Augmented Material Interfaces

Exploring bidirectional microinteractions enabled by radical elements.

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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

Master of Science in Media Arts and Sciences
at the Massachussetts Institute of Technology

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Abstract

Advances in material science and miniaturization of electromechanical devices are liberating the surface of the embedded device from its rigid shell. These new modes of dynamic expression have to be coupled with sensing capabilities in order to create comprehensible interactions. This thesis explores the space of augmented materials that are bidirectional transducers, called *radical elements.* We present currently available radical elements that facilitate embodied interactions through sensing and actuation methods on the same modality. To exemplify how a radical element can be fabricated with simple materials, we present a thin film shape-changing composite *uniMorph.* It is based on a flexible circuit composite that is able to actuate its own shape by combining the thermo-electric characteristics of copper with the high thermal expansion rate of ultra-high molecular weight polyethylene. Finally, a taxonomy for augmented materials is presented that explores how new material capabilites can extend the perceived behavior of materials in the context of microinteractions. This thesis concludes with a survey of tangible interface projects in the design space of radical element enabled augmented materials.

Thesis Supervisor

Hiroshi Ishii

Jerome B. Wiesner Professor of Media Arts and Sciences

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Danke Opa.

- *Felix*

In nova fert animus mutatas dicere formas/ corpora;
I intend to speak of forms changed into new entities;

Ovid
Metamorphoseon, Book I
lines 1–2
8 AD

Initial Remarks

Physical materials and digital systems are considered to have inherently opposite characteristics. Materials are static, passive, and permanent, deriving a set of abstract qualities such as affordance, ambience and calmness. Tangible User Interfaces are successful because they combine these qualities with dynamic, active, and programmable digital information. They embody and tame the radical nature of computation and enable bodily interaction with it.

Enabled by advances in material sciences, current human computer interaction research continues to blur the lines between the physical and digital world. New dynamic materials are introduced that give physical expression to digital computation. While this frontier has great opportunities, we also require rules for how to use this new layers of dynamic materiality to successfully synthesize computation and physical elements without losing the inherent qualities of either.

This thesis presents three complementary research threads. The first one is a taxonomy for bidirectional transducers, called '*Radical Elements*', that defines the current design space for the design of bidirectional microinteractions. The second one presents a novel shape-changing composite that enables designers to create these bidirectional microinteractions. Finally, the last thread presents a design space for future computationally controlled dynamic materials.

Hopefully, this thesis will inspire and guide the development towards a future in which bits and atoms can be truly integrated without losing the inherent qualities of physical materials or computation.

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Motivation

Advances in synthetic materials have paved the way to a reversed design process with new possibilities. Instead of a design iteration that is informed and constrained by the available materials, custom materials can now be engineered to fit the design requirements. In addition, a recent frontier of material engineering is trying to liberate materials from their static nature and make them dynamic in form and function.
This thesis deals with both, the incorporation of dynamic materials and minituarized electromechanical devices into electronic objects and the implications for interacting with the resulting artifacts.

Dynamic materials offer new modes of expression for objects with embedded computation. They could help connect us with the computational processes that are executed inside electronic objects in our daily life. The once static shell of an object might be able to match the dynamic nature of the computation it embeds. In concert with material-embedded sensing, this could allow for haptic connection between immaterial computation and human touch, mediated by the material. Dynamic materials could inform us by embodying object's internal computational state through transformations instead of blinking LEDs.


Figure 1: TRANSFORM is a shape-changing piece of furniture that also creates a canvas for new expressions for artists and designers .

Fabrication of synthetic materials enabled a new breed of materials with customized properties, leading to a design process that can is not informed by material properties, but defines new materials for its purpose. Now new dynamic materials are being developed new dynamic materials with properties that are not pre-defined during fabrication but can be changed computationally. When designed correctly, those materials might inform us not just about their own materiality, but also connect us to the underlying computational models by sensing and answering our actions through transformations - human-material interaction.

In the vision paper 'Radical Atoms' Ishii et al. proclaimed that new materials have to be able to transform its shape, conform to constraints and inform users of interaction possibilities [Ishii, 2008]. In order to achieve all of those qualities, the material has to be able to actuate and sense the very same modality. This bidirectionality is the focus of this thesis from the technical (enabling) and the interaction side.

To make sense of these new qualities we need to chart the new qualities that these materials offer for designing interactions. This is common when new technologies are introduced, and prunes particularly important in this case where we blur the lines between the static physical and dynamic digital world.

This is a grand challenge and this thesis merely offers explorations into this new field of interaction. In the tradition of the Tangible Media Group, the "answers you'll find offered here are half technology (how it can be done now) and half philosophy (how it should be done eventually)" [Underkoffler, 1999].

Thesis Aims

This thesis postulates that the ability to understand, design, and prototype interactions with dynamic materials is becoming increasingly important. While enabling technologies are advancing at increasing speed, we have to strive to incorporate human interaction with those materials into the agenda of research.

This thesis examines bidirectional interactive materials that combine sensing and actuation of the same modality. Only these materials can actively transform and conform with the human body and create truely bidirectional interactions. Currently available materials and electromechanical devices that enable both sensing and actuating are surveyed and ordered in a '*Periodic Table of Radical Elements*'. The goal of this table is to create a comprehensive list of input/output (I/O) transducers as well as the categorization of future radical elements.

Following this table of generally available materials, the thesis highlights the creation of a new radical element called *uniMorph*. The thin-sheet composite shows how common materials can be leveraged to create a shape-changing composite with inert sensing capabilities. With uniMorph we aim to democratize and spread the capabilities of dynamic materials with computational control.

Thesis Contributions

This thesis offers the following contributions:

1.

A perspective on enabling technologies for bidirectional dynamic materials: *Radical Elements.*

2.

A thin-film composite that exemplifies the creation of new radical elements and democratizes prototyping of shape changing interfaces.

3.

A taxonomy and design space for microinteractions with dynamic materials.

Thesis Outline

The following chapters describe the evolution of ideas in this thesis:

Chapter 2 briefly discusses interactions with electrical (digital) systems, surveys the concepts of input/output coincidence, dynamic materials, and microinteractions, and briefly discusses the potential of dynamic materials in that context.

Chapter 3 presents components and materials that facilitate sensing and actuation transducing on the same modality and the periodic table of radical elements.

Chapter 4 presents uniMorph, a thin-film composite for shape-changing interfaces that is easy to fabricate and exemplifies how radical elements can be engineered on a material level.

Chapter 5 surveys interactions with electric objects from a historic and taxonomy point of view. Finally, it presents a design space and taxonomy for bidirectional interactions with radical elements.

Chapter 6 discusses limitations and future work.

Chapter 7 concludes the thesis with a summary.

Background

Introduction

The following chapter partially defines the space in which this thesis is placed and explains the way certain terms are being used. It discusses different terms concerned with materials and locates the conducted research in the field of *'Body - Object - Space'.*

Finally, it describes the term *'microinteractions'* and briefly explores how we interact with electric objects from the technical and human side by discussing digital control loops and the concept of input/output coincidence.

Material: A brief discussion

"We shall speak of a 'material' not by defining 'what it is' but describing 'what it does'"
- *Ezio Manzini*

In the course of this thesis, the term material will be used frequently and in different contexts. This section defines different permutations of the term, but the most important definition is the term '*material*' itself. What constitutes a material is a complex question and the presented definition is specific to the context of this thesis and by no means generalizable.

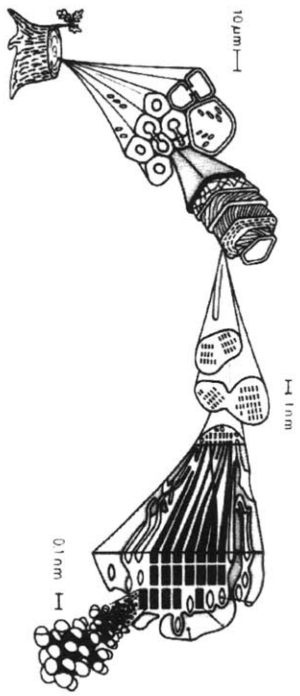


Figure 2: Wood exemplifies the recursiveness of materials with strcutures from cellulose chain molecules to wood cells and fibers.

Material describes the matter which artifacts and natural objects are made of. The perception of a material is that of a single entity. However, smaller entities, which can also be described as materials, are often found within a material upon closer inspection. For example, wood is perceived as one material, but a close examination reveals layers and rings that make up the wood. Even closer inspection reveals small fibers that make up those rings. Another example are composite materials that are made of multiple layers but are perceived as one material after fabrication.

The term 'material' is highly recursive, with the chemical elements and their molecules as the smallest functional unit. At a molecular scale, every material is a structure. Molecules form structures with various patterns depending on their energy stability. These molecular structures define the properties that a material exhibits.

In this thesis, the term 'material' and its recursive use are expanded a little more. We include electromechanical devices such as motors and electromagnets in the definition of what a material can be. It is important to notice that in their current scale and deployment, those devices do not constitute a material, but a structure. However, the scale of these devices has been shrinking continuously, pointing to a future of electromechanical structures so small, that their structures can be perceived as materials.

Additionally, dynamic materials that create effects similar to motors are engineered and synthesized on the molecular level. It is only a matter of time until the active qualities and functionalities that we currently associate with electromechanical devices will be perceived as material properties. To deeply root this evolution in the vocabulary of this thesis, we refer to these structures as materials.

The other following terms are being used:

Digital Material is a type of material that is assembled of small-scale, discrete building blocks. Similar to larger scale LEGO-blocks, they allow for only discrete positions and rotations in reference to each other. This makes them simple to manufacture and possibly fully recyclable. They also exemplify the use of the word material for an assembly of discrete blocks.

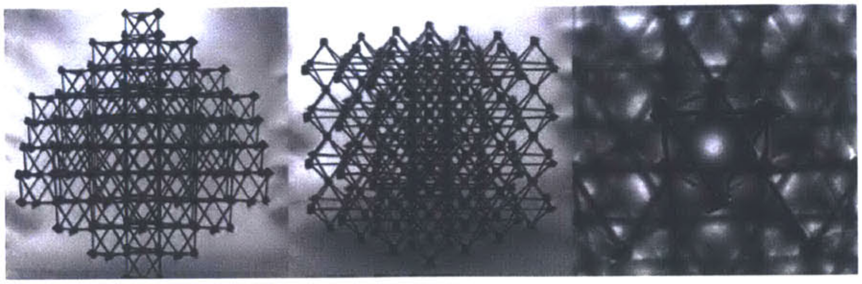


Figure 3: Digital Cellular Solids by K.C. Cheung is an example for a digital material.

Programmable Matter can change properties and sense environmental or human stimuli. The focus of programmable matter research is on self-sufficient systems that can reassemble into any shape or property. The goal of creating a general purpose material contrasts this approach to dynamic, programmable materials.

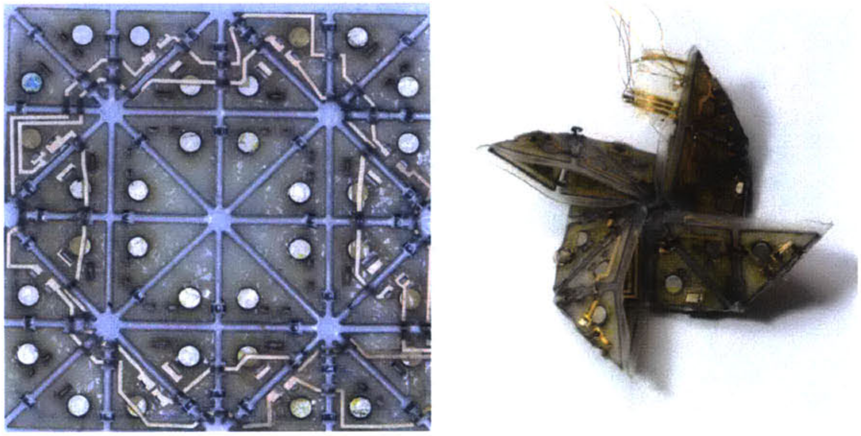


Figure 4: Programmable Matter (here exemplified byt work of the Wyss Institute) is a concept for reconfigurable systems, in this example based on self-folding sheets of robotic origami.

Dynamic Material describes materials with dynamic properties. Usually these materials are engineered and synthesized to either respond to environmental or computational stimuli. While dynamic properties with environmental stimuli can also be found in natural materials (eg. wood), the time scale at which these property changes occur is usually too slow to be characterized as dynamic.

Figure 5: Dynamic materials can change their material properties quickly, often controlled by computers. This includes, but is not limited to shape. Here shown is a transforming carbon fiber by Skylar Tibbits.

Object - Body - Space

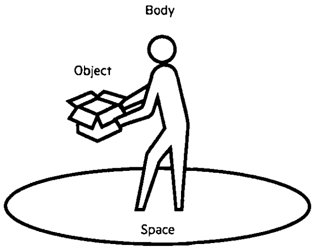


Figure 6: A common view of interactions is on Object-Body-Space.

This thesis deals with physical representations of digital infortmation that enable physical interactions. Specifically physical microinteractions with electric objects. From the perspective of Object-Body-Space, this excludes aspects of space from the focus of this thesis and rather discusses and explores the relation between the body and the (electric) object.
This thesis will not focus on spatial aspects as they do not influence most physical microinteractions. Hence, the following brief definition is sufficient:
We are spatial, physical beings whose bodies are embedded in a physical space together with other humans, objects and materials, and whose intersections of physicalities we call interactions.

The following section discusses the role of the remaining two categories: Body and Object in more detail. Since the focus of these descriptions is the interaction (or intersection) of these categories, the explanations reference each other.

Body

Our body is a living, experiencing, feeling entity. When interacting with physical objects we use a multitude of senses. Our multimodal haptic sense allows us to feel temperature, surface friction, weight, and more. The sense of our own body comes with a set of kinaesthetic, proprioceptive, and tactile qualities that we leverage naturally in mundane and complex physical (inter-)actions.

We understand the world in reference to our own body and our sense of touch reminds us that we are embodied beings [Böhme, 1998]. Touching something is "responsive and dialogic and can be deeply emotional; the aesthetics of touch have immediate emotional responses" [Hornecker, 2011].

When designing physical, embodied interactions, one has to consider the experience of the living human body, as well as the materiality of the world we interact with. This requires an understanding of how the human body experiences, from sensory organs to bodily intelligence. Particularly when designing dynamic tangible interfaces, designers have to recognize the intimacy of their design space, since one can not touch without being touched.

Object

We interact with natural and man-made objects *(artifacts)* everyday. The physicality of objects gives them persistence and allows us to use our bodies in interactions with them. Form and material leverage cultural references that enable us to infer possible and intended interactions with the object *(affordances)*.

With new technical skills, humans developed more categories of artifacts with a new richness of functionalities. The evolution of interactions with artifacts developed from interacting solely with materials, to controlling complexity by translating mechanical movements with gears and pulleys and more recently amplifying forces with the help of motors.
With the introduction of the microcomputer, the physical form of artifacts has been liberated from its function, as a large part of the functional digital complexity is encapsulated in small integrated circuits. So called electrical objects [Dunne, 1999]

combine a static, physical shell with dynamic computation and create a bridge between the material and digital immaterial.

Electric objects, a form of augmented artifacts permeate our lives. While they have traditionally been bound to the static nature of their comprising materials, their modes of expression will soon expand beyond attached screens and indication lights. Dynamic Materials that can change their material properties such as shape, stiffness, color or temperature will expand the vocabulary of interfaces that mediates between the two worlds.

This thesis explores the nature of interactions with the surface of the electric object, which can be described as the boundary between the immaterial computation and the human. It examines how digital data can be embodied by the materials that comprise the surface and how this embodiment can be tailored to the human body.

Microinteractions

"The details are not the details; they make the product,"
- Charles and Ray Eames

A *microinteraction* is a small interaction (often within a larger system) that is dedicated to a single task and only does one thing [Saffer, 2013]. Simple examples for microinteractions are switching on the light or adjusting the volume of a device. They span from purely GUI based interactions such as liking a Facebook status to physical interactions such as washing hands.

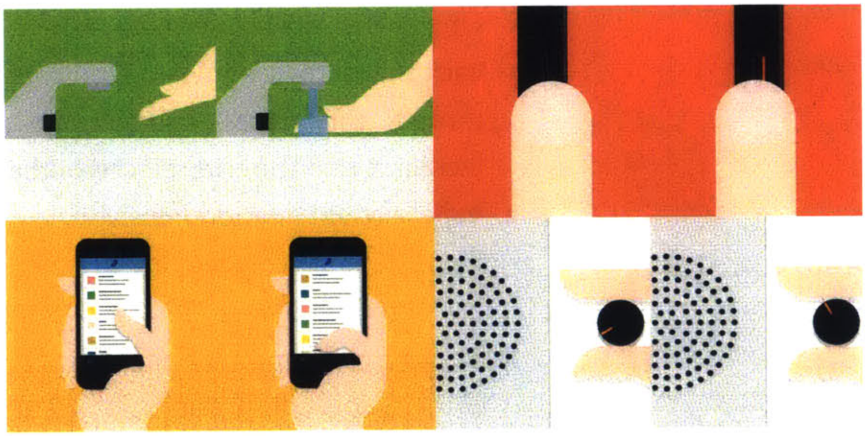
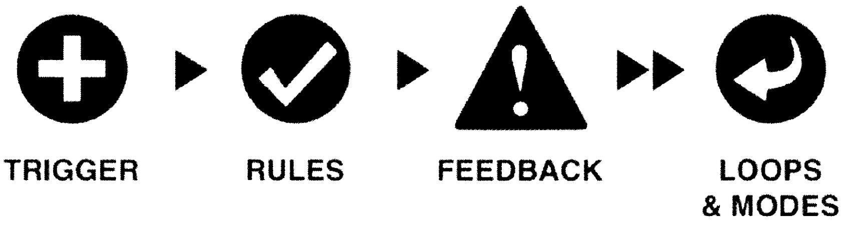


Figure 7: Microinteractions of the daily life

Microinteractions are ephemeral and simple. However "the difference between a product we love and a product we just tolerate are often the microinteractions we have with it" [Saffer, 2013].

The components of microinteractions are triggers, rules, feedback, and loops/modes (Figure 8).

Figure 8: The structure of Microinteractions as presented by Saffer [Saffer, 2013].

