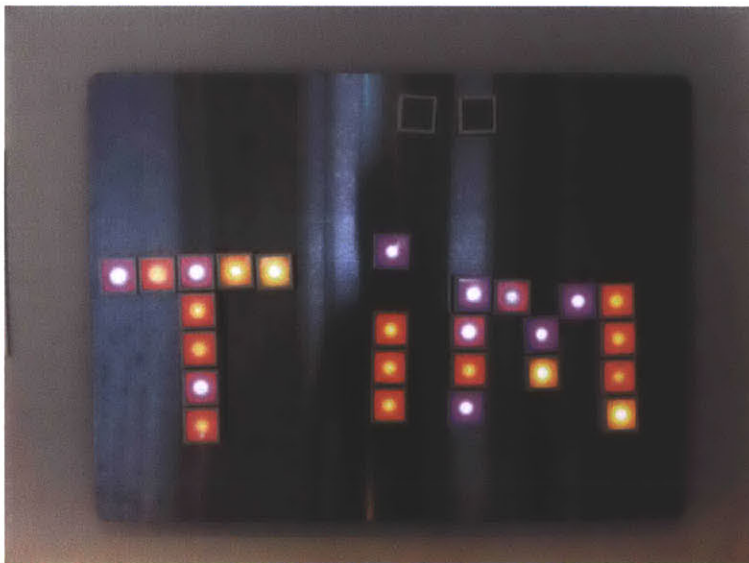


Figure 28. Six-Forty by Four-Eighty arrangement during Tim O'Reilly's visit to the MIT Media Lab.

While in a conference setting, Six-Forty by Four-Eighty was primarily assessed for its technical and theoretical contribution to the human-computer interaction community, at the MIT Media Lab it became a regular stop point for visitors and a public message board (Figures 28 and 29). Occasionally, during special dates and events, the pixels are reconfigured by the public to reflect a mood or something that is happening that day.



Figure 29. Six-Forty by Four-Eighty arrangement during Valentine's Day.

## Environmental Factors

### Signage

It has been interesting to note the role that signage plays in how users interpret Six-Forty by Four-Eighty. At the Media Lab installation there is a small diagrammatic sign next to the piece that graphically instructs users in four different ways to interact with the pixels: by moving them around, touching them to change their color, cloning color from one pixel into another, and using the remote for aggregate level interactions.

When confronted with this kind of explanation for how the work should function I have found that users are less likely to explore the work in an open-ended way, discovering what can be done and being delighted by their findings. Instead, they try to operate the pixels as instructed and can often become frustrated if they don't get their assumed results.

Without signage and without watching another more experienced person, I have observed an interesting and common development in behavior from viewers. At first, they are not always sure that they are allowed to touch the work. When they

realize that they can, their initial hesitation transforms into curiosity and excitement. As mentioned earlier, most often artworks are not to be touched and this reversal of fortune is often an unexpected and happy surprise.

Interaction with the pixels normally starts by moving them around, like fridge magnets, or by touching the glass screen and cycling through colors. After this first encounter, viewers start to make patterns and spell out words or their names. During this increased level of interaction, viewers will sometimes trigger a pixel's cloning mode — indicated by a pulsating light — without being aware of what they are doing. In some situations, this indication of data transmission is erroneously interpreted as being a heart rate measurement. In a similar fashion, color changes are sometimes interpreted as being triggered by a viewer's mood, since they associate touch and color change to liquid crystal "mood" rings, which color with changes in temperature. These misperceptions however do not seem to hinder the piece's experience and in fact they often enhance it. Even when viewers find out that they were wrong, the magic of their discovery still seems to linger.

Without a demonstration or signage, most people will not discover how to clone colors on their own. If the remote is present, very few people, if any, will fully understand its button-mappings although nearly all are able to use the remote in an enjoyable way. We have observed some frustration in users operating the remote without instruction, especially when they turn the pixels off by accident, but in most cases they appear to enjoy using the remote to control the pixels in a new way.