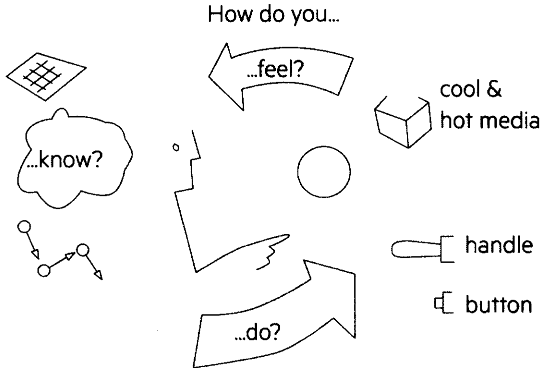


Triggers are the start of any microinteraction. They usually are initialized by the user (eg. by pressing a button). Hence the design of the system has to identify its triggers clearly, often by leveraging *affordances*. Triggers can also be initialized by an external event like receiving an email.
Rules describe the logic that specifies the system's mechanic. This is where *digital computation* generates its feedback behavior that is either directly coupled to the trigger or is presented somewhere else. One of the major challenges of designing for microinteractions is making the outcome of this imperceivable process transparent for the user.
One of the most important parts in this process is the **feedback** that provides information back to the user either directly through the trigger or somewhere else. It is only through this feedback that the user perceives the computational system as *responsive* and comprehensive.
Finally **Loops & Modes** can be used to customize the rules within microinteractions. This allows microinteractions to change according to computational states, triggered by the user or machines. This computational structure completes the interaction feedback loop.

An interesting aspect about the microinteraction paradigm is its similarity with the interaction design abstraction popularized by Professor Bill Verplank.

His question of "How do you do?" relates to the triggers the device offers. "How do you feel?" corresponds to the microinteraction's feedback. "How do you know?" does not directly correlate

Figure 9: Bill Verplank's questions of interaction design.



to a step in the microinteraction perspective. However, the *rules* and *Loops and Modes* in microinteractons determine how the user perceives the system. This relationship shows the different consideration of either approach and the simplification that each bring with it. While microinteractions take the perspective of the computational medium, Bill Verplank considers the user's side of the interaction. The microinteraction perspective does not consider more abstract concepts like metaphors or mind-maps as Verplank does, but focuses on a simple mapping between inputs and outputs as executed by the machine.

This thesis looks at interaction design with dynamic materiality from the microinteraction perspective. While there is also a need for a more holistic approach to this topic, the focus on microinteractions from a machine-side allows for a more focused perspective and much needed basic insights.
In this context, the hypothesis is: Dynamic materials can embody the both *trigger* and (augmented) *feedback* for microinteractions. This interaction is similar to the interaction with inert materials, only instead the materialilty of the trigger is computationally augmented. The following chapter will present a list of materials and electromechanical devices that can facilitate this type of interaction. Chapter 5 presents a taxonomy of perceptual qualities that interactions with dynamic materials can afford.

Computational Control & Feedback

Figure 10: Most analog control systems have been replaced with digital technology, as exemplified here by an analog honeywell and a modern nest thermostat.

Control systems are ubiquitous in objects around us. They appear in our homes, cars, and communication systems, to name just a few examples. While there are still some analog control systems, most control systems are built with a digital computation unit at heart. In electronic objects, control systems allow computation to materialize outcomes of algorithms or computational states. They are an irreplaceable part of the transduction between digital and physical. They are the interface between the immaterial and the material.

From an engineering perspective, there are two different categories of control systems, open-loop and closed-loop. This section is going to briefly explain the two concepts and explain why the use of closed loop systems is fruitful for physical human-computer interaction.

Open-Loop Control

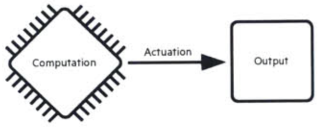


Figure 11: Open-loop control example

In an open-loop control system the digital part of the system only has means of physical actuation and no sensor feedback from its actions. Controlling the speed of a DC-motor with just applied power is a simple example of open-loop control. Open-loop control systems are useful for well-defined systems with physical behavior that can be modeled with mathematical formulas or simple simulation. The actuation is then carried out with no regard for physical deviations from the programmed models.

Closed-Loop Control

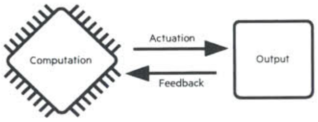


Figure 12: Closed-loop control incorporates sensor information

Sensors are key elements of closed-loop control systems because they provide feedback from the actuation process and close the control loop. Ideally, sensors are in-line, meaning that they measure the direct effect of the actuation, but there are also loops with sensors that capture a derivate effect of the actuators effect.

A good example of a closed-loop system is a servo motor. A servo motor is an assembly of a DC motor, gears, and a potentiometer. The rotation of the DC motor is geared down and the resulting rotation is measured by the potentiometer. This closed-loop assembly allows for precise angular control with high torque. Additionally, it can also adapt to changes in its system. Furthermore, if the servo's position is altered by external forces, the control system can adjust.

More complex applications of control systems take the behavior of the physical system into account. To account for static friction and inertia effects of physical systems, engineers deploy more advanced control algorithms such as PID (Power, Integral, Differential) controls.

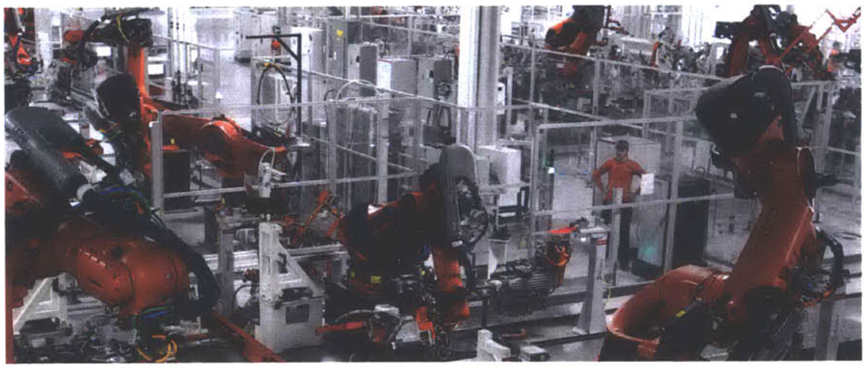


Figure 13: Closed loop control systems in automation often don't take human interaction into account. In effect, machines and humans have to be physically separated for safety reasons.

Interactive Closed-Loop Systems

The control systems presented so far do not account for human presence or interaction. Especially in automation systems, where machines execute preprogrammed sequences of motions, sensors are often deployed merely for feedback on machine performance and accuracy. In the most extreme scenario, human interference would be interpreted as an obstacle and pose physically dangerous situations to humans. This often results in physical separations of humans and automated machines as shown in f(Figure 13).

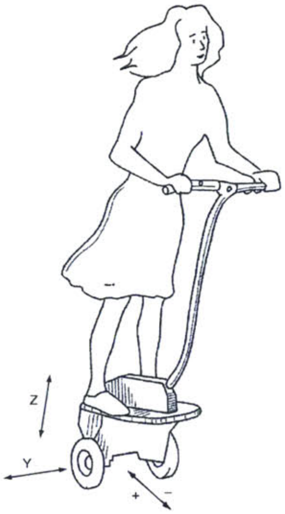


Figure 14: The Segway is an example of a closed loop system with human interaction mind. By changing the systems center of mass, the human controls the device's speed.

Other control loops are configured to specifically consider human factors. The Segway is a two-wheeled self-balancing vehicle invented by Dean Kamen (Figure 14). The control loop is configured to balance the two wheeled vehicle vertically. When a driver stands on the device and offsets the center of gravity by leaning forward, the control-system attempts to restore its balance by moving forward. The driver can control the vehicle by leaning back and forward, interacting with the control system.

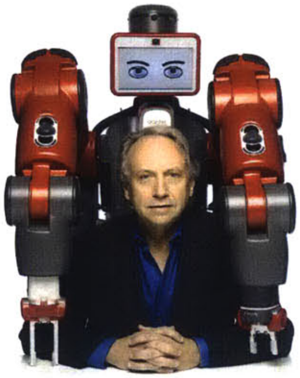


Figure 15: The Segway is an example of a closed loop system with human interaction mind. By changing the systems center of mass, the human controls the device's speed.

Another way of creating interactive closed-loop control systems is to incorporate multiple sensor streams to inform the computational model not just about the state of its own actuation, but also data about human interaction. The social robot "Baxter" (Figure 15) is a good example of a system that is designed to collaborate with humans instead of working (physically) separated from it. The robot is equipped with pressure sensors and cameras to sense a user's presence and interpret his/her intent. Next to its pressure sensors and camera, the robot also incorporates a screen to inform the user about the machine's intention. This feedback loop creates transparency and safety when collaborating with the device.

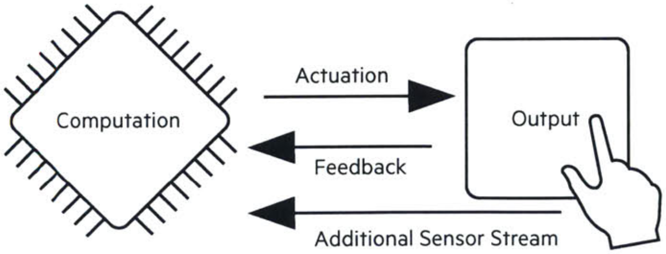


Figure 16: Additional sensor data can be used to inform the controller about human interaction.

I/O Coincidence & Embodiment

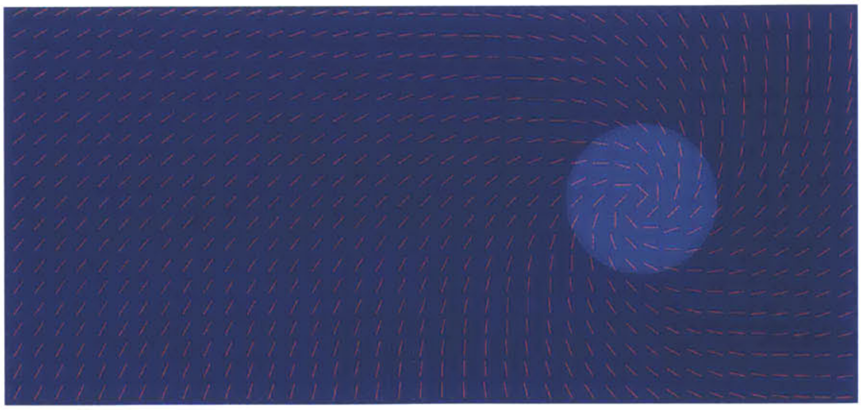
At the heart of human-computer interaction, specifically tangible media, stand two very important concepts:

I/O Coincidence & Embodiment

I/O coincidence describes the perceptual coupling of two events as 'action and reaction'. In the context of interacting with electric objects or computational systems, this usually implies a sense of causality in which occuring events are interpreted as a reaction to one's actions. For example, when one taps an app icon on a smartphone screen, the app opens. When we put our hands under an automated faucet, water comes out (sometimes slightly delayed, blurring the impression of IO coincidence). When interacting with inert physical objects and materials, a physical reaction to any physical action is inherent to their physicality. Newton's Third Law defines that for every action, there is an equal and opposite reaction. When applying a force on a piece of wood, the wood is not just being bent but the material also stores the work invested by the human and acts on the bender by pushing back. A similar example is the interaction with a touchscreen of a smartphone. When pushing the finger on the touchscreen, the rigid touchscreen resists the pressure and creates an equal and opposite force on the finger. When the phone is turned on, the perception of the interaction changes because a tap on the touchscreen not only creates a feedback force, but also causes a reaction in the computational system, represented with underlying pixels. While this computational feedback is not a haptic sensation, it still is perceived as action and reaction because of its immediacy and colocation. While this interaction loop is very efficient for a wide variety of applications, it is missing an augmented physical sensation that would enable a physical interaction with underlying computation instead of its rigid shell.

With the introduction of new dynamic materials, those interactions become possible but also potentially more complex. As the example of the smartphone shows, we are used to interacting with physically inert objects that usually actuate with immaterial pixels. The haptic feedback and reaction we get from these devices is static and predictable and makes the role division between physical and digital clear. With the introduction of dynamic materials, this once clear border is being blurred, which creates new possibilites and challenges. One challenge for designers of these interactions is to clarify the action performed by the machine as a reaction to the human's behavior. Only when succesfully designed does the human understand the cause-reaction chain and, on a broader note, how to interact with the system. Similar to paradigms in GUIs, active and passive materials need to be disambiguated. Material behavior, just as pixel behavior, has to be designed in a way that creates a cognitive link between the user's input, the computational function and the material actuation. The material has to *embody* computation and offer tirggers to interact with it.

Figure 17: One of the guiding principles of GUI design is : "All energy derives from the user". Here illustrated by Google's Material Design manifesto.



Embodied Interaction is a broader term that deals with ways of bringing the interface to digital systems of the screen and into the real world (Dourish, 2001). However, as we will show in chapter 5, the term embodiment expands beyond physical entities. With physical objects that are augmented with and linked to computation and data, changes in the digital world are represented in the object and interactions with the object have impact on the computation. This relationship calls for a bidirectionality that blurs the boundary of the immaterial digital and physical world, as actuators mediate digital expression and sensors inform the machine about human interaction.

Successful design of I/O coincidences is important for understanding the design of an embodied interaction and a well designed embodiment gives meaning to I/O coincidences. They need each other to create meaningful and understandable embodied interactions. The hypothesis of this thesis is that a direct feedback on the input modality can create new material mediated human-computer interactions. One of the most important aspects of those interactions is the direct coupling of trigger and feedback. The following chapter surveys currently available materials that are at designers' disposal to create embodied interactions and proposes a taxonomy for bidirectional transducer devices called *'radical elements'*.

Radical Elements

Radical Elements

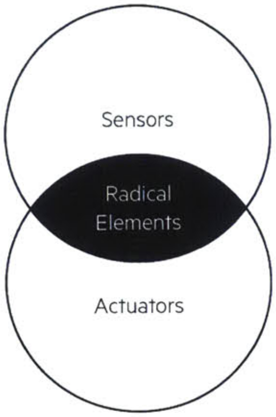


Figure 18: Radical Elements are situated at the intersection of sensors and actuators. They are bidirectional Transducers.

The past section briefly discussed interactions with electrical (digital) systems, surveyed concepts of I/O coincidence and dynamic materials, and briefly discussed the potential of dynamic materials that embody the trigger as well as the feedback of microinteractions. This chapter presents components that facilitate this embodiment by offering sensing and actuation methods on the same modalities. In reference to the vision of *Radical Atoms* by Ishii et al. [Ishii, 2008], these components are called '*Radical Elements*', as they are the building blocks for the physically embodied computational objects envisioned.

Derived from a decade of experience in tangible interactions, Hiroshi Ishii formulated a vision of 'Radical Atoms' in 2008. The vision describes a future of human-material interaction, in which "all digital information has physical manifestation so that we can interact directly with it" [Ishii, 2008]. Ishii et al. describe the qualities that 'Radical Atoms' should facilitate; transform, conform, and inform.

While transform and inform are well explored pillars of this vision, the ability to conform actively is underexplored in HCI research. Conforming alone is not a very interesting design space, however, to create safe and intuitive devices for human interaction, every transformation of material properties should happen with a real time awareness of its impact.

As discussed in the section about control loops, each actuator needs to be coupled to sensing capabilities not only to create a safe environment, but also to create new modes of interaction.

Figure 19: Radical Atoms is the vision of fully embodied computation and human-material interaction

Radical Elements are enabling technologies that unite transformation and conformation. By integrating both functionalities, dynamic affordances can be expressed even during interactions as the device is able to sense the human body and give dynamic feedback on its interactive modalities.

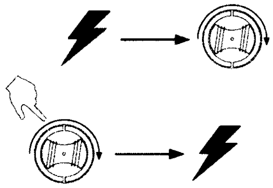


Figure 21: Radical Elements can translate voltage into physical actuation and physical actuation into an electrical signal or electrical power.

Radical Elements range from electromechanical devices to material structures, from simple actuators to complex assemblies. What they have in common is that they unify modes of sensing and actuating on the very same sensory modality. For example a DC-motor spins when electrical power is applied. When the motor is spun manually, it translates the kinetic movement to electrical power. This bidirectional transducer quality enables a microcontroller to sense the users' actions and act on them directly. *Radical Elements* are translators between the user and

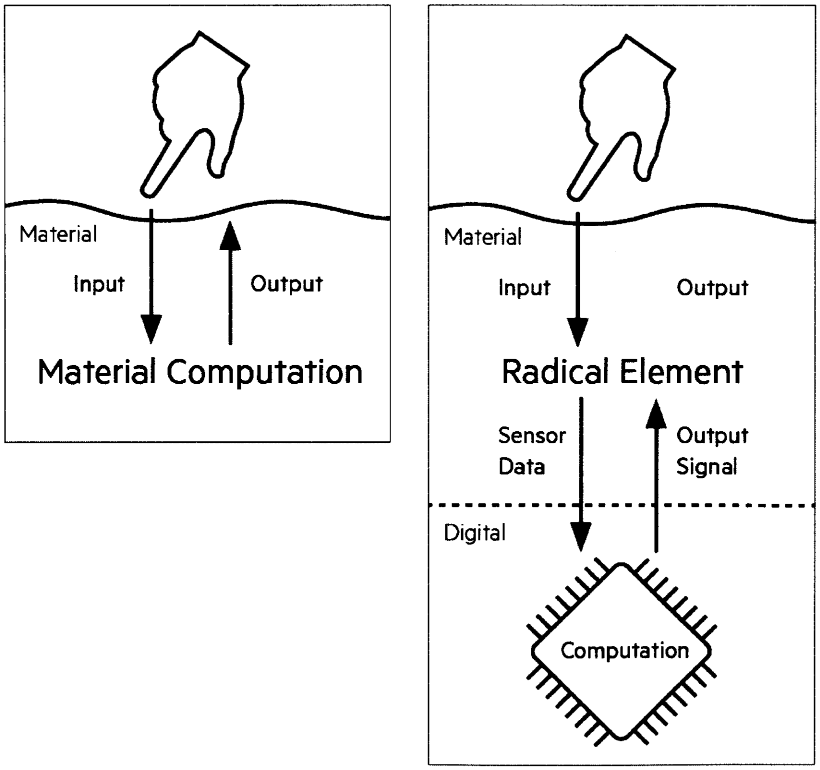


Figure 20: Radical Elements are bidirectional transducers that can create new modes of expressions for materials by sensing and actuating the same modality

the microcontroller. From a technical perspective, that entails a translation from electrical energy to physical output as well as a physical input to electrical voltage. This makes not only assemblies with electromechanical effects, but also a range of enabling materials interesting media.

The bidirectionality of radical elements creates an interesting space in which the reaction of materials to a physical input, often called material computation, can be augmented by the underlying computation (Figure 20).

As discussed earlier, inert materials always create haptic feedback. When one pushes a brick wall, the wall resists the force and creates pressure on the hand pushing it. When trying to warm up a piece of metal with one's hand, the metal will in turn also cool down the hand.

When these materials are equipped with sensors, this direct feedback is complemented with a reaction of the digital system, mediated by pixels and other modalities. This feedback is often colocated and immediate, but very rarely is on the same modality as the input.

Radical elements enable sensing and actuation on the same modality and are able to directly mediate between the user's touch and the computation through the material itself. In the most extreme case of this scenario, the material properties can be completely overwritten by the computational system. The material then purely mediates digital information.

Periodic Table of Radical Elements

If the task of the display is to serve as a looking glass into the mathematical wonderland constructed in computer memory, it should serve as many senses as possible.
Ivan E. Sutherland

The following section surveys a list of currently available radical elements and orders them in a periodic table. The nature of periodic tables is to incorporate recurring trends, in order to derive relationships between properties of the elements and to predict properties of the new, yet to be discovered or synthesized, elements.
The periods (columns) of this table of radical elements describe the modality in which each element can sense and actuate. The rows losely describe the level of artificial complexity that the element requires to attain this functionality. For example, the period '*Rotation*' starts with a simple DC-motor as the simplest element to actuate and sense this modality. This is followed by the stepper motor that introduces more complexity in its coil and magnet structure to create more precise, step-based rotations. The final element is the servo-motor, that uses an assembly of a DC-motor, a potentiometer, mechanical gears, and some electrical control systems to abstract the rotation of the DC-motor to a controlled angular position. The general order implies that the the further down in its period the element is, the more complex (and sophisticated) is its functionality.

Radical elements are not the only means for designers to create interactions. There are many actuation and sensing methods available that do not have a counterpart to make them bidirectional. This is either caused by technical or perceptual limitations (Eg. How does one control a material's stiffness with human input?). This table merely focuses on elements that afford bidirectionality. They are components that physically unify the trigger and feedback of physical microinteractions and enable direct computational feedback on any human input on top of other functionalities.

The purpose of this table is to list and order the devices and technologies at the disposal of interaction designers to create those bidirectional interfaces. Simple interactions can be crafted by using just one radical element, while connecting multiple elements can create more complex embodied interfaces and interactions.

Light	Temperature	Magnetism	Vibration/Sound	Linear Motion	Rotation	Bending/Volume
LED LED Light	Copper Cu Heat	Electromagnet EM Magnetism	Speaker Sp Vibration	Solenoid Sol Push	DC-Motor DCM Rotation	uniMorph uM anisotropic bend
	Peltier Pe Temperature	Electropermanent Magnet EPM Semipermanent Magnetism	Piezo Pz Vibration	Linear DC Motor LDC Linear Position	Stepper Stp Rotation Steps	Pneumatics Pn Anisotropic Shape Change
				Motorized Slider Sl Linear Position	Servo SRV Angular Position	

Figure 22: The periodic table of radical elements lists and categorizes bidirectional I/O transducers.

Electromechanical Radical Elements

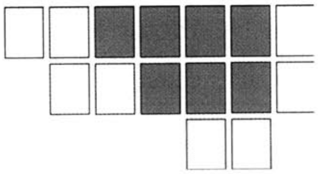


Figure 25: Electromechanical Radical Elements

> "It's electromagnetism (EM) in all its many forms that has been so basic, that haunts us and guides us."
> *Nick Holonyak Jr.*

Electromagnetism has been leveraged in a multitude of actuators and can be found in a variety of configurations. Most electromechanical devices work bidirectionally, as sensors and actuators. However, different levels of accuracy often lead to the employment of additional sensors.
The electromagnetic devices presented here exemplify an interesting recursiveness, similar to the term 'material' discussed earlier.

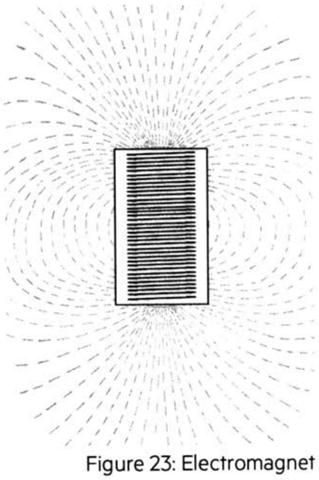


Figure 23: Electromagnet

Electromagnets can create magnetic forces when electric current is applied. The force and size of the field are dependent on the electric current and the magnetic field disappears when the current is removed. External changes to the magnetic field induce a Lorentz Force into the copper coil and create measurable voltage changes. Electromagnets are primarily actuators and can be paired with Hall Effect sensors for increased sensing accuracy. While electromagnetism can not be perceivable directly, a lot of effects derived from it can be.

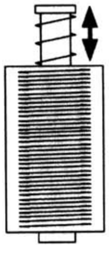


Figure 24: Solenoid

Solenoids are built similarly to electromagnets, with the exception of a loose shaft that moves when current is applied to the surrounding electromagnet. Usually the shaft is mechanically restrained to not leave the electromagnets core. The exerting force of the shaft is dependent on the current applied to the solenoid's coil. Similar to electromagnets, movement of the magnetized core shaft will induce a Lorentz Force that is measurable in voltage change.

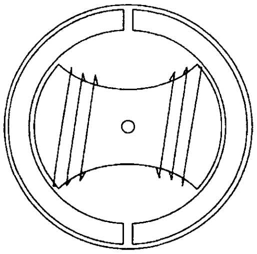


Figure 26: DC-motor

DC-motors are devices that turn electrical current into rotation and rotation into electrical current. An ideal DC-motor would do this without energy loss but friction and heat dissipation reduce the energy efficiency of the system.
The speed of a DC-motor is dependent on the electrical current and vice versa. For more precise sensor readings, the DC-motor can be paired with a rotary encoder.

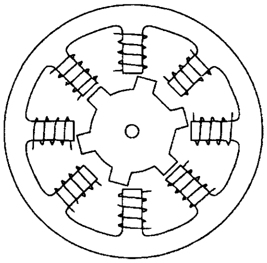


Figure 27: Stepper motor

Stepper motors act similar to DC-motors, but are more complex. By using multiple coils and magnets, the way the device rotates is based on steps and not continuous rotation. This requires more complex control structures but also allows for a very precise control of rotation.

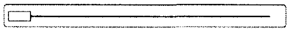


Figure 28: Linear slider

Linear actuators use a DC-motor, a potentiometer, and a belt transmission to move a slider to a defined position. The potentiometer and DC-motor create a closed-loop control for the slider's position. The potentiometer can also sense external interaction with the slider's position.

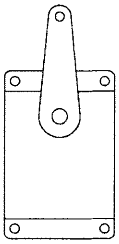


Figure 29: Servo-motor

Servo motors leverage a DC-motor, a potentiometer, mechanical gears, and a control system to abstract the simple rotation of a dc-motor into angular control, usually in a 180° radius. Usually the sensor feedback remains internal, however some servos allow direct reading of the potentiometer values.

Molecular Radical Elements

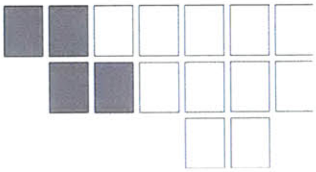


Figure 31: Molecular Radical Elements

The concept of radical elements transcends the traditional categories of materials and electromechanical actuators. While electromechanical devices are relatively large scale structures other *radical elements* are enabled by small molecular structures. These molecular-enabled *radical elements* exhibit different electric phenomena that can be leveraged for bidirectional transduction.

Figure 30: A home-made "Rochelle Salt" crystal with piezo-electric transducer qualities.

One example is a **piezoelectric** material (Figure 30) that can sense and actuate vibration. Many molecules exhibit piezoelectric behavior, including crystals of potassium sodium tartrate and barium titanate ceramic. When two electrodes are connected to the crystals those molecules form, they can be used to sense and actuate sound vibrations.

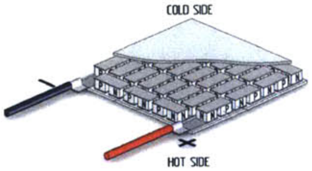


Figure 32: A peltier junction can translate electrical into thermal energy and vice versa.

Another example for a material-based radical element is a **Peltier Junction**. It is based on two thermoelectric effects discovered in 1821 and 1834. The first is the Seebeck effect, which describes that a temperature difference between two dissimilar (semi-)conductors produces a voltage between the substances.

The second is the Peltier effect, which shows that heat generation (or removal) occurs when a current is made to flow through a junction between two dissimilar conductors. Together, these two effects result in a Peltier Junction that produces a temperature difference when current is applied and generates electrical power when exposed to a temperature difference.

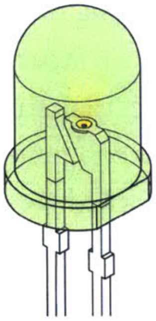


Figure 33: An LED is known for emitting light, but can also be used to sense light.

A widespread *radical element* is the **LED**. Known for its capability of emitting light in various colors, this component is deployed in almost every electrical device for purposes of indication, illumination and even displays. LEDs are not just actuators, but can also be used to sense light intensity, making them a radical element for light.

Another curious *radical element* is an electrical conductor, which is usually made of **copper**. The electrical conductivity of copper decreases with an increase in temperature. Heat can be generated by copper conductors through resistive heating. Since copper has great thermal conductivity, environmental heat radiation can also increase copper's temperature.

Radical Element Reactions

The previous sections introduced various radical elements function as unified input and output devices. While they sense and actuate various modalities, they all have voltage as a 'common language'. This allows for interesting connections between them, that translates inputs of one modality to outputs of another. Some of these connections are already being implemented in current systems, while others promise interesting new mappings.

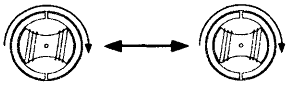


Figure 34: Two radical elements can be connected to create new behaviors.

The simplest of connection that can be made is between two identical radical elements. Given the element is efficient at translating the input energy into electrical energy and back, this allows for the cloning of inputs. An example for this is connecting two stepper motors directly. When one is rotated manually, the other motor will mirror these same movements. The behavior of this structure is symmetric, as both modules can be used as an input or output of equal power.

When two different radical elements are connected, they create interesting cross modality behaviors. A DC-motor connected to an LED causes the LED to light up when the motor is spun in the right direction. This effect is used to make bike lights that are powered by the rotation of the bike wheel.
This kind of connection is assymetric, as the power that the LED can create is not enough to drive the DC-motor. In order to make this connection symmetric, electrical amplification circuits that provide additional energy from power sources such as batteries have to be used.

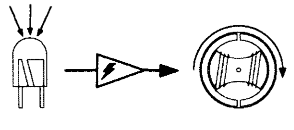


Figure 35: Electrical Amplification allows assymetric connections of radical atoms to work.

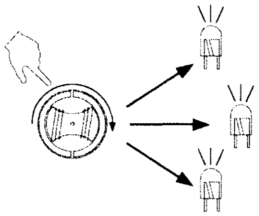
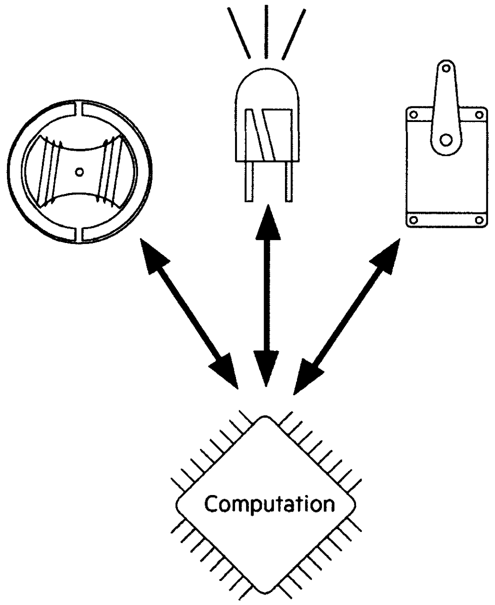


Figure 36: Assymetric connections allow one element to drive multiple other elements.

Similar to chemical elements, certain combinations of radical elements are 'stable', or in this case symmetric, while others need additional energy to work.
Many types of structures of varying complexities and different quantities of *radical elements* can be built. For example, one DC-motor can light up multiple LEDs and actuate an additional Peltier Device.

Even more complexity is introduced when the elements are not connected directly but connected through a computational unit. While cause and effect are very simple with direct connections, computation introduces algorithmic complexity into the behavior of these elements.
Chapter 5 discusses the new capabilites of radical elements and computation in comparison to inert materials in greater detail.

Figure 37: Computation and external energy sources allow the creation of complex and dynamic rulesets for physical behavior.



uniMorph

Introduction

This chapter presents uniMorph, a thin-sheet shape-changing composite that enables shape actuation and sensing. The chapter exemplifies how a new *radical elements* can be fabricated with cheap and available materials.

As discussed earlier, most currently available radical elements are engineered from electromechanical devices. While the argument is made that these devices will be miniaturized and additional new synthetic materials will be engineered to create similar functionality, the list of currently available materials that can change and sense their own shape is still short.

(a) Tunable Clay (b) Transparent Haptic Lens

(c) Behind-the-Tablet Jamming (d) ShapePhone

Figure 38: Organic User Interfaces enable new modes of mediation between computation and humans. Here exemplified by stiffness-changing interfaces.

Recently emerged printed electronics are a powerful and enabling technology for HCI products and prototypes that leverage these qualities. Embedding sensors into flat sheets creates possibilities for thin media as input devices [Lahey, 2011], while dynamic sheet materials with active shape-change have been employed as a computational output. In particular user interfaces powered by transitive materials [Girouard, 2011] are of great interest, as seen in works investigating soft user interfaces [Tarun, 2011][Yao, 2013], flexible sensing techniques [Rekimoto, 2002, Gong, 2014] and dynamic stiffness explorations [Ou, 2014]. Liberated from rigid mechanical structures and electro-mechanical components [Girouard, 2011] these augmented sheets allow for expressive, precise, and tangible interactions with digital data.

We are used to interacting with passive thin sheet-like paper or other raw materials in our daily lives and have internalized the affordances that this form factor offers. Recently emerging technologies such as OLEDs [Geller, 2011] or custom thin-film displays [Olberding, 2014] release GUIs from their confined rigid form factor and leverage these qualities. The use of this new dimension for input possibilities has been explored in several papers [Lahey, 2011][Rekimoto, 2002][Tarun, 2011] [Wightman, 2011][Gong, 2014], however there is considerably less work on active shape output for this medium [Roudaut, 2013][Gomes, 2013][Yao, 2013]. One of the barriers to further research in this field is the complicated and expensive fabrication processes required to create shape-changing material mechanics.

By combining the thermoelectric characteristics of copper with the high thermal expansion rate of ultra-high molecular weight polyethylene (UHMW PE), one can shape-actuate flexible circuit composites directly. The shape-changing actuation is enabled by a temperature driven mechanism, similar to bi-metal strips [Howes, 2012] and dramatically reduces the complexity of fabrication. The copper layer enables capacitive sensing for either bend-angle or touch sensing, making this composite. Furthermore it affords the embedding of sensors, additional actuators, or even micro-controllers, making it a true computational composite [Vallgarda, 2007]. This enables more HCI researchers to design and fabricate thin-film shape-changing interfaces.

The availability and ease of fabricating this composite democratize the design and fabrication of shape-changing interfaces. For this reason, the steps and materials needed to create this material are documented not just in this thesis, but also in a video online. This way we hope to inspire more HCI researchers and makers to engage in this promising field.

Dynamic Materials

New materials not only improve existing material qualities, but also introduce new qualities, especially in connection with computation. A range of sensing materials and composites are introduced that allow everything from stress monitoring to traffic counting by embedding sensors into the material.

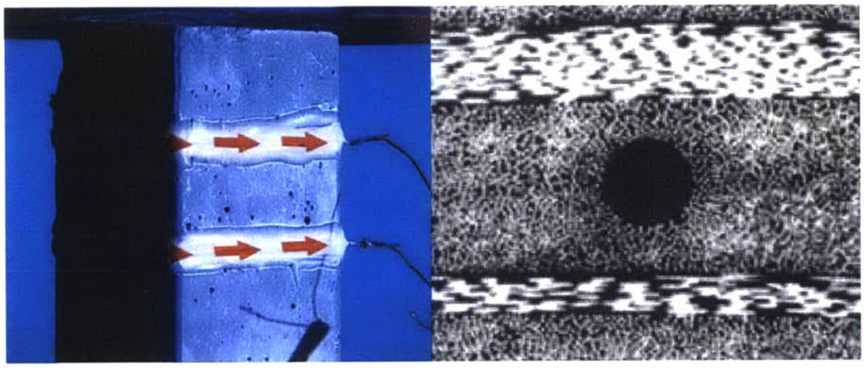


Figure 39: Sensors can be embedded into materials and composites to monitor material stress computationally. These 'smart' materials can range from large concrete sandwiches (left) to small optical fibre sensors embedded in carbon fibre composites.

Other materials extend the palette of actuators that was previously dominated by electromechanical devices. A large variety of shape-changing materials and composites have been utilized by designers to create and assemble new active artifacts. The following part will present a non-conclusive list of those materials.

One category of dynamic materials is materials that change their shape in response to environmental stimuli without the need for sensing, digital computation, or addtional energy. Those techniques are especially valuable for large-scale architectural applications that would require a lot of energy and wearables that do not require the attachment of rigid batteries.

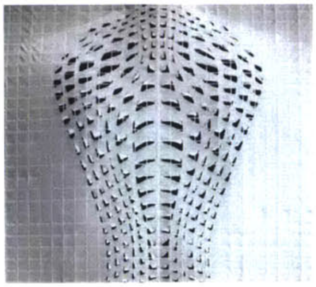


Figure 40: The bioLogic project explores humidity responsive wearables that do not require additional power or computation.

One example in the space of wearables is the bioLogic project, which utilizes the natural responsiveness of natto Cells to create a shape-changing mechanism. One of the design applications for this technique is a shirt with permeability that responds to the wearers sweat.