## **Crowds**

Occasionally Six-Forty by Four-Eighty installations have been swarmed by crowds of people. The Creators Project exhibitions in New York and San Francisco were good examples of this. On both occasions two full-time docents and a security guard were required full-time during the exhibitions. In New York, the crowd was layered five people deep at times, with up to forty people crushing up against the 14' wide wall plate and a 200-pixel sized installation. In this environment, viewers try to push entire clusters of pixels around to form new patterns, using their forearms to move dozens of pixels at one time. While the fast pace of use resulted in many interesting forms, the deeper levels of interaction, such as cloning and animating, were hardly ever explored as deeply as without large crowds.

## **Ropes and Staff**

For large exhibitions ropes and staff are required to ensure that the work is not damaged or stolen. At The Creators Project San Francisco event 220-pixel were exhibited on a 14' wide, free-standing wall plate. The production staff roped off the front of the wall and placed a security guard to ensure that no more than ten

people were inside the roped area using the piece at any point. Two docents were staged to the right and left of the wall to help guide people in using the piece and to keep an eye out for theft.

The effect of this security and care around the work was that viewers seemed to treat it much more carefully and slowly. Most viewers had to wait between 5 and 10 minutes to have a chance to experience the pixels, and once they got inside the roped area, they took a longer time exploring what the installation can do. In this environment we observed some of the most interesting and intricate design patterns so far.

### 7.7.2 Interaction Development

As outlined earlier, Six-Forty by Four-Eighty is motivated by a desire to provide viewers with a first hand experience of programmable matter by transforming light into a tangible material. On one hand its affordances resemble those of bricks or tiles which can be assembled into different shapes and configurations, while on the other it allows a visual display to be reconfigured at will depending on the kinds of information being displayed. These behaviors were observed during its exhibition through different interaction scenarios.

#### Body and Social Engagement

At the Corcoran Gallery of Art, a group of teachers became very interested in the limitation of color cloning (Figure 30). They set the record for cloning through the most people, using a chain of ten people to copy color from one pixel to another. They also wondered if they could use their faces to transmit the colors; they could.



Figure 30. Color cloning across several people.

At the Rifleman Gallery, a contemporary art gallery in London, Six-Forty by Four-Eighty received considerable attention in the media, and one art critic, James Lindley, wrote:

“Critics of the digital often concentrate on how our constant immersion in digital worlds cuts out the possibilities of real human interaction, suggesting that the online and hi-tech are somehow replacing our existence in the 'real' world. However, [Six-Forty by Four-Eighty] blocks side step this accusation to a degree by relying so much on physical human presence, on touch and play.”

And then, later:

“Maybe it is through this very human touch that digital technology comes to life for us, seems real.”

### Display on Demand

In San Francisco, a group of three college friends used the pixels to create a luminous outline around one of them. When asked what they were doing, they said “We’re just outlining a little bit” (Figure 31).



Figure 31. Pixels used to create a person's outline.

During the New York Fashion Week, the pixels were used as a backdrop for photos, like the common step-and-repeat patterns used in red carpet events. In this case, the light from the pixels was washed out by the flash, but for the photographer and viewers of Six-Forty by Four-Eighty in this situation, the light or its interactivity wasn't necessarily the important part, but rather the possibility of arranging them into different visual configurations.





Figure 32. Six-Forty by Four-Eighty at New York Fashion Week.

## 7.8 Conclusion

This chapter describes the development and behaviors of Six-Forty by Four-Eighty, a light-emitting material unit and stochastically distributed surface, which can provide a substrate for reconfigurable illumination and information display. In the immediate future, I plan to continue exploring the capabilities of amorphous displays, both by experimenting with different pixel form factors, such as circles or hexagons, which are conducive to different kinds of distribution patterns, as well as new location sensing techniques for the creating of smaller and larger scale programmable surfaces.