On the architectural level, Doris Kim Sung exploits the shape-changing dynamic of bimetals that bend when warmed up or cooled down. Her breathing facades open and close solely powered by the sun's rays.

Figure 41: Doris Kim Sungs work with bimetal structures exemplifies heat responsive architectural structures.

Achim Menges exloits the natural shape-changing qualities of wood to create a pavillon with semi-permeable elements that respond to humidity.

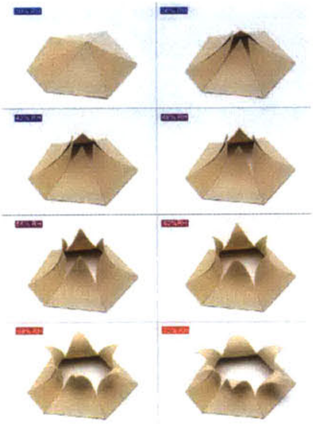


Figure 42: Achim Menges' Hygroskin utilizes the natural humidity responsiveness of wood.

Studio Roosegaarde's 'Lotus Dome' exempifies the artistic expression that responsive materials can have. The Dome's surface consists of a very thin foil material that bends when heated. An internal directional light source follows people in the space and is revealed by the 'blooming' foil.

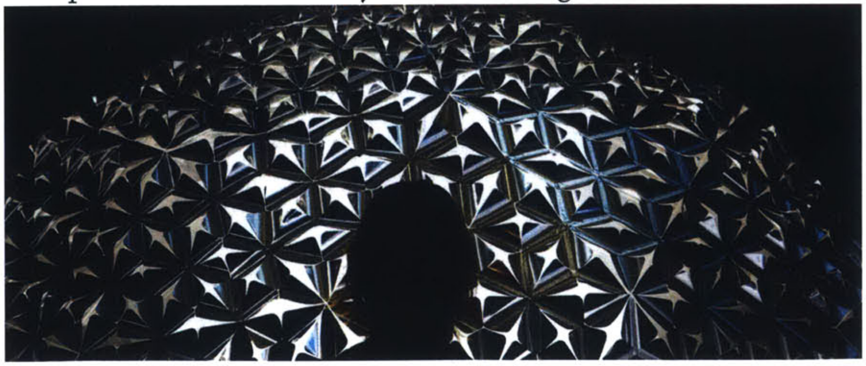


Figure 43: The Lotus Dome by Studio Roosegaarde is actuated by the internal light source.

Figure 44: Additive Manufacturing Techniques make material transformations more controllable.

Recent work by Skylar Tibbits shows how the transformation of wood can be controlled by leveraging 3D-printing techniques. By defining the fiberous structure of the wood during fabrication, the wood's humidity-responsive transformation can be defined. A similar approach works for carbon fibre, which responds to heat that can be generated by means of resistive heating.

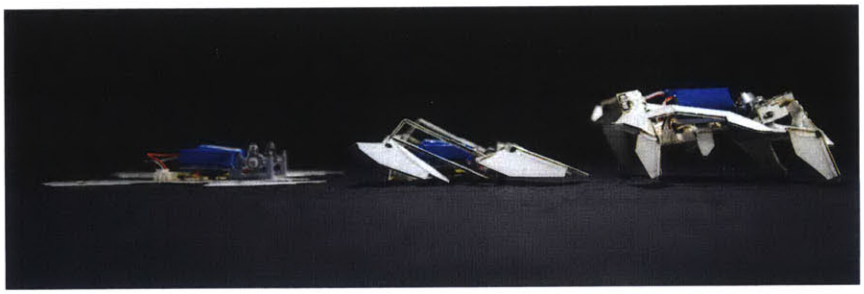


Figure 45: Pre-streched Polyethylene sheets allow for one time self-assemblies .

Another group of dynamic materials can be actively controlled by computation. Pre-stretched polystyrene sheets are used as one-time actuators to assemble devices from flat sheets. The actuation mechanism is based on the energy stored in the pre-stretched material. When an area of the material is heated up it shrinks and bends. This behavior is very controllable and can be used for complex assemblies like the robot by Felton et al. seen in Figure 45`.

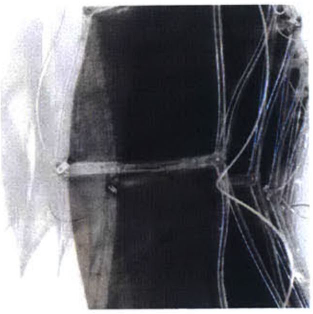
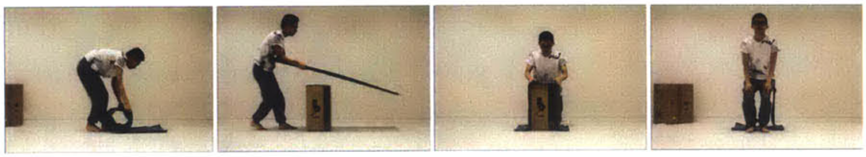


Figure 46: Electro-active polymers change their shape when high voltages are applied.

Electroactive polymers change their size when stimulated by an electric field. They can create large deformation forces and are often referred to as artificial muscles. They often require thousands of volts, but very little electrical current. Due to their high transformation forces, they are often used in experimental architectural contexts.

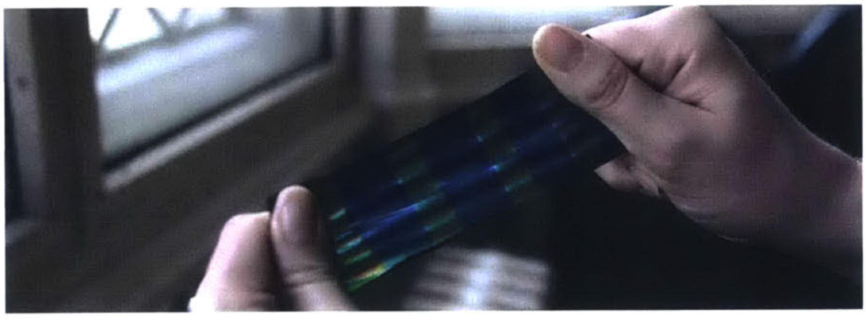
Materials can also change properties other than shape. Multiple approaches have been proven successful to control material stiffness. Layer jamming uses negative air pressure to increase surface friction of a loose composite to control its stiffness. Another approach is using electroactive polymers that, instead of changing their size, become stiff when voltage is applied.

Figure 48: Controllable stiffness creates new affordances for ad-hoc furnitures.



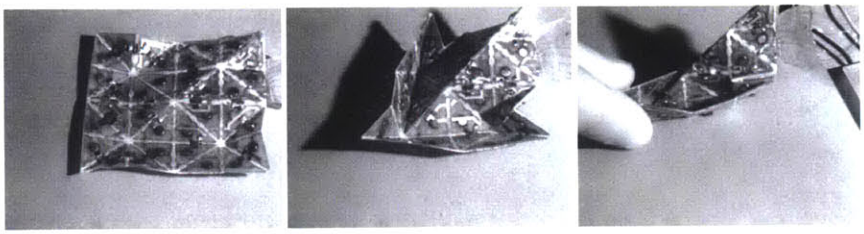
Another controllable property of a material is its color. Most commonly used is thermochromic material that changes its color based on temperature. Thermochromic material is available as dye powder and can be mixed with and applied to a wide variety of materials. Other lesser known effects are photochromism, electrochromism (e-paper) or materials changing their color based on physical stress.

Figure 47: This artificial material passes through a full rainbow of colors as it's stretched



Shape-memory alloys are one of the widest known materials used for shape change. It is sometimes referred to as 'smart material' because it is not limited to just changing its shape but also can store a preprogrammed shape and return to it after deformation. Shape memory alloys can be created from a wide variety of metals. However, the most popular materials are nickel and titanium. This material comes in wire or sheet form and is actuated by means of (joule) heating.

Figure 50: By leveraging folding mechanisms one sheet can transform into different shapes.



Finally, materials can be engineered and synthesized to transcend any behaviors found in nature. Those materials are categorized as metamaterials. Optical metamaterials range from physically flat lenses to invisibility cloaks while mechanical metamaterials can show auxetic behavior that cannot be found in nature.

Figure 49: Metamaterials are structures that behave in ways that can't be found in nature.

Digital Fabrication of flexible electronics

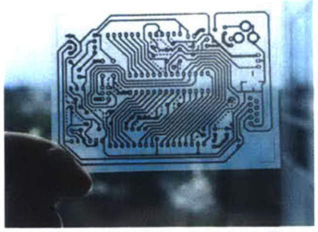


Figure 51: Inkjet printing allows direct printing of conductive patterns on a wide variety of mateirals. Shown here is one example: flexible PET.

Recent interest in new form factors and shape changing interfaces brought an advent of flexible printed circuits (FPC's). The low-cost and ease of fabrication with high precision make them an interesting medium for a wide range of projects from prototyping to complex DIY projects [Tarun, 2012]. Research in inkjet printing with conductive inks [Kawahara, 2013] shows how flexible circuit fabrication can be moved from labs onto desktop printers.
HCI projects like Gummi [Schwesig, 2004], Paperphone [Lahey, 2011] and Snaplet [Tarun, 2011] show how shape sensing can be integrated with flexible circuit sheets without sacrificing the flexibility of the material. The robotics field uses flexible circuits for resistive heating of pre-defined areas [Felton, 2013].

Flexible Sensing Technologies

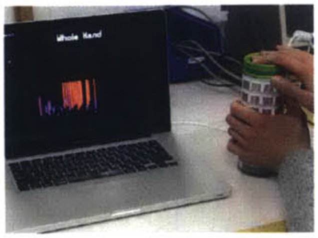


Figure 52: Printed sensors on flexible substrates can be wrapped around objects to augment their functionality.

A variety of sensing techniques on flexible surfaces have been explored in HCI. Bend sensor composites [Lahey, 2011], optical sensors [Follmer, 2012] and flexible capacitive sensing [Gong, 2014] are among some common approaches to sensing human interaction as well as the material topology itself. Capacitive sensing techniques present a particularly interesting opportunity as they are able to detect human interaction and determine their own topology [Gong, 2014], while possibly also providing the architecture for electrical components.

Organic User Interfaces & Transitive Materials

The field of organic user interfaces (OUI) explores future scenarios "as computationally controlled materials become commonplace" [Girouard, 2011]. The OUI movement is led by the idea that the physical shape of objects and displays will and should deviate from its current flat static form and become as malleable as the pixels on a screen [Ishii, 2012]. This transformation is powered by "transitive materials" [Girouard, 2011] that sense and conform to the users molding and actively drive its own shape-change [Ishii, 2012].

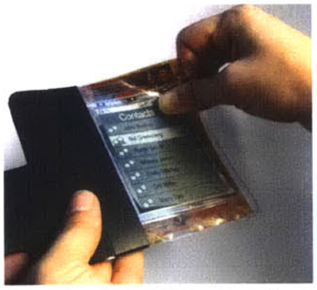


Figure 53: Organic User Interfaces enable new interactions with digital systems.

While OUI research includes explorations into stiffness changing [Ou, 2014][Yao, 2013] and stretchy mediums [Kramer, 2011], we are most focussed on sheet interactions in this context. Previous work on interaction with foldable [Gomes, 2015] and flexible [Lahey, 2011] sheet-devices are concerned with exploring them for malleable screens [Olberding, 2014], more abstract forms [Balakrishnan, 1999], or materials including fabrics [Gioberto, 2013]. For thin sheet materials with active shape-change, techniques include soft user interfaces actuated by air pressure [Yao, 2013] as well as flexible mobile devices driven by nitinol [Gomes, 2013][Roudaut, 2013].

Shape Changing Sheet Technologies

The field of robotics is primarily concerned with the structural assembly of robots or sensors, as well as developing new techniques for creating stronger and faster shape-changing materials. In this paper, we are focused on making shape-changing techniques available to the HCI field. We leverage existing techniques like joule heating copper, and combine it with cheap, accessible, and easy to fabricate materials to create a shape-changing composite and fabrication method that is reproducible for HCI researchers.

Self-folding robotics is a domain dedicated to developing autonomously self-assembling robots, often inspired by origami folding patterns [Hawkes, 2010][Na, 2015][Okuzaki, 2008]. In contrast to other electromechanical methods for self-assembly, self-folding robotics focuses on shape actuation using material actuation mechanics [Hawkes, 2010] instead of motors or other external actuators.

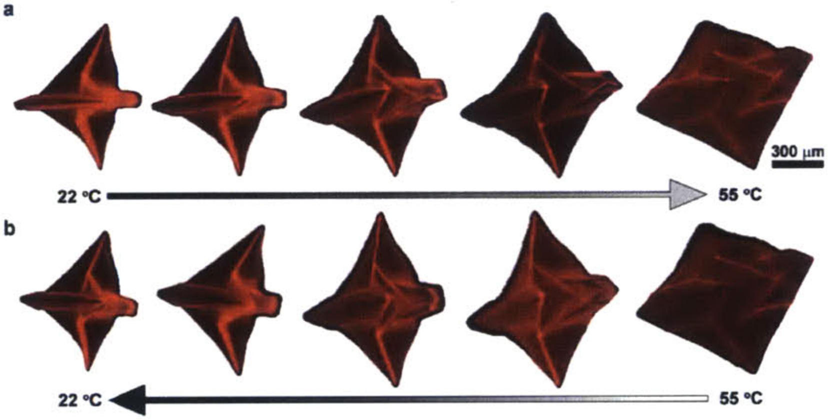


Figure 54: Origami techniques are used to fold materials into three dimensional structures at scales as small as 300 um.

A large area of this research is dedicated to materials for self-assembly with non-reversible actuation. Shrinking sheet materials are used to assemble structural [Felton, 2013] and functional parts [Shin, 2014]. While some use external actuation energy like baking [Na, 2015] or local light absorption [Liu, 2012], some researchers leverage the advantages of joule heating with thin copper traces for local heat actuation [Felton, 2013]. Previous work on reversible material shape actuation for sheets using nitinol [Hawkes, 2010] and electroactive polymers [Okuzaki, 2008] is impossible to reproduce without expensive equipment.

Unimorph Actuation Mechanism

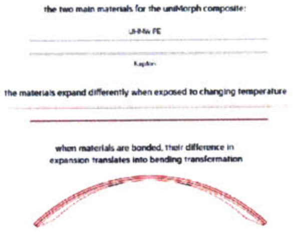


Figure 55: The unimorph actuation mechanism is based on different thermal expansions of materials.

Two flexible materials with vastly different coefficients of thermal expansion composited form a mechanism called unimorph actuator. As the composite is heated, the material with the higher coefficient of thermal expansion exerts a shear stress on the adjacent, less expanding material, causing the composite to bend perpendicular to the plane of the composite as seen in Figure 55. Cooling the composite down bends the composite in the opposite direction. The actuation of unimorph actuators is fully reversible and well understood. Generally, the curvature can be described using classical laminate theory [Hashin, 1979].

A variety of material combinations can be used to create this kind of unimorph actuator. For the composite presented in this paper (we call it "uniMorph"), we use Ultra-High Molecular Weight Polyethylene (UHMW PE) and Pyralux® by DuPont® - a flexible copper clad with Kapton® as a carrier material. In addition to its availability and low price, we chose these materials for the high difference in thermal expansion and the possibility of easily embedding resistive heating by etching the Pyralux material.

Kapton and copper have similar linear thermal expansion coefficient of 20 x 10^{-6} K and 20 x 10^{-6} K while UHMW PE has a coefficient of approximately 200 x 10^{-6} K at 20° C. Given these coefficients, the UHMW PE expands greatly compared to the Kapton, causing the composite to bend. When cooled, the UHMW PE shrinks faster, causing a bend in the opposite direction. The maximum composite temperature for reversible actuation is 95° C. The speed at which the composite actuates is controlled by the temperature differential with respect to the environment. This allows for precisely controllable actuation with variable accelerations when heating the material. However, cooling speed is constant, leading to possibly asymmetric actuation times. Two approaches of addressing this behavior are presented in the upcoming section.

Passive Shape-Change

The simplest way of changing the temperature of a uniMorph composite is by modifying the temperature of its outside environment. Heat is a common waste-product of household and industry devices that is usually not utilized. Passively shape-changing composites offer interesting possibilities to use this excess energy for shape-actuation with functional and/or aesthetic purposes.

As seen in Figure 55, one simply needs to create a two-layer composite of Kapton and UHMW PE (or other materials with a large difference in thermal expansion to create a passive shape-changing composite). When the passive uniMorph composite is designed for light absorption, the composite should be darkened by either painting it or using black Kapton. Local light absorption as seen in Liu et al. [Liu, 2012] can be leveraged for actuating specific parts of the composite. Once composited, the sheet can be cut into arbitrary shapes by using digital fabrication tools like vinyl or lasercutters.

Active Shape-Change

For a uniMorph composite to actively change its own shape, it has to change its own temperature. As seen in Felton et al. [Felton, 2013], thin trace serpentine routing can used as resistive heating circuits to enable computational control of the composite's temperature (Figure 64). Custom design of resistive heating patterns allows for addressed heating of specific areas. These resistive heating structures can be easily integrated into a thin-film composite using a Pyralux, Kapton and copperlaminate as shown in Figure 62.

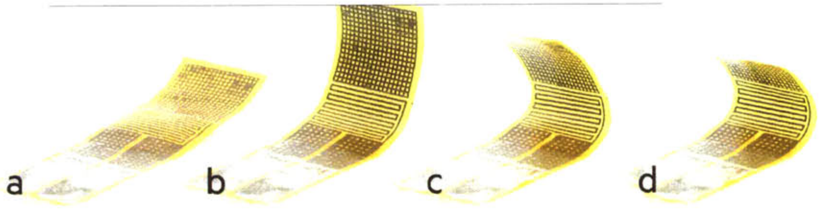


Figure 56: The bending behavior of the uniMorph composite. Only the area with resistive serpentine routing bends.

The temperature of areas containing resistive heating patterns is controlled by the electrical power applied to them . Hence, the actuation speed of the composite can be controlled through a simple pulse-width modulation method. This allows for full actuation speeds from under a second to infinitely slow.
While the increase in temperature can be computationally controlled with resistive heating, the cooling of a composite is normally solely dependent on its surrounding temperature and its thermal resistance and cannot be computationally controlled. We explored multiple ways of addressing this issue.
Adhering a Peltier Element onto the copper enables active cooling of the composite. Because of the high thermal conductivity of copper, the thermal energy is removed from the system very efficiently. We found this method can increase the cooling speed up by a factor of four and additionally enables computational control of the cooling process. Another method is using

pyrolytic graphite, a sheet material with even higher thermal conductivity than Copper. By placing this material onto the copper layer of the uniMorph composite, the cooling speed can be increased by 2.2x without additional power usage. The two methods together add up to 5x faster cooling speeds.

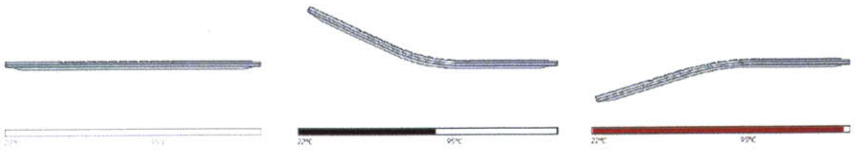
Another advantage of using the copper layer for heating the composite is the ability to have multiple heating circuits that can be addressed independently. This enables multiple shape-changing behaviors with one composite as well as sequential actuation.

Neutral State Programming

Ultra-high molecular weight polyethylene has a working temperature of 95° C. For regular reversible actuation this temperature must not be exceeded. However, when its temperature exceeds this limit, the material undergoes a molecular reorganization, leading to a room temperature state of higher density that ultimately results in a pre-curled neutral state. The following actuation in regular range continues to work. However, the resting position of the material is now bent and the maximum actuation is a straight sheet (Figure 57).

To achieve the pre-curled state, the composite can be either heated up in an oven or embedded heating structures can be used to pre-load the material. The latter method allows for a combination of flat and pre-curled neutral states in the same composite, since the heating elements are individually addressable. Alternatively, the materials can be composited at a temperature different from normal room temperature. This way, the material is already partially actuated at room-temperature.

Figure 57: The neutral position of the uniMorph composite can be programmed by overheating the composite.



Actuation Performance

When designing the uniMorph composite, several different factors affect the bending behavior of the composite. For this thesis, we characterized the behavior of simple bending composites as seen in Figure 56.

When concerned with bending actuation range, the most important factor is heater length - the length of the area covered by the resistive heating pattern. The longer the heater length, the bigger the maximum bending angle of the composite.

When designing shape-changing composites with stiffeners (see section primitives), the most determining factor is is hinge length, which is defined as the length of the area in between two stiffeners. The larger the hinge-length, the larger the bending angle becomes. When using stiffeners the heater length has no noticeable effect on the bending angle as long as it covers the length of the hinge completely.

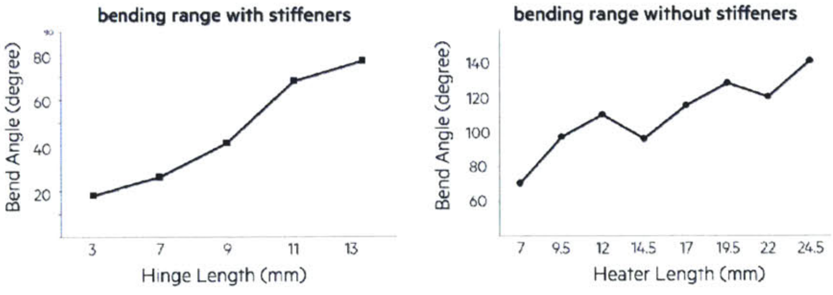
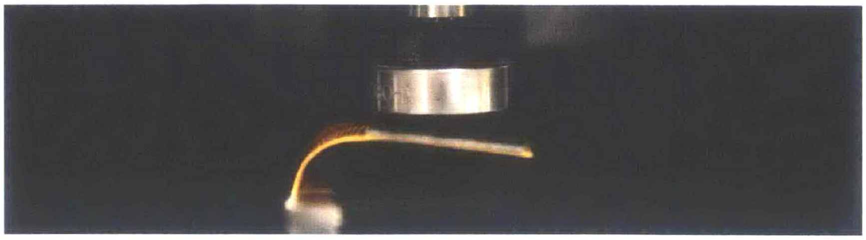


Figure 58: Bending characteristics of uniMoprh composites with and without stiffeners.

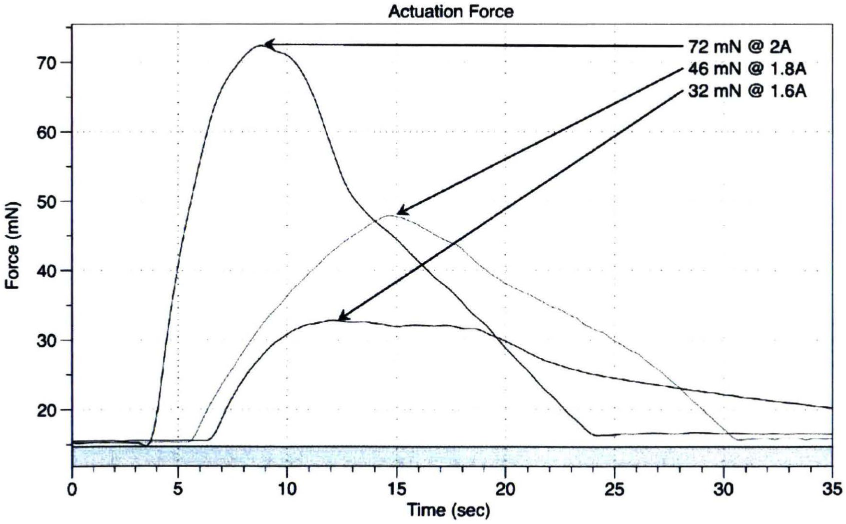
Figure 59: Torque testing for the unIMorph composite has been conducted with an "Instron" electromechanical force measurement system.



As can be seen in Figure 60 the actuation force (torque) of the composite is dependent on the thickness of the UHMW PE layer and the applied power. 12 mil thick UHMW PE film was used for the force tests. The sample was 1.5" wide with a 0.6" x 1.5" heating area and 1" x 1.5" area to lift. The tests were conducted with an Instron force measuring system with constant power supply to the composite (Figure 59). While the torque is comparably small, it is still remarkable for the thickness of the composite.

It is important to note that the composite has repeatable force and actuation characteristics as long as it is not overheated. As soon the UHMW PE reaches temperatures of over 90°C, the actuation force decreases in addition to the shape actuation range offset.

Figure 60: Actuation Force is dependent on the applied current as well



Design Space

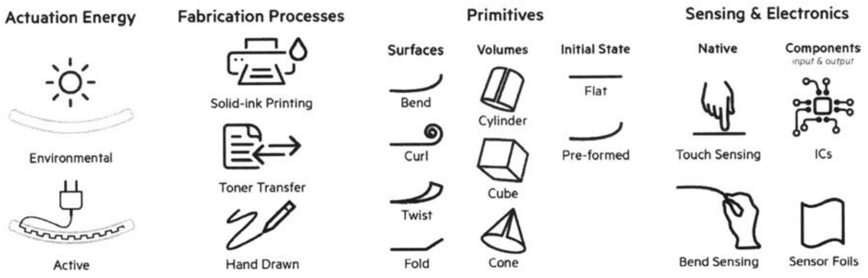


Figure 61: Four-dimensional design space for digital fabrication of custom uniMorph composites.

Custom made uniMorph composites offer many degrees of freedom for design. We found four dimensions of the digital fabrication of uniMorph composites that clarify the choices in design. This section provides an overview of these dimensions that will be described in more detail later. The design space is additionally illustrated in Figure 61.

Actuation Energy

The shape-change of uniMorph composites is powered by temperature change. Temperature change can be purely environmental or achieved by resistive heating elements in the composite. We define these modes of actuation as active and passive shape-change. Passive shape-change lacks computational control, but does not require any additional energy. Active shape-change on the other hand offers very precise and local actuation of the material while requiring energy. UniMorph composites can be designed for either passive or both passive and active shape-change.

Fabrication Process

We propose a digital fabrication approach for the production of customized uniMorph composites. For digital fabrication, the designer generates a digital pattern for the conductive layer as well as the overall shape of the composite using familiar tools like CadSoft Eagle or Adobe's Illustrator. Ideally the pattern could be printed directly onto the Kapton using conductive ink and then automatically laminated. This would enable rapid prototyping with faster iterations.

We show how to create uniMorph composites by printing patterns directly onto the Pyralux laminate using solid ink printing. The printed Pyralux is then etched in the same manner as in DIY PCBs. While solid ink printers are not very widespread, this method comes closest to the instant process automatic fabrication. Since solid-ink printing is not available in most labs, we also present a toner transfer method that matches the quality of solid-ink printing with slightly longer fabrication times. Finally, we demosntrate a free hand prototyping method that does not involve digital fabrication but works by directly drawing onto the copper.

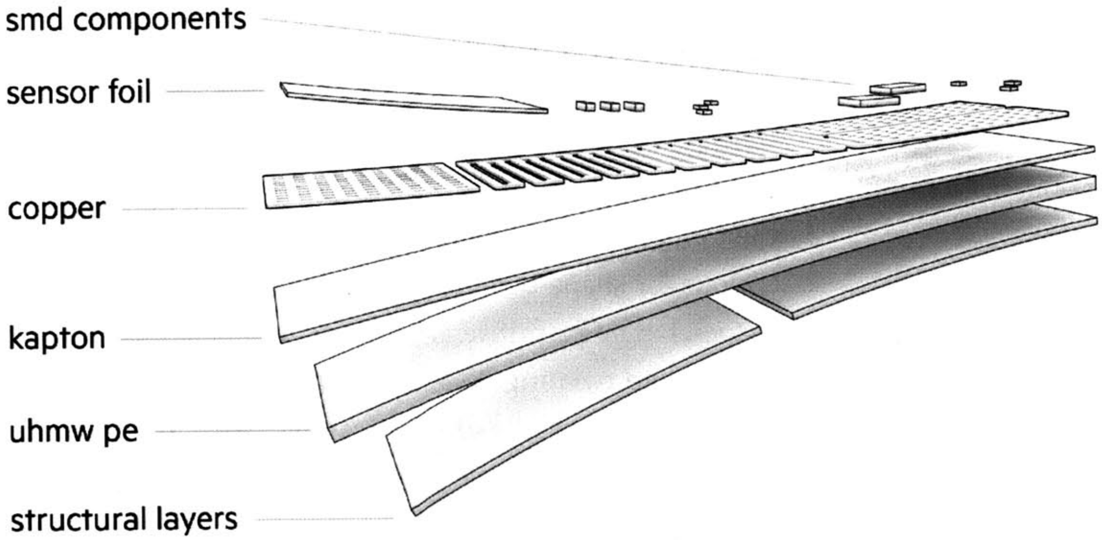
Shape-Changing Primitives

Customized uniMorph composites offer a variety of design options for shape-change as seen in Figure 61. The natural shape-change primitive is bending, which can be modified into curling and twisting. Materials that are stiffer than the film itself, which we call stiffeners, can be added to the composite to restrain and amplify the bending behavior. Using this technique, designers are able to create folds and three dimensional structures. While the passive composite's shape-change is fully determined during its digital fabrication, the active composite can change into multiple states after fabrication since the actuation elements are individually addressable. Finally, the uniMorph composite's neutral state can be changed from flat to pre-curled by heating the composite to a temperature higher than its working temperature.

Integrated Sensing & Electronic components

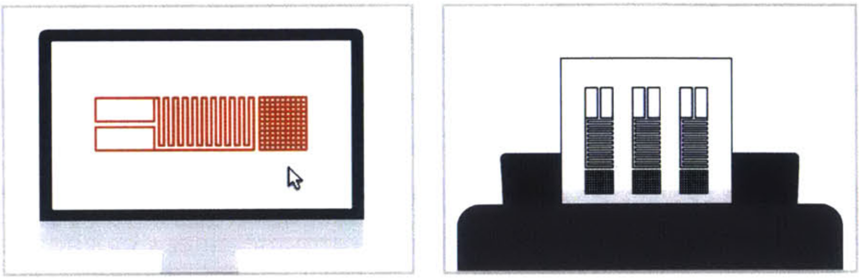
Sensing user input is crucial for using uniMorph in HCI applications. We present three ways of sensing user input on the uniMorph composite. One approach leverages the copper structure as a sensor for both human input and its own topology. Alternatively, we show how the force resistive foil material Velostat can be easily integrated into the uniMorph composite for force and bendsensing. Finally, the Pyralux laminate allows for an easy integration of surface mount components, which significantly expands the sensing capabilities of the uniMorph composite.

Figure 62: The layer structure of the uniMorph composite.



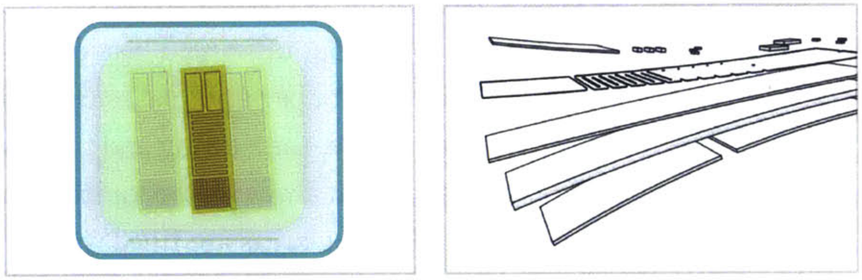
Digital Design & Fabrication

Figure 63: The design and fabrication process of the uniMorph composite takes has four steps.



1. Computational design

2. Printing onto copper



3. Etching / toner removal

4. Final compositing

The fabrication of uniMorph composites can be divided into four steps. The designer creates a digital model of the composite structure (Figure 63.a), then fabricates this structure using print and etching methods (Figure 63.b-c), and finally composites the Pyralux laminate with the UHMW PE and other additional materials (Figure 63.d).

Digital Design

As with most active material composites, the range of possible shape-change is defined in the fabrication process [Coelho, 2011]. The dominant factor for the behavior of the uniMorph composite is the layout of the thin resistive heating copper traces. Designing heating elements of different shapes and distributions leads to new shape-changing behavior. The patterns can be designed with digital tools and then materialized through a bitmap print. This allows for the use of common applications such as Illustrator, Photoshop and Eagle for the digital design.

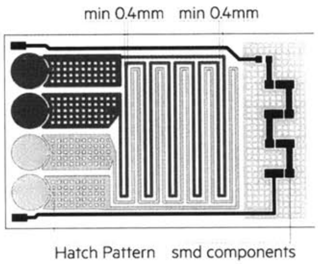


Figure 64: The copper-layer of the uniMorph composite enables resistive heat actuation. By creating two interweaving patterns (here seen in dark in light grey), the heating structure can also be used for bend-sensing through mutual capacitance. Furthermore, SMD components can be embedded.

Resistive heating elements are generated by creating thin copper traces that conduct high currents. We found the minimum width of traces that can be reliably fabricated to be 0.4mm (16mil) (see Figure 64). To heat up a designated area, a space-filling meandering pattern is used (as seen in Felton et al. [Felton, 2013] . Non-heating traces that carry load should be as wide as possible to ensure current supply to the heating areas without unwanted heat dissipation.
Since the copper also makes up a large part of the material structure, the heating and transport patterns have to be designed in a way to support the materials deformation. Non-heating areas are filled with a hatched copper plane that combines high conductivity with the motion range of a flexible composite. For heating areas, the traces should be angled perpendicular to the bending direction to not interfere with the shape-change.
An alternative approach to digital design and print is using permanent markers to draw directly onto the copper-layer. While this method does not allow for the same accuracy as digital graphics and routing tools, it allows for faster and more expressive pieces. We also found this technique to be extremely useful to repair missing patches in the toner transfer method described later.

Stiffeners

Sheets of different materials can be applied to part of the uniMorph composite to stop it from bending in that particular area. In addition to its stabilizing and restricting properties, it also amplifies the bending effect in neighboring areas, as the thermal expansion of the material is redirected into those areas (Figure 65). To leverage this effect accordingly, the stiffened and heating areas should be overlapping by at least 1 cm. We found sheets of paper between 100gsm and 130gsm to have the right balance of weight and stiffness.

Figure 65: Adding a stiffening layer to the composite creates a hinge.

Fabrication

After designing the copper layer, the design is materialized through a bitmap print. The method available to most people is printing on glossy paper with a toner-printer, followed by a heat-transfer onto the copper layer of the Pyralux [DIY-FPC]. If available, a solid ink printer can be used to print directly onto the copper, eliminating the toner transfer [DIY-FPC]. We found that this method decreases fabrication errors and fabrication time while increasing the accuracy of the end product. Since solid ink printers are not commonly available, all design parameters and qualitative data presented in this paper are intended for or derived from the toner transfer method.
After the print has been applied, the Pyralux is then placed in an agitated bath of 2 parts HCl and 1 part H_2O_2 until the bare copper is etched off. Once withdrawn from the bath and cleaned with water, the sheet is stripped off with acetone or other solvents. Finally a UHMW PE sheet is applied to the material. While we found the Kapton side of the composite to have better adhesive qualities, the sheet can also be adhered to the copper side for an inverted bending behavior. Pressure is applied to activate the adhesive, and then left to cure for at least 10 minutes. After curing, the laminate material can be cut to the correct dimensions either by using hand tools or a laser/vinyl cutter.

Circuit components can be soldered using traditional solder methods. This should be done before adhering the UHMW PE sheet, as the high temperatures would affect the material. Finally, additional materials with stiffening, aesthetic, or other functionalities can be added to the composite. We successfully used the spray adhesive 3M Holdfast 77 to apply our desired modules, as it has good adhesion combined with high flexibility.