# 8 Contributions and Conclusion

## 8.1 Contributions

At its core, this thesis seeks to inspire and equip designers to create a future that preserves the full breadth of material richness we find today in nature and our built environments, while harnessing computation to create truly unique human experiences. With that in mind, it has sought to provide the following contributions:

- The development of techniques for the creation and control of programmable composites and surfaces.
- The application of programmable composites to a variety of art and design contexts.
- The definition of a vocabulary and taxonomy to describe and compare previous work in this area, revealing unexplored design opportunities.
- The uncovering of design principles for the development of a future programmable material and surface aesthetics

## 8.2 Recap and Future Materials

This document evolves through a narrative that starts by questioning the nature of materials and surfaces and culminates with several example designs and applications where materials are used for their programmable properties. In this section, I will present a short recap of what has been covered with the goal of identifying where some of this work will lead us and what remains to be done by future material researchers.

Chapter 3 provides material and surface definitions that differ from science and engineering approaches by placing a focus on how materials are experienced in the world. Additionally, it looks at how materials have been transformed over the years for their static, directional, bidirectional, programmable and reprogrammable behaviors, placing computers on a continuous development path with the rest of

our design and material history. Of particular importance for future researchers are reprogrammable materials, which remain relatively unexplored as a form of material behavior.

Chapter 4 presents a taxonomy which classifies and details the first-order, programmable material and surface properties available to designers. However, a lot of work still remains to be done in terms of material characterization and sensorial matching. Growing the branches of this taxonomy will help us develop technologies that will take advantage of the full, high bandwidth richness of our senses, which is specially crucial for the least characterized ones, such as a gustation and olfaction.

Chapter 5-7 provides concrete examples of how programmable materials can be created and applied to the real world. Chapter 5 provides a process for the creation of new materials behaviors and reveals the extent to which programmable materials can be created from materials as unorthodox as textiles, food and paper. Future work in this area should attempt to expand this material palette to living and 'dead' biological materials, such as wood or leather, and seek more sustainable ways to create and reuse material composites.

Chapter 6 dives in deeper into shape-change and provides a finer look at the design principles under the spatial branch of the material taxonomy. If developments in material science and fabrication continue to create materials that can reconfigure their form on demand, the techniques and soft mechanical alphabet discussed here will provide a powerful tool in the design of form transformation.

Finally, in chapter 7, Six-Forty by Four-Eighty provides a framework for exploring material organizations that break off the grid, providing an alternative to the rigid lattice distributions we have been stuck with since the invention of the cathode ray tube. Developing appropriate technique for material localization and control in stochastic distributions is a big challenge, but it promises exciting new opportunities for interaction designers.

As an artist and designer, I believe that the fundamental value of this work is in its ability to enable new forms of representation, storytelling and reflection. As science advances our understanding of the natural world and our ability to manipulate it, these new forms of communication will become essential tools for translating the underlying processes of our surrounding environments into something that can we fully comprehend and act upon.

# Bibliography

## Chapter 2

Addington, M., and Schodek, D. (2004) *Smart Materials and Technologies in Architecture*. Architectural Press.

Ahn, B. Y., Shoji, D., Hansen, C. J., Hong, E., Dunand, D. C. and Lewis, J. A. (2010) Printed Origami Structures. *Advanced Materials*, 22: 2251–2254.

Gilpin, K. and Rus, D. (2012) Digital Fabrication by Shape Duplication. *IEEE International Conference on Robotics and Automation (ICRA)*. 2012. In Press.

Gleick, J. (2011) *The Information: A History, a Theory, a Flood*. Knopf Doubleday Publishing Group.

Ritter, A. (2006) *Smart Materials in Architecture, Interior Architecture and Design*. Birkhäuser Basel.

Schwesig, C., Popyrev, I., and Mori, E. (2004) Gummi: A Bendable Computer. In *Proceedings of the SIGCHI conference on Human factors in computing systems (CHI '04)*. ACM, New York, NY, USA, 263-270.