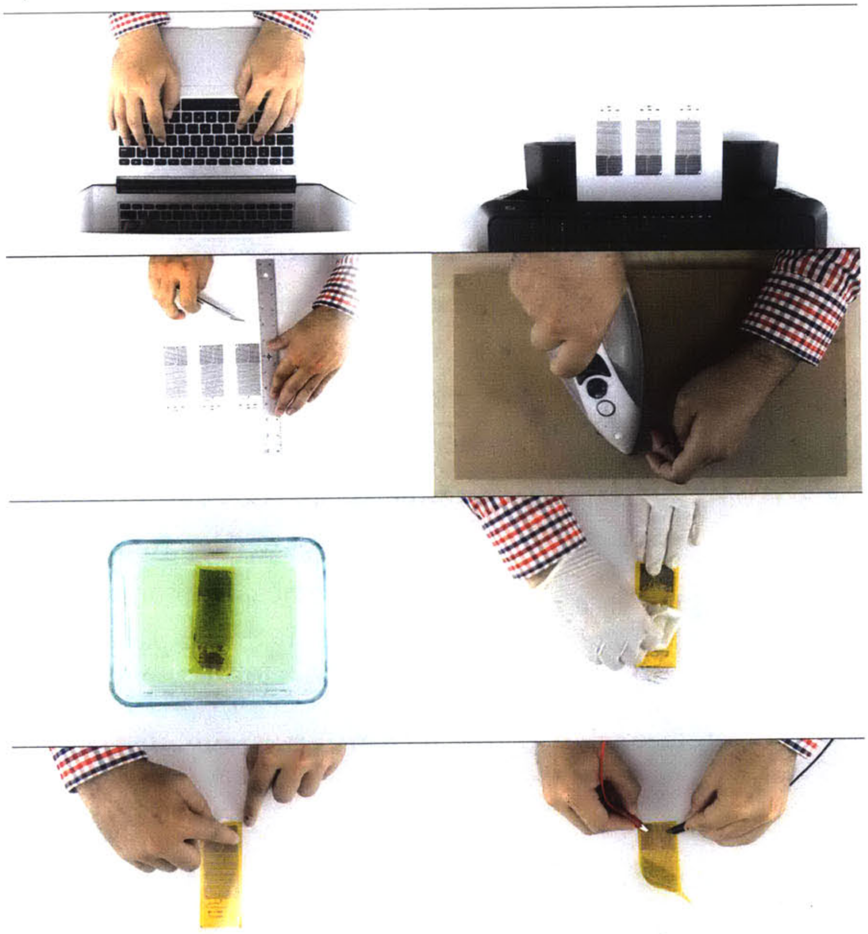


Figure 66: Fabrication of the uniMorph composite.

Primitives

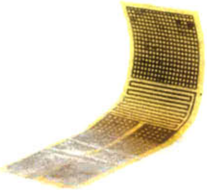


Figure 67: Simple bending behavior by the uniMorph composite.

The uniMorph composite's basic actuation mechanism is bending. The parameters for this behavior have been discussed in earlier sections. Depending on the area of the heating pattern and shape of the composite, the bending angle and curvatures vary. While short patterns will lead to small bending angles, long patterns will lead to large bending angles. The composite can even curl up multiple times, if the composite has heating patterns all the way up to the edge.
While bending and curling have already been used for a wide range of applications, more shape-changing primitives extend the applications for the uniMorph composite. In the following section we will show second order shape-change primitives that are derived from the basic bending mechanism.

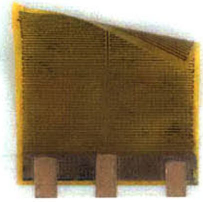


Figure 68: Twisting

Addressability - One of the major advantages of the uniMorph composite is the ability to define heating areas for actuation. Regular bending perpendicular to the flat composite requires even heating of the composite in the bending area. When applying heat to only one side of the bending line, the heated side will actuate more and twist (Figure 68). This requires a relatively wide bending area to create a noticeable effect.

Folding - Some applications may require flat sheets that fold in defined areas (Figure 69). For example, parts of the composite might be populated with larger electrical components. By designing localized heating patterns, one can create bends with a relatively small bending radius. If more defined bending is needed, one can add sheet materials to the non-bending areas.

As briefly explained before, this creates a folding effect with a higher bending angle while having the same length, since the thermal strain redistributes across the fold.

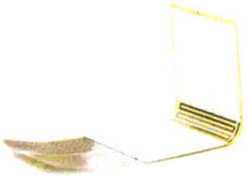


Figure 69: Hinging

Volumes - While surfaces are already used for a wide variety of applications, the HCI field has an increasing interest in actuated three-dimensional structures [Yao, 2013] built with origami techniques. Using the folding mechanism, one can create simple origami structures that can self-fold and continue to move (Figure 70). Round volumes can be achieved by simple curling (Figure 70). These two actuation primitives can be combined to construct a multitude of dynamic three dimensional shapes out of the sheet composite.

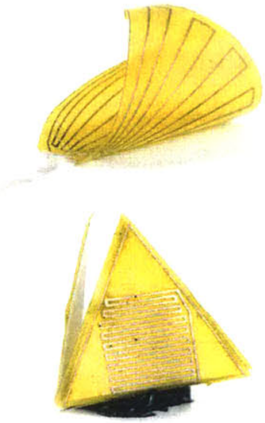


Figure 70: Creation of volumes by folding or curling.

Pre-Curling - The uniMorph composite can be set to a precurled state. As seen in the actuation section, the UHMW PE changes its density when heated to a temperature higher than its working temperature. After being exposed one heat cycle above its working temperature, the composite's neutral state is set in the opposite direction of its usual direction of actuation. When fully heat-treated, the amplitude of this bend equals the inverse of the prior maximum actuations while the new maximum actuation of a pre-curled composite is its neutral state. This makes it perfect for folded three-dimensional structures that open up when actuated.

Figure 71: This flower opens when actuated because it was pre-curled.

Integrated Sensing & Additional Electronics

Adding electronic components to shape-changing composites is crucial for building interactive prototypes. They complement the native actuation and sensing functionalities of the composite. Leveraging its copper layer, the uniMorph composite affords a multitude of extensions.

Capacitive Sensing for Touch and Topology

Because of its great conductance, copper can be used as a capacitive sensor element. This allows for not just the sensing of human touch or presence, but also the determination of material topology. When designed correctly, this meandering heating structure can double as a mutual capacitance angle-sensing mechanism. Instead of using a single trace for heating, two interweaving serpentine routes can be integrated as seen in Figure 64. This way, a mutual capacitance [Yao, 2013] can be measured between the alternating paths to infer the angle of the bent composite. We found the accuracy of this sensing method to be about 6 °.

Capacitive sensing does not work during resistive heating phases, but a time-sharing implementation allows both functionalities to use the same conductor without visible effects on the performance of the composite.

Velostat as force and bend sensor

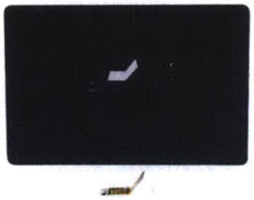


Figure 72: Computational and Physical model can be synchronized by embedding Velostat material as sensor.

A range of semiconducting materials can be embedded into the composite to provide additional sensing abilities. Velostat is a pressure sensitive material that enables sensing the force of human touch. When composited inbetween the copper and UHMW PE layers, the differential strain between these layers compresses the Velostat, enabling bend sensing. We were able to achieve accuracy of up to 3°. The resistance of Velostat also changes with heat, which has to be accounted for when writing sensing algorithms. The copper of the Pyralux can be used to create pads to connect the Velostat to the micro-controller.

Additional Electronics

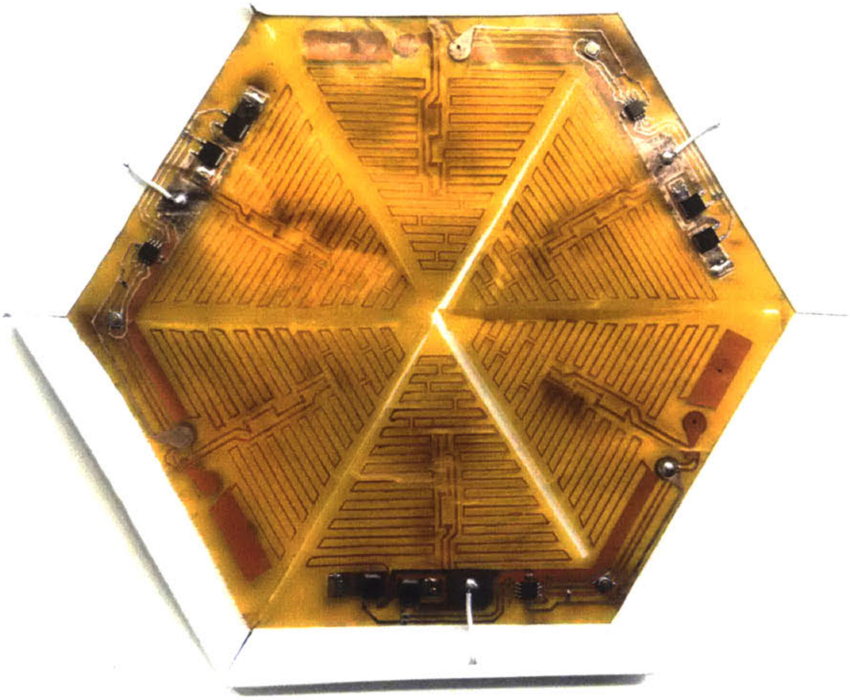
Additional electronic components are often added to shape-changing composites to create effects that are not achievable with just the native qualities of the composite. Because of their changing shape, these composites make it hard to embed rigid PCBs. This leads to either manual wiring or the use of flexible printed circuits to connect the two parts of the system. Either way, a separate architecture has to be used to achieve the desired functionality.

The Pyralux in the uniMorph composite can be used to easily embed surface mount components. Layout and routing of these components can be done with traditional tools like Eagle. This makes it simple to add components like LEDs or additional sensors. The precise fabrication method with solid ink printing allows for tiny footprints. We have successfully used components with as small as 8mil pitch and were able to create self-contained composites with microcontrollers, MOSFETs, and sensors embedded into the material.

The wiring of the electronics and placing of the components has to be done with the designed shape-change in mind.

Components must not be placed on strongly bending areas and wiring should optimally not cross bending areas. Symmetric crossing prevents any negative effects on the bending behavior. Due to its relatively low heat resistance, the soldering of components should be done before adding the UHMW PE. Alternatively, conductive epoxy can be used to attach components to the material.

Figure 73: The flexible circuit material enables direct embedding of electrical SMD components.



Applications

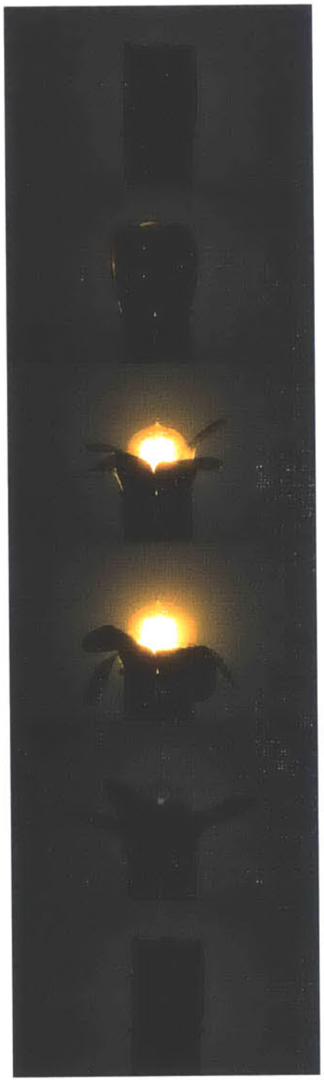


Figure 74: A lamp built from passive composites reveals light when blooming.

Flower Lamp Shade

passive bend actuation - The flower lampshade is a dynamic lampshade with the shape and analog behavior of a flower. Enchanted by its responsive materiality, the flower opens to distribute light instead of pollen (Figure 74). This artifact's shape-change is driven solely by the heat dissipated from the light bulb, exemplifying how unimorph structures can be used to inform us about ambient or local temperatures without the need of control circuits or power supplies on the material side. By imposing a lateral curvature onto the leaves with the holding structure, a drastic movement of the individual leaves is achieved as the bending force has to overcome the holding force of the material similar to a bistable spring.

With modern energy-efficient fluorescent or LED light bulbs, similar artifacts could be used to spatially dim light by shading it in different amplitudes using active uniMorph composites. The leaves of this artifact are composited of solely a layer of UHMW PE and a layer of black Kapton. The materials were composited in large sheets and then laser cut into shape. A laser cut acrylic structure holds the leaves around the bulb.

Responsive Bookmark Light

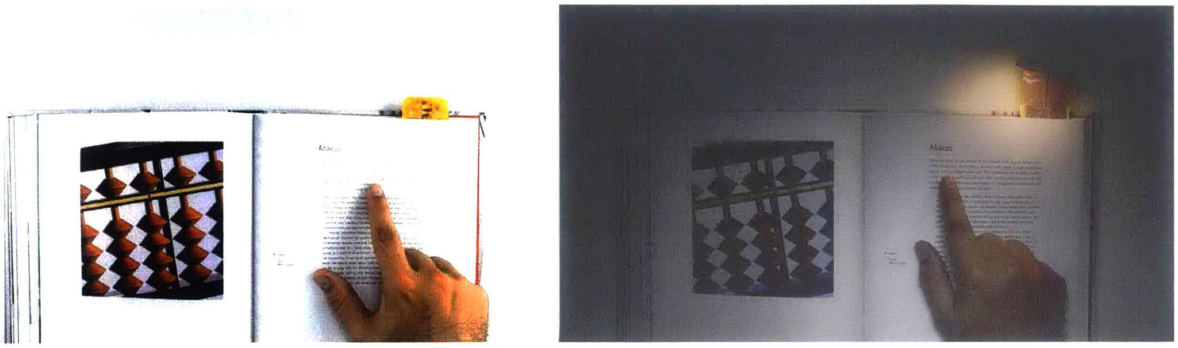


Figure 75: A responsive bookmark detects darkness and curls up to enable continued reading.

active bend actuation - This prototype doubles as a bookmark and a dynamic reading light. The bookmark automatically bends up and shines a light on the text when it becomes too dark to read (Figure 75). When the reader is done, simply sliding the light back into the book re-enables its use as a bookmark. The composite senses its new shape and turns off the light. This prototype exemplifies the ease of both embedding electrical components into the uniMorph composite constructing embedded bend sensing using Velostat foil.

After the active sheet has been composited, as described earlier in the paper, the SMD components are soldered on carefully, in this case with a reflow heat tool. The Velostat is electrically insulated from the underlying copper wire with 0.3mil Kapton. To ensure a higher reliability, the Velostat is glued to the copper pads with a thin layer of conductive epoxy.

Post-it Notes

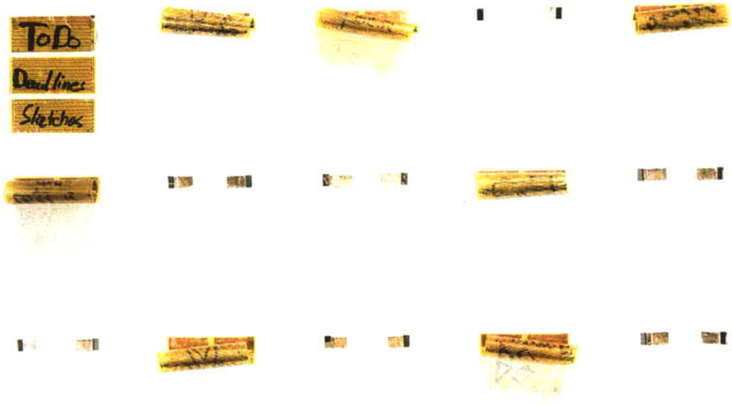


Figure 76: A board comprised of actuated post-its enables novel ways of browsing post-its

active curl actuation, capacitive touch sensing - The ubiquity of Post-It notes inspired several projects that digitally augment [Mistry, 2008cy] or even physically actuate them [Probst, 2014]. In this example, we show a post-it system that enables the Post-Its to curl up individually in order to structure or order content (Figure 76).

This function could be used in brainstorms to filter or group certain notes through curling. A timeline function could uncurl the Post-Its in the chronological order of creation. Animated motions can be designed as notifiers for notes of temporal importance (e.g. an upcoming deadline).

While the Post-Its are simple three layer composites as described earlier, the Post-It board controls the individual notes with a custom MOSFET Arduino board. Currently, categories have to be assigned manually but future versions could recognize them by more intelligent means like optical character recoginition.

Dynamic iPad Cover

Figure 77: A dynamic iPad Cover notifies the user and offers improvised interactions

Originally created as passive devices to protect tablet screens, tablet covers and their affordances have recently been explored as physical input devices by applications like Evernote ®. In this application, we show a shape-changing iPad cover with the ability to inform and notify a user about the state of the iPad it contains. This is a form of ambient media and also affords simple interactions to the user.

The iPad cover opens slightly when there is a notification waiting to be addressed by the user (Figure 77). While the opening angle can signify the amount of notifications, more urgent or specific messages can be displayed by specific movement patterns. Fast opening and closing might indicate a very urgent message, while a movement inspired by a heartbeat could signify a message sent from a loved one. The opening of the cover creates a designed affordance for the user to open the cover completely. It also allows for more improvised interactions, like putting an object on top of the iPad cover to mute any kind of notification.

The hinge is actuated by four identical modules in parallel. A strip of Velostat in each of the hinges informs the control circuit about the current angle of the cover, creating a closed driver loop while also detecting external interaction.

Interactions with Radical Elements & Augmented Materials

Introduction

Thus far, this thesis discussed the technical side of augmented materiality. It presented a taxonomy of bidirectional transducers called *'radical elements'* and exemplified how new radical elements can be designed and fabricated with common materials with the introduction of uniMorph.

This chapter discusses the implications that augmented materiality has on human interactions with artifacts.
It briefly discusses the history of human-artifact interaction and how different innovations have lead to new types of interaction. Subsequently, different taxonomies of current interactions with tangible interfaces are being surveyed. Finally, a new taxonomy is presented that outlines novel capabilities that augmented materials and computation introduce for interacting with artifacts. The chapter closes with a survey of successfull projects of the Tangible Media Group and a mapping of design spaces that are still to be explored.

A brief historical overview of human-artifact interaction

This section briefly illuminates the evolution of human-artifact interactions. Each leap of this evolution is spawned by the development and introduction of new techniques and/or technologies and the artifacts they produced.
While each of those innovation leaps introduced new capabilities to humans, they have also introduced new (complex) interactions that allow for control and understanding of the artifact's qualities and functions.
This transformed the role of designers from craftsmen to semiotician [Dunne, 1999] who are trying to make the functionality of the increasingly complex artifacts transparent.

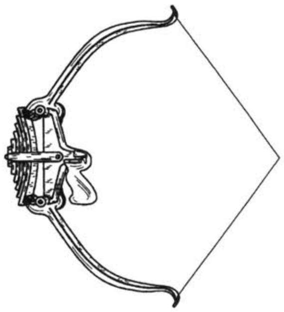


Figure 78: A bow stores the human work in the Form of wood tension. The stored energy constantly acts on the marksman until he releases the shot.