Sutherland, I. (1965) The Ultimate Display. *Proceedings of IFIPS Congress 1965*, New York, May 1965, Vol. 2, pp. 506-508.

## Chapter 3

Abelson, H., Allen, D., Coore, D., Hanson, C., Homsy, G., Knight, T., Nagpal, R., Rauch, E., Sussman, G., and Weiss, R. (2000) Amorphous computing. *Communications ACM* 43, 5 (May 2000), 74-82.

Addington, M., and Schodek, D. (2004) *Smart Materials and Technologies in Architecture*. Architectural Press.

Berzowska, J. (2005) Memory Rich Clothing: Second Skins that Communicate Physical Memory, Proceedings of the 5th conference on Creativity & Cognition, ACM Press, New York, 32 – 40.

Berzowska, J., & Coelho, M. (2005). Kukkia and Vilkas: Kinetic Electronic Garments. In the Proceedings of the Symposium on Wearable Computers (ISWC'05) (pp. 82-85). IEEE.

Coelho, M., Hall, L., Berzowska, J., and Maes, P. (2007) Pulp-Based Computing: A Framework for Building Computers Out of Paper. The 9th International Conference on Ubiquitous Computing (UbiComp '07). Innsbruck, Austria.

Bouchard, D. (2007) Embodied Emergence : Distributed Computing Manipulatives. MS Thesis. MIT Media Lab.

Gibson, J. (1979) The ecological approach to visual perception. Boston: Houghton Mifflin.

Gilpin, K., Knaian, A. and Rus, D. (2010) Robot Pebbles: One Centimeter Modules for Programmable Matter through Self-Disassembly. IEEE ICRA'10, May 3-8, Anchorage, Alaska.

Hiller, J., Lipson, H. (2009) Fully Recyclable Multi-Material Printing. Solid Freeform Fabrication Symposium (SFF'09), Aug 3-5 2009, Austin, TX, USA.

Ingold, T. (2007) Materials against materiality. Archaeological Dialogues. 14 , pp 1-16.

Merrill, D. (2009) Interaction with Embodied Media. PhD Thesis. MIT Media Lab.

Norman, D. (1990) The Design of Everyday Things. New York: Doubleday/Currency.

Post, E., Orth, M., Russo, P., & Gershenfeld, N. (2000) E-broidery: Design and fabrication of textile-based computing. IBM Systems Journal , 39.

Ritter, A. (2006) Smart Materials in Architecture, Interior Architecture and Design. Birkhäuser Basel.

Taylor, M. (2003). Surface Consciousness: Surface-Talk. Architectural Design , 73.

## Chapter 4

Alonso-Mora, J., Breitenmoser, A., Rufli, M., Siegwart, R. and Beardsley, P. (2011) Multi-robot system for artistic pattern formation. IEEE International Conference on Robotics and Automation (ICRA), pp.4512-4517, 9-13 May 2011

ART+COM (2012) Kinetic Sculpture. Retrieved 03 August 2012 <http://www.artcom.de/en/projects/project/detail/kinetic-sculpture>.

Bacci, F. and Melcher, D. (2011) Art & The Senses. Oxford University Press, USA.

Db, J. (2011) Nils + Sven Völker: Captured - an Homage to Light and Air at Made Space. Designboom. Published 1 July 2011. Retrieved 03 August 2012. <http://www.designboom.com/weblog/cat/10/view/15448/nils-sven-volker-captured-an-homage-to-light-and-air-at-made-space.html>

Delwiche, J. (2004) The impact of perceptual interactions on perceived flavor. Food Quality and Preference, 15(2), 137-146.