Material Reaction - When interacting with passive materials, we have an intuition for what the behavior of the material is. Input and output are coupled by the material and give immediate feedback. Bending a flexible piece of wood causes the wood to exert an equal force on the bender. This behavior has been formalized in Newton's Third Law, which defines that "for every action, there is an equal and opposite reaction" and is experienced when one, for example, draws a bow. The work that the marksman puts into the bow is stored in the form of tension and constantly acts on the marksman's hand until he releases the shot (Figure 78).

Translation - Material assemblies can create complex mechanisms with sophisticated input-output behavior that introduce new complexity into simple material behavior. Gears and pulleys can translate directionality, speed, and force in various

ways. The complexity of these translations range from a simple pulley to complex automata like the orrery. In the "mechanical age" people believed that human bodies worked in this fashion and could be recreated with automata machinery.
Although automata contraptions translate forces and movements, the physicality of those systems still remains a physical connection between input and output. The user feels the gears turning and resistances of the moved objects. All of these mechanisms are naturally embodied through their physicality. This allows the human to control and understand the complex movements, as seen in the example of the orrery. (Figure 79).

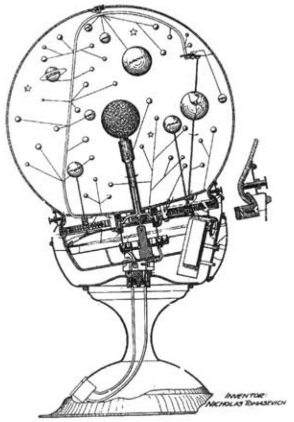
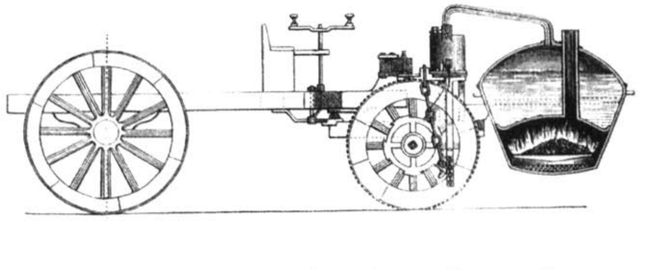


Figure 79: An orrery translates simple rotary motion of the crank into mulitple complex movements.

Amplification - While the orrery was powered by hand, the industrial revolution introduced motors to mechanical systems that amplified human actions. At first, the most widespread application of this was automation of factories. However, more advanced, smaller motors produced personal devices for human use. The introduction of motor-actuation to objects allowed for the amplification of human input forces. No longer was are the sum of all perceived forces equal in the system, but additional energy could be released to amplify the humans actions. When driving a car, pushing down the gaspedal accelerates the car, entailing an amplification, as the force needed to control the pedal is way smaller than the one that the car's wheels exert on the street to move forward.

Figure 80: The first self-propelled vehicle built by Nicolas-Joseph Cugnot in 1769 enabled drivers to control steam power for transportation. The power unit was articulated to the "trailer" and steered from there by means of a double handle arrangement.



Computation - Amplification combined with mechanical translations can achieve behaviors of high complexity. The physicality of those systems, however limits their applications and possible complexities. The introduction of electronics and computation lead to complete liberation from those limitations. While electronic systems replace prior physical linkages with immaterial, imperceivable electrical power and signals, computation enables arbitrary complexity of connections and rules. Computationally augmented objects are microelectronic 'black-boxes' which functionality can no longer be determined by their form. They are placed on the threshold of immateriality, offering a material surface as interface to the computational.

Figure 81: The introduction of digital computation frees the form of an object from its function. This enables higher complexity but also hides it.

Transformation - Along with the miniaturization of electromechanical actuation systems material science has helped to liberate the computational object from its stasis. In concert with prior innovations, this has created the opportunity for computation to find expression in materials. New dynamic materials with sensing capabilities haven given designers of computational artifacts modes of expression that match the dynamic and malleable nature of the digital world.

Figure 82: The inForm table is able to transform rapidly to give physical shape to digital information.

"With great power, comes great responsibility". Thus as we develop these much needed modes of expression for computational artifacts, we also have to recognize that designing . interactions for those artifacts involves more dimensions than designing for the world of pixels liberated only within the confines of screens.

Taxonomies for Tangible User Interfaces

The following section surveys a selection of existing frameworks and taxonomies for examining interactions with tangible interfaces. The focus of this survey is to examine how materials (dynamic and static) and their properties are taken into account. Finally, a new paradigm will be presented to extend the popular taxonomy presented by Fishkin [Fishkin, 2004] and a design space for augmented materiality will be defined.

Experiential & Representational Embodiment

In his PhD thesis 'Encountering the Digital', Fabian Hemmert distinguishes two categories of embodiment in tangible user interfaces. 'Representational embodiment' describes embodiments of digital information, while 'experiential embodiment' is based on how "experience of one's socio-physical world is fundamentally grounded in having a living body" [Hemmert, 2014].

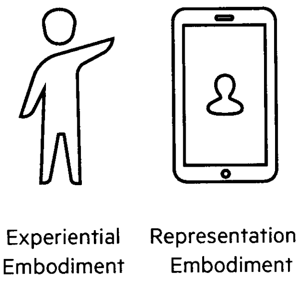


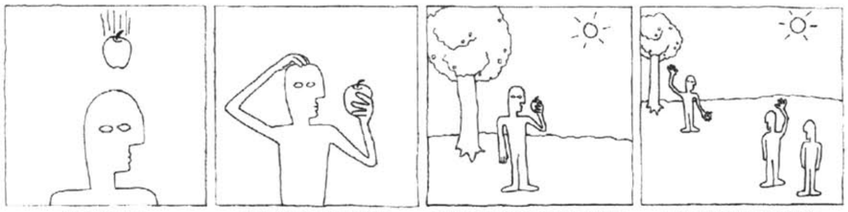
Figure 83: Hemmert presents two archetypes of emodiment. One is linked to the experience and skills of having a body. The other is material representation of digital informations.

The key question that he formulates for this design space is how the embodiment of digital information can be designed in a way that leverages the user's embodiment. He explores possible answers to this question in a 'research through design' approach in which he builds and tests multiple mobile phone devices with dynamic material properties, namely shape and center of weight. His evaluation concludes that following this path, designers can create interactions that are "perceived as richer, less invasive, and more familiar" [Hemmert, 2014].

The framework of augmented materiality presented later in this chapter is inspired by his approach of matching the human perception with modes of computational expression.

Reality Based Interaction

Reality-Based Interaction is a framework developed by Jacob et al. that attempts to unify interactions that “draw strength by building on users’ pre-existing knowledge of the everyday, non-digital world”[Jacob, 2008]. By moving from instructing the computer using command line to directly interacting with objects, we are able to leverage different skills and qualities from the physical world. The framework sorts these qualities into four categories shown in (Figure 84). In the context of this thesis, the categories of naïve physics and body awareness and skills are especially interesting, as they find application within physical microinteractions.



Naïve Physics

Body Awareness & Skills

Environment Awareness & Skills

Social Awareness & Skills

Figure 84: The four dimensions of reality-based interactions presented by Jacobs et al.

‘Naïve Physics’ is a term describing the world as most people perceive it - in direct contrast to how physicists think about it. It entails common knowledge about the world including concepts like gravity, friction, velocity, and persistence of objects. Similar to Hemmert [Hemmert, 2014], this framework also references body awareness and skills as a theme for reality based interactions. Humans’ proprioception and ability to control and sense their own body is leveraged with almost every physical manifestation of digital information, as well as virtual reality applications.

In accordance with Ishii and Ullmer [Ishii, 1997], Jacob et al. show that researchers often implicitly leverage users' knowledge and interaction with the real world for interacting with digital information by embodying them in physical systems. They conclude that interacting with physical computational systems can be very similar to interactions with the inert physical world, with the addition of 'special command' modaliites.

Level of coherence

Koleva [Kovela, 2003] considers the different ways of coupling between digital and physical objects. He describes current asymmetries between physical and digital states and establishes 'degree of coherence' as a distinguishing property for classifying tangible interfaces. The level of coherence is defined as the degree to which the physical and digital system are perceived to be the same.

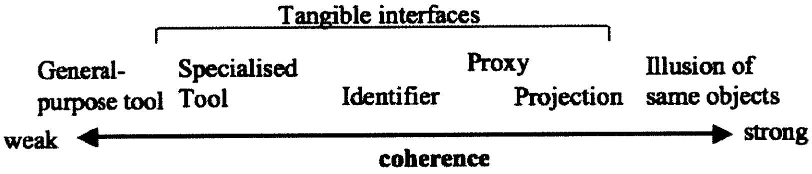


Figure 85: The scale of coherence for Human-Computer Interfaces presented by Kovela et al.

The level of coherence for tangible interfaces spans from special purpose tools (eg. I/O Brush) that can be connected to various applications, to identifiers that act as physical bookmarks for digital informations (eg. RFID Tags) to proxy projections that have digital shadows linked to physical tokens (eg. URP). Not included in the category of tangible interfaces in this framework, but most interesting in the context of the taxonomy of augmented materials, is the category 'illusion of the same object', where the physical and digital states are perceived as the same.

The taxonomy's highest resolution is 'the object' and its link to the digital. It does not take dynamic materials and the possibility of linking material properties to digital information into account. However, the paper briefly mentions 'Tangibles that push back' as a category of interesting tangibles that are able to answer the user's haptic actions with haptic feedback.

Fishkin

One of the most commonly known and inclusive taxonomies for tangible interfaces is formulated by Fishkin [Fishkin, 2004]. He defines a two dimensional space for tangibles, with different degrees of embodiment and metaphors as the axises. Once parts of an interface are made physically tangible, a whole realm of physically afforded metaphors becomes available. A designer can use the shape, size, color, weight, smell, and texture of the object to invoke any number of metaphorical links.

Figure 86: Fishkin's taxonomy for tangible interactions produces a two dimensional table with Metaphor and Embodiment as its two dimensions.

Metaphor Embodiment	None	Noun	Verb	Noun & Verb	Full
Full					
Nearby					
Environmental					
Distant					

For the purpose of this thesis, Fishkin's degrees of embodiment are especially interesting. The question that he poses is: 'How closely is the input focus tied to the output focus?'. Closeness in his framework is interpreted both physically and perceptually.

Fishkin distinguished four degrees of embodiment. 'Distant' describes scenarios in which the user manipulates a remote object or system (remote control). 'Environmental embodiment' is concerned with 'non-graspable' (ambient) media around us such as audio or temperature. A 'nearby embodiment' has an output physically close to the input device.

Finally, Fishkin describes a 'full embodiment' as the limit case when the output device is the input device. He compares it with the interactions that we have with physical objects/materials such as sculpting clay. Pushing the clay yields an immediate feedback and result from the physical system. Only in fully embodied systems can direct haptic feedback be experienced.

In the last section of his taxonomy paper, Fishkin plots recent approaches to tangible interfaces in the two-dimensional space of his taxonomy. He notes that, over time the evolution of tangibles progressed into the corner of full embodiment and full metaphor. The focus of the framework in this thesis is to explore this corner at a higher resolution, with a focus on bidirectional interactions.

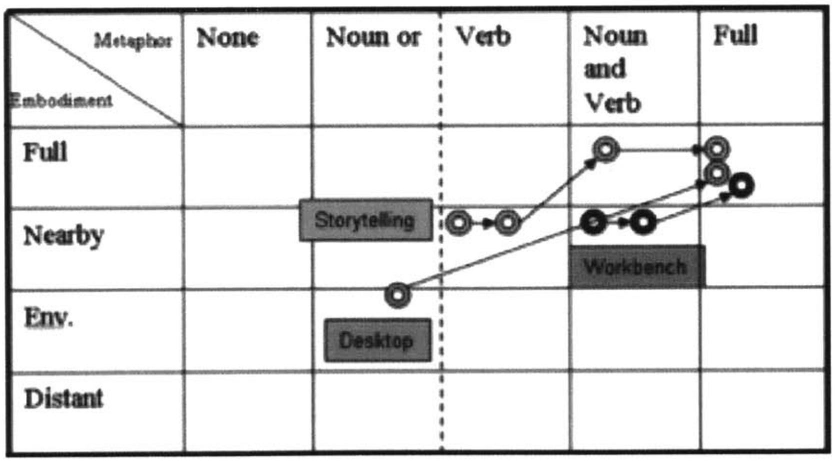
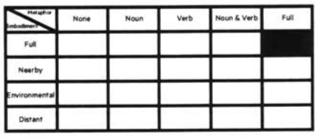


Figure 87: The evolution of different categories of tangible interfaces over time as presented by Fishkin.

A Framework for Augmented Materiality

There is no reason why the objects displayed by a computer have to follow the ordinary rules of physical reality with which we are familiar.
Ivan E. Sutherland

After surveying and analyzing a selection of tangible interface frameworks and taxonomies, it is apparent that the interaction capabilities of augmented materials with sensing capabilities are not fully captured in any framework. Some frameworks address the role of materials or the human perception of them, but none offer a framework that specifically adresses interactions with materials that can change their properties and sense human interaction.



Metaphor / Embodiment	None	Noun	Verb	Noun & Verb	Full
Full					■
Nearby					
Environmental					
Distant					

Figure 88: The framework of Augmented Materials is situated in the full metaphor, full embodiment corner

The most commonly used taxonomy by Fishkin lists 'full embodiment' as the limit case in which the "output device *is* the input device" [Fishkin, 2004]. In the design space of this thesis, where augmented materials create and connect different input and output capabilities within the electric object, this taxonomy is merely a tautology. For interaction design with dynamic materials, there is a need for a higher resolution within the space of 'full embodiment'. The following part of this thesis attempts to define such a framework by highlighting how bidirectional transducer materials and computation can create functionalities that derive from the behavior of inert materials.

As previously shown, microinteractions with electric objects and their comprising (dynamic) materials draw strength by building on users' pre-existing knowledge of the everyday, non-digital world. This is a reoccurring topic in vision papers by Ishii etl al. [Ishii, 1997][Ishii, 2012] and frameworks by Fishkin [Fishkin, 2008], Jacob et al. [Jacob, 2008] and Hemmert [Hemmert, 2014]. They all stress the advantage of leveraging knowledge about the physical, non-digital world for interaction with computation.

Newton's Laws of Motion are the theoretical foundation of man's basic knowledge about the physical world. Even though people might not be able to formulate them, these laws formalize their understanding and expectations of mechanical behavior. Dynamic materials change our perception of what objects can do, and even though we know that Newton's Laws still apply to the underlying physics, we abstract the behavior of those augmented objects into something that often defies those rules.
The reason for this perception is blackboxing. Bruno Latour explains this mental phenomena as follows: "When a machine runs efficiently [..] one need to focus only on its inputs and outputs and not on its internal complexity. Thus, paradoxically, the more science and technology succeed, the more opaque and obscure they become." Especially when using computers through GUI interfaces, this is how we deal with the underlying complexity. We do not think about the thousands of transistors or algorithmic logical units, but instead we think of actions such as dragging a file into the trash bin.

The introduction of dynamic matter for representational embodiment changes our relation to the physical world. Physical materials, one of the basic elements for our understanding of physical objects, have become augmented and can act based on potentially complex rules. This evolution from inert materials makes its behavior something that we have to blackbox, instead of something that we inherently understand. Furthermore, dynamic materials change our view and expectations of our capabilities in conjunction with the objects they comprise.

For the design of objects with dynamic materials, it is important to understand how the perceived material behavior can alter from that of passive, inert materials. The difference between the categories is the design space that is enabled by augmented materiality.

This thesis presents the following 5 dimensions in which augmented materiality can create new and interesting behaviors for human-artifact interactions:

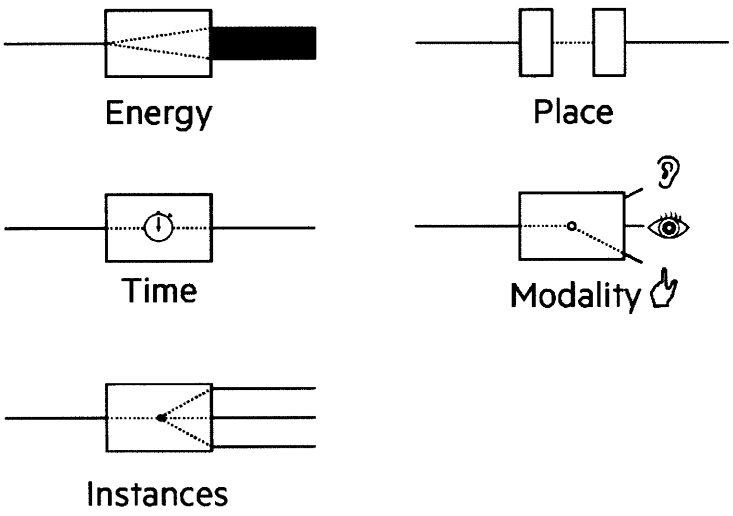


Figure 89: The five dimensions in which dynamic materials could augment the human perception of reality.

The following part will discuss each dimension and survey existing tangible interactions to exemplify succesfull applications of these augmentations.

Energy

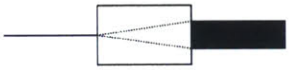


Figure 90: Input energy can be amplified or dampened.

It is difficult to give a comprehensive definition of what energy is, as it can be stored and constituted in various ways. In the context of physical microinteractions, the focus is on the energy invested by the user during the interaction.

As discussed earlier, when interacting with inert materials, all the energy in the system is the energy invested by the user. When shooting a bow, the work that the marksman puts into the bow is stored in the form of tension and constantly acts on the marksman's hand until he releases the shot. The speed and range of the shot are directly related to the marksman's work. In contrast, when shooting a gun, the only force the shooter has to overcome is the force of the trigger. This releases the bullet with a speed and energy that is much higher then the energy that the shooter had to invest.
While in the case of a gun, the energy is stored in black powder and released through its combustion, energy in current devices is mostly electrical, either stored in batteries or provided by a powerline. A wellknown example for one-way amplification is a megaphone, a more expressive example is the earthquake generator seen in (Figure 91).

Figure 91: The Earthquake Generator by Julijonas Urbonas amplifies a simple knock on the door to earthquake-like vibrations.