Goods, D., Hafermaas, N. and Koblin, A. (2010) The eCloud. Retrieved 03 August 2012. <http://www.ecloudproject.com/>

Haque: Design Research. (2012) Scent of Space. Retrieved 03 August 2012. <http://www.haque.co.uk/scentsofspace.php>

Ino, S., Shimizu, S., Odagawa, T., Sato, M., Takahashi, M., Izumi, T., Ifukube, T. (1993) A tactile display for presenting quality of materials by changing the temperature of skin surface. Proceedings of 2nd IEEE International Workshop on Robot and Human Communication, pp.220-224, 3-5 Nov 1993

Iwata, H., Yano, H., Uemura, T., & Moriya, T. (2004). Food simulator: a haptic interface for biting. IEEE Virtual Reality 2004, 51-57. IEEE.

Jones, L., and Berris, M. (2002) The Psychophysics of Temperature Perception and Thermal-Interface Design. Proceedings of the 10th Symp. On Haptic Interfaces For Virtual Envir. & Teleoperator Systs. (HAPTICS'02).

Kaye, J. (2004) Making Scents: aromatic output for HCI. Interactions 11, 1 (January 2004), 48-61.

Leithinger, D. and Ishii, H. (2010) Relief: a scalable actuated shape display. In Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction (TEI '10). ACM, New York, NY, USA, 221-222.

Lifton, J., Broxton, M. and Paradiso, J. (2005) Experiences and directions in pushpin computing. In Proceedings of the 4th international symposium on Information processing in sensor networks (IPSN '05). IEEE Press, Piscataway, NJ, USA, , Article 57 .

Livingstone, M. (2002) Vision and Art: The Biology of Seeing. Harry N. Abrams

Nakaizumi, F., Noma, H., Hosaka, K. and Yanagida, Y. (2006) SpotScents: A Novel Method of Natural Scent Delivery Using Multiple Scent Projectors. In Proceedings of the IEEE conference on Virtual Reality (VR '06). IEEE Computer Society, Washington, DC, USA, 207-214.

Narumi, T., Kajinami, T., Tanikawa, T., & Hirose, M. (2010) Meta cookie. ACM SIGGRAPH 2010 Emerging Technologies on - SIGGRAPH '10, 1-1. New York, New York, USA: ACM Press.

Ochiai, Y. and Takai, H. (2011) The cyclone display: rotation, reflection, flicker and recognition combined to the pixels. In ACM SIGGRAPH 2011 Emerging Technologies (SIGGRAPH '11). ACM, New York, NY, USA.

rAndom International. (2009) You Fade to Light. Retrieved 03 August 2012. <http://random-international.com/work/you-fade-to-light/>

Rozin, D. (2002) Shiny Balls Mirror. Retrieved 03 August 2012. <http://www.smoothware.com/danny/newshinyballsmirror.html>

Rozin, D. (2005) Circles Mirror. Retrieved 03 August 2012. <http://www.smoothware.com/danny/circlesmirror.html>

Sosolimited, Plebian Design, Hypersonic Engineering and Design and Patten Studio. (2012) Patterned by Nature. Retrieved 03 August 2012. <http://sosolimited.com/patterned-by-nature/>

Sugimoto, S., Noguchi, D., Bannai, Y., and Okada, K. (2010) Ink jet olfactory display enabling instantaneous switches of scents. Proceedings of the international conference on Multimedia - MM '10, 301.



Troika. (2010) Shoal. Retrieved 03 August 2012. <http://troika.uk.com/shoal>

United Visual Artists. (2010) Focus. Retrieved 03 August 2012. <http://www.uva.co.uk/work/focus>

## Chapter 5

Berzowska, J. (2005) Memory Rich Clothing: Second Skins that Communicate Physical Memory, Proceedings of the 5th Conference on Creativity & Cognition (C&C '05).

Berzowska, J., & Coelho, M. (2005) Kukkia and Vilkas: Kinetic Electronic Garments. In the Proceedings of the Symposium on Wearable Computers (ISWC'05) (pp. 82-85). IEEE.

Coelho, M., Hall, L., Berzowska, J. and Maes, P. (2007) Pulp-Based Computing: A Framework for Building Computers Out of Paper, in the 9th International Conference on Ubiquitous Computing (UbiComp '07).

Zoran, A. and Coelho, M. (2011) Cornucopia: The Concept of Digital Gastronomy, in Leonardo: Journal of the International Society for the Arts, Sciences and Technology. Volume 44, Number 5, October 2011, pp. 425-431.

## Chapter 6

Berzowska, J., & Coelho, M. (2005) Kukkia and Vilkas: Kinetic Electronic Garments. In the Proceedings of the Symposium on Wearable Computers (ISWC'05) (pp. 82-85). IEEE.

Cassinelli, A. and Ishikawa, M. (2005) Khronos projector. In ACM SIGGRAPH 2005 Emerging technologies (SIGGRAPH '05), Donna Cox (Ed.). ACM, New York, NY, USA, Article 10 .

Coelho, M. (2007) Programming the Material World: A Proposition for the Application and Design of Transitive Materials. The 9th International Conference on Ubiquitous Computing (UbiComp '07). Innsbruck, Austria.

Coelho, M., & Maes, P. (2008) Sprout I/O: A Texturally Rich Interface. In the Proceedings of Tangible and Embedded Interaction (TEI'08). Bonn, Germany: ACM Press.

Coelho, M., Ishii, H., & Maes, P. (2008) Surfex: A Programmable Surface for the Design of Tangible Interfaces. In the Extended Abstracts of Conference on Human Factors in Computing Systems (CHI '08). Florence, Italy: ACM.

Coelho, M. and Maes, P. (2009) Shutters: A Permeable Surface for Environmental Control and Communication. In the 3rd Tangible and Embedded Interaction Conference (TEI '09). Cambridge, UK: ACM Press.

Fan, J.-N., and Schodek, D. (2007) Personalized Furniture within the Condition of Mass Production. The 9th International Conference on Ubiquitous Computing (Ubicomp '07). Innsbruck, Austria.

Goulthorpe, M. (2000) Hyposurface. Retrieved 7 30, 2008, from <http://hyposurface.org/>

Hutchins, E.L. et al. (1986) Direct Manipulation Interfaces. In User Centered System Design. Lawrence Erlbaum.

Interrante, V., Fuchs, H., and Pizer, S. M. (1997) Conveying the 3D Shape of Smoothly Curving Transparent Surfaces via Texture. IEEE Transactions on Visualization and Computer Graphics, 3, pp. 98-117.

Lynn, G. (1999) Animate Form: A Book & Interactive CD-ROM. Princeton Architectural Press.

Michelitsch, G., Williams, J., Osen, M., Jimenez, B., & Rapp, S. (2004) Haptic Chameleon: A New Concept of Shape-Changing User Interface Controls with Force Feedback. In the extended abstracts on Human factors in computing systems (CHI '04) (pp. 1305 - 1308). Vienna, Austria : ACM Press.

Norman, D. (1990) The Design of Everyday Things. New York: Doubleday/Currency.

Poupyrev, I., Nashida, T., & Okabe, M. (2007) Actuation and Tangible User Interfaces: the Vaucanson Duck, Robots, and Shape Displays. Proceedings of TEI'07 (pp. 205-212). ACM.

Raffle, H., Ishii, H., & Tichenor, J. (2004) Super Cilia Skin: A Textural Membrane. *Textile: The Journal of Cloth and Culture* , 2 (3), 328-347.

Raffle, H. S., Parkes, A. J., & Ishii, H. (2004) Topobo: a constructive assembly system with kinetic memory. Proceedings of the SIGCHI conference on Human factors in computing systems (pp. 647 - 654). Vienna, Austria: ACM Press.

Strandh, S. (1988) Christopher Polhem and his mechanical alphabet. *Techniques et culture* , 10, 143-168.

Taylor, M. (2003) Surface Consciousness: Surface-Talk. *Architectural Design* , 73.

Thompson, D. (1992) *On Growth and Form*. (J. T. Bonner, Ed.) Cambridge, UK: Cambridge University Press.

Trimmer, B. A., Takesian, A. E., Sweet, B. M., Rogers, C. B., Hake, D. C., and Rogers, D. J. (2006) Caterpillar locomotion: A new model for soft-bodied climbing and burrowing robots. In the 7th International Symposium on Technology and the Mine Problem. Monterey, CA: Mine Warfare Association.

Zigelbaum, J., Chang, A., Gouldstone, J., Monzen, J., & Ishii, H. (2008) SpeakCup: Simplicity, BABL, and Shape Change. In the Proceedings of the Second International Conference on Tangible and Embedded Interaction (TEI'08). Bonn, German.

## Chapter 7

Mathiowetz, V., Kashman, N., Volland, G., Weber, K., Dowe, M., and Rogers, S. (1985) Grip and pinch strength: normative data for adults. *Archives of physical medicine and rehabilitation*, 66(2), 69-74.

Frazer, J. (1995) *An Evolutionary Architecture*. Architectural Association Publications.

Gleick, J. (2011) *The Information: A History, a Theory, a Flood*. Knopf Doubleday Publishing Group.

Harrison, C., Horstman, J., Hsieh, G. and Hudson, S. E. (2012) Unlocking the Expressivity of Point Lights. Proceedings of the 30th Annual SIGCHI Conference on Human Factors in Computing Systems (CHI '12). ACM, New York, NY.

Hawkes, E., An, B., Benbernou, N. M., Tanaka, H., Kim, S., Demaine, E. D., Rus, D., and Wood, R. J. (2010) Programmable matter by folding. Proceedings of the National Academy of Sciences of the United States of America, 107(28), 12441-5.

Heaton, K. (2000) Physical Pixel. MIT Media Lab Thesis.

Lifton, J., Broxton, M. and Paradiso, J. (2005) Experiences and directions in pushpin computing. In Proceedings of the 4th international symposium on Information processing in sensor networks (IPSN '05). IEEE Press, Piscataway, NJ, USA, , Article 57 .

Merrill, D. (2009) Interaction with Embodied Media. PhD Thesis. MIT Media Lab.

Muniz, V. (2005) Reflex: A Vik Muniz Primer. Aperture.

Murata, S., Yoshida, E., Kamimura, A., Kurokawa, H., Tomita, K. and Kokaji, S. (2002) M-TRAN: self-reconfigurable modular robotic system. IEEE/ASME Transactions on Mechatronics, vol.7, no.4, pp.431-441.

Seitinger, S., Perry, D. S., and Mitchell, W. J. (2009) Urban pixels: painting the city with light. In Proceedings of the 27th international Conference on Human Factors in Computing Systems (Boston, MA, USA, April 04 - 09, 2009). CHI '09. ACM, New York, NY, 839-848.

Seitinger, S. (2010) Liberated pixels : alternative narratives for lighting future cities. PhD Thesis. MIT Media Lab.

Silver, J. S. (2009) Nature as interface: MacGyver'ing and Martha-Stewart'ing interactivity with trees, pencils, grandpa, even the kitchen sink. In Proceeding of the Seventh ACM Conference on Creativity and Cognition (C&C '09). ACM, New York, NY, 483-484.

Sun, A. (2012) Programmable Surfaces. PhD Thesis. MIT Media Lab.

Toffoli, T. and Margolus, N. (1991) Programmable Matter - Concepts and Realization. Physica D, 47:263-272, 1991.

Yoshida, E., Kamimura, A., Kurokawa, H., Tomita, K. and Kokaji, S. (2002) M-TRAN: Self-Reconfigurable Modular Robotic System. Transactions on Mechatronics, IEEE/ASME. Vol 7, Issue 4, pp. 431 - 441.

Zimmerman, Thomas. (1995) Personal Area Networks (PAN): Near-Field Intra-Body Communication. MIT Media Lab Thesis.