A utilitarian example for bidirectional energy augmentation is the CityHOME project by the Changing Places Group at the MIT Media Lab. The goal of the project is to enable easy reconfiguration of a small space. In this implementation, the surfaces of heavy objects and walls are equipped with pressure sensors. When one of those surfaces is pushed, embedded motors in the object support the actions of the user and make the object easier to move.

Figure 92: The CityHome project enables easy movement of heavy furniture by implementing force-resistive surface areas and motors into the furniture.

Time

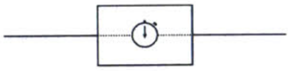


Figure 93: Reaction time can be changed in speed and timing.

Physical objects provide immediate feedback in interactions with them. When one applies a force to a stiff object, the part of the body used to apply the force immediately experiences a pressure.

Figure 94: Computer games like Braid experiment with different time manipulations and make time a crucial part of their mechanics.

Computers operate on a certain frequency, however their response times are usually immediate, given the task is relatively simple. So while computation is able to provide immediate feedback to human input, it can also alter the speed and timing of its response. An example is the slow motion effect in Mac OS X. When pressing the shift key, animations of the GUI play slower. The dimension of time has been explored in interesting ways in computer games such as Braid (Figure 94). An interesting example that changes personal perception of time is the Decelerator-Helmet by Lorenz Potthast, which enables the user to create timing offsets and even slow down the personal experience of time (Figure 95).

Figure 95: The Decelerator Helmet allows the user to perceive the world in slow motion.

When dynamic materials are combined with computation, this computational quality of parametric time is inherited by the material. This enables different kinds of new behaviors for materials such as delay, slow-motion, fast-forward, rewind, and even replay of stored sequences.

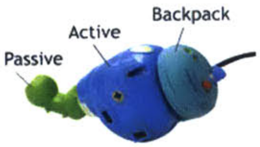


Figure 96: The Topobo Backpack sysyem allows the manipulation of time for replays of recorded motion.

Topobo overcomes the limit of immediate responses by recording user created motion patterns and playing them back to the user. Topobo extends the possible manipulations of time with the backpack set, that allows the user to adjust delays and speeds (Figure 96).

Place

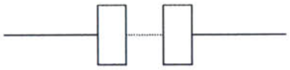


Figure 97: Material Reaction can happen at a different place.

Response of inert materials is usually colocated with the human input. Mechanical structures such as gears and pulleys can transport different kinds of kinetic energy. For example, a pipe organ mechanically connects the keys of the keyboard to the valves of the organ pipes (Figure 98). Usage of electrical energy transmission removes these mechanical complexities and enables energy to travel longer distances.

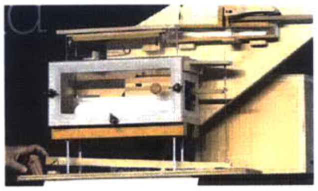


Figure 98: A pipe organ mechanism translates (and amplifies) the kinetic energy of the player to the distant organ pipes.

Computational data is transported not as electrical power, but as electrical signal that carries almost no power and enables fast and lossless travel over long distances. Its connection to computation allows augmented materials to evoke a reaction at a remote place, either by utilizing transport of electrical energy through wires or encoding instructions into data that can be sent wirelessly.

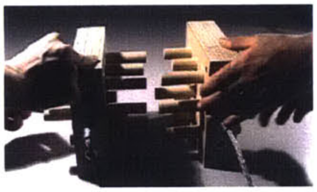


Figure 99: PegBlocks mirrors movements of pegs by transmitting the generated energy of one peg to the corresponding peg on the other block.

Interesting examples of this technique are PegBlocks and inTouch. While PegBlocks transports the generated energy directly from one block to the other, inTouch translates the energy into digital data and utilizes signal transmission protocols to send rotational and force informations to the connected module. Another interesting example is the remote collaboration application of the Transform. The connection of corresponding pins over distance enables a shared workspace at remote locations (Figure 100).

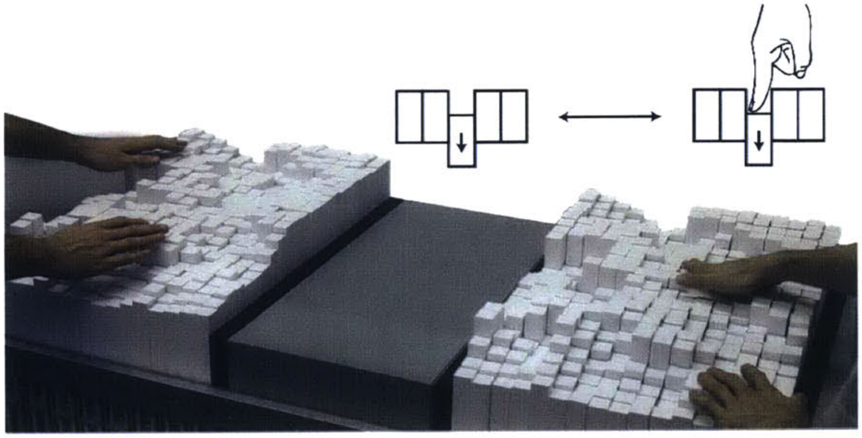


Figure 100: The TRANSFORM table creates a common workspace by mirroring the states of corresponding pins.

Modality

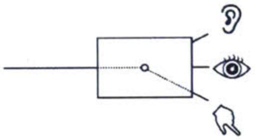


Figure 101: The output modality can alter from the input modality

When manipulating an inert physical object or material, the object always generates an immediate feedback. This feedback is usually on the same modality. For example, when trying to push a heavy object, the object pushes back. When warming up a material, the material cools down the hand touching it.

Gears, pulleys, and other material structures can translate one mechanical movement into another. These translations introduce more complex interactions, however they are still acting on similar modalities and their translation can be observed and mantained by a physical connection between the user and the output.

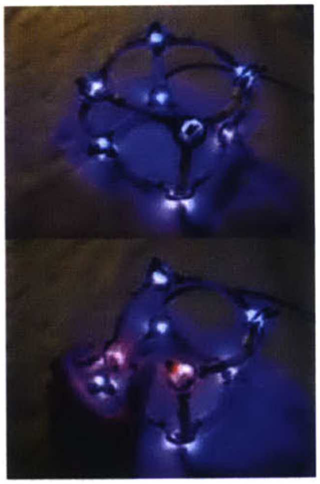


Figure 102: Senspectra makes mechanical stress that occurs in the assembly visible by translatesing it to light .

Dynamic materials, especially the subgroup comprised of radical elements, can translate input into (invisible) voltage and back to physical (visible) effects. Connecting radical elements of different categories can create interesting causalities across modalities.
Many one-directional examples can be found. For example, pushing a light-switch seemingly connects the kinetic movement of the switch to the state of the light.

Cross-modal projects in human computer interaction usually revolve around sound or light, as those modalities are hard to manipulate directly. Senspectra is a project that visualizes structural stress of an assembly with joints that light up (Figure 102).
Exploring cross-modal bidirectionality could be a fruitfull field for further research. However, very little research has been done on this topic.

Instances

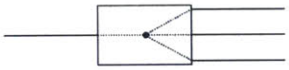


Figure 103: Multiple reactions can be instantiated.

Inert material reactions are usually singular. There are some examples of mechanical or biological chain reactions in which a single input creates multiple reactions. For example, the Mimosa plant reacts by retracting all of its leaves when just one of them is touched (Figure 104).
The Domino Effect describes a chain of similar events that can be set off by one action, similar to what is observed when literal dominos are knocked over. Rube Goldberg machines often experiment with changing the modality of energy multiple times during a pre-programmed sequence.
Electrical energy and computation allow for reactions to be instantiated multiple times. Each of those instantiations can either be the same or varied in any of the four earlier dimensions.

Figure 104: The mimosa plant retracts all of its leafs when just one is touched.

Topobo and its backpack system are a good example for this. One master unit is hooked up to a series of slave units which mirror any action the master creates (Figure 105).
New instantiations of a reaction do not have to mirror the action at another place. Instantiations are recursive as each of the new instances can be augmented in the four other dimensions. With Topobo, the time modality can be changed for earch module using the backpack system (see Time section).

Figure 105: Special orange parts called 'queens' can control many other actives. All motions made to a queen are mimicked by the other actives connected to the queen.

A brief survey of Tangible Interactions

The following section presents projects that are enabled by radical elements and exemplify different contexts of interacting with said elements. All of the presented projects leverage radical elements and implement at least one of the material augmentations discussed earlier.

PegBlocks & inTouch

An early example for use of a radical element is PegBlocks, a set of wooden blocks with nine protruding pegs. Each peg is coupled to a DC motor that converts kinetic energy to electrical energy and vice versa. Connecting blocks allows energy generated by moving a peg to travel to another block and move the according peg the same way. The fact that the system does not require additional energy shows that the motor/dynamo tiles are able to convert the majority of kinetic energy into electrical energy and back to kinetic energy again.

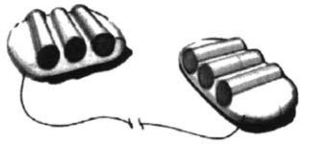


Figure 106: The inTouch system mirrors the movements of two remote devices over a distance.

Similarly, inTouch connects a pair of artifacts with three cylindrical rollers over a distance. Instead of transmitting the electrical power from one base to the other, the inTouch system simply transmits rotation data. This enables connection of inTouch modules over large distances by simply connecting them to the internet. Additionally, the DC motor and rotary encoder system

Curlybot & Topobo

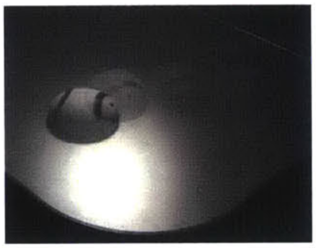


Figure 107: curlybot can record and playback physical motion.

Curlybot is a toy that can record and play back physical motion (Figure 107). The *'radical element'* it uses is a DC motor with an additional rotary encoder for higher precision. It exemplifies how the time modality of material augmentation can be used.

Topobo is "constructive assembly system with kinetic memory" that allows children to learn about movement and animal locomotion. In its simplest configuration, the active component consists of a servomotor that is used to record motions created by the user and then play them back. In this form it exemplifies a basic time augmentation.

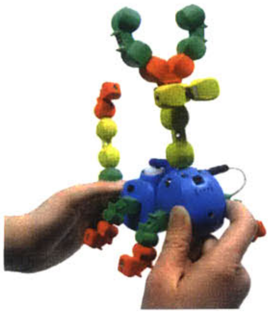


Figure 108: curlybot can record and playback physical motion.

Topobo has additional modes that experiment with other augmentations. As shown earlier, a queen module can control multiple other modules (instances) and the backpack system augments time in more sophisticated ways such as adding delays or changing the speed. Furthermore, the backpack system also facilitates amplification and attenuation of movement.

Actuated Workbench & inForm

The Actuated Workbench prototype leverages electromagnets to create active tokens on top of a table surface. The tokens are either ferromagnetic objects or custom tokens with passive magnets embedded inside them. This enables an interesting interaction in which the user interacts with tokens that experience forces that the user cannot feel, as they are magnetic. Thus, the token is the translater between the computational system and the user, as the token translates the magnetic force into lateral translations and kinetic force. Additionally, the system can track the token's position, which allows the user to interact with it by changing the token's position.

Applications for the actuated workbench also show material augmentations. For example, the pico prototype shows how the behavior of two tokens can be mirroredover a distance to create a connected workspace.

The inForm system is a shape-display with 30x30 linear actuators which can actuate and sense their vertical position. Because of its high resolution and added projection, the inForm system is able to render physical objects in 2.5D. The high speed of the actuators allows for the impression of objects moving laterally. Each pin of the shape-display is a *radical element,* since it can actuate and sense its z-position. Linear actuators, the driving engine of the shape-display, are part of the table of radical elements.

PneUI & uniMorph


Figure 109: Pneui can leverage sensing qualities of the air-pressure used for shape actuation

PneUI is a prototype that leverages pneumatic actuation and anisotropic transformations to create shape-changing interfaces. The prototype employs multiple sensing strategies, including sensing of air pressure. The use of this control loop, in which air pressure can be controlled by the computer and the user, enables direct feedback for user input and thus qualifies as a *radical element.*

The uniMorph composite presented in this thesis exemplifies how new material actuators can be turned into *radical elements.* The deformation of the material, that can be is sensed through mutual capacitive sensing and closes the control and interaction loop this way.

A Survey of Augmented Material Examples

This chapter thus far has determined five dimensions where the percepion of inert materiality would be expanded by dynamic materials. Chapter 3 presented a list of bidirectional transducers called *'radical elements'* that enable these augmentations with true bidirectional interactivity.
This section presents a table that maps past projects of the Tangible Media Group into these categories. The-axis indicates the *radical element* that is used, while the x-axis indicates different categories of material augmentation presented in this chapter.

Figure 110: The table maps projects of the tangible media group in a space of radical elements and the additional capabilites they provide in comparison to inert materials.

	Energy	Time	Space	Modality	Instances
Light		I/O Brush	SynchroLight		
Temperature					
Magnetism		Actuated Workbench	Actuated Workbench		
Vibration	The Sound of Touch				
Linear		inForm	PegBlocks		
Rotation		topobo curlybot	inTouch Linked-Stick		topobo backpack
Anisotropic			PneUI		

When analyzing this chart, one can see that examples of energy augmentation are very limited. While there are a lot of unidirectional amplification examples, prototypes implementing bidirectionality have not been built yet. This is surprising, as in crucial contexts such as driving a car with power steering, maintaining bidirectionality is crucial for the degree of control that the driver experiences.

One can see a very dense population of projects in the categories of time and space augmentation categories. They are naturally interesting, especially in the context of the 'ghostly presence' concept that was presented by the Ishii et al.

While there are a lot of unidirectional examples for energy variations or modality mappings, they have not been many projects that considered direct feedback across modalities. This is an interesting space for conceptual and perceptual mappings between two modalities. Simple examples include a lightswitch and lightbulb that are bidirectionally connected, so the user can feel the logarithmic power consumption of typical LEDs. This is a space where kinesthetic effects can be explored and exploited to generate interesting interactions with modalities like stiffness and color that we usually do not have intuitive control over.

Creating bidirection mappings over multiple mediums (or instances) has not been deeply explored. Even the example of Topobo's backpack system is a fringe, case as the queen module does not receive feedback from the slaves. The design space is very interesting with a lot of unexpored questions. How does it feel to control multiple properties with one controller and receive feedback from all of them? What are good mechanisms to distinguish between the feedback of each instance?

In conclusion, this map shows that there is still a grand and interesting space to explore in beyond the obvious categories in material augmentations.

The challenge of Material Innovation

"For the first time in history, we can design materials precisely to fit our needs, molecule by molecule, atom by atom."
- Merton Flemings

"A world of nameless materials is taking shape .... In this new world, we seem to perceive only surface, only local and momentary relationships. In a word, we perceive only appearances."
- Ezio Manzini

Figure 111: The materials in an axe inform the user of the artifact's affordances.

Historically, humans and materials have always been intertwined. Archaeologists label civilizations by their capability to utilize or create certain materials: Stone Age, Bronze Age, Iron Age, and Silicon Age show the great impact that materials have had on human society's development. Each of those leaps has been derived from new fabrication techniques and yielded new advances in various fields of human life.
While every of these leaps has brought new capabilities to humanity, they have also introduced new complexities into interactions with artifacts. Not long ago, the list of materials that could be used for an artifact was short. The available materials were distinct from each other and remained constant over time. [Manzini, 1989]. Material properties were well know and a "material identity was constructed on the basis of knowledge taken as predictable behavior" [Manzini, 1989]. Hence, people had an inert understanding of how an artifact could be used by just considering its materials and their identities.
Currently, materials can be almost completely engineered to fit the specifications of the final design, rather than utilizing ma-

terials as part of the generative design process. The advent of these synthetic on demand materials has partially removed the cultural references described earlier. It is becoming an expert task to know the qualities of an ever growing list of materials. Polymers can be engineered to optically resemble almost any material, so visual cues are certainly not enough to understand a material's true nature. For example, an object with a metallic reflective surface might be an inflated Mylar balloon, while an object that appears to be soft can be inflated steel (Figure 112).

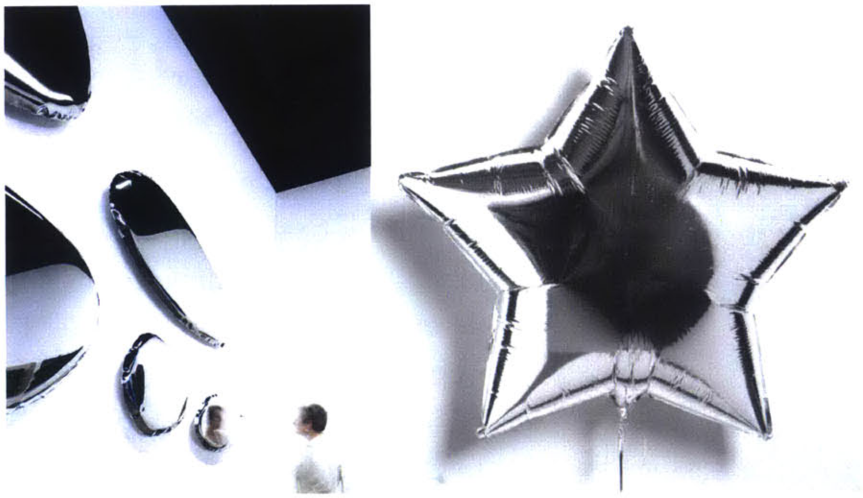


Figure 112: Innovations in material manufacturing lead to a loss of common material identities. A silver , shiny surface can be an inflated Mylar balloon (on the right) while an object with the characteristics of inflated objects can be made out of steel.

We are not confused by the multitude of materials, we have just lost the certainty of material's identities. We do not know if a certain plastic will float in water or burn without consulting the material property sheet. What informs us about material properties is now more likely to be its application than the material itself. More than ever, it is the designer's responsibility to make sense of the material world.
What role can dynamic materiality play in the communication of 'hidden' material properties?

Material Design

" Material is the Metaphor"
- *Google on their 'Material Design' approach*

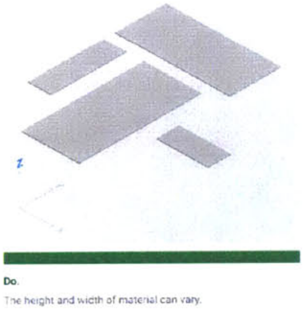


Figure 113: The materials of an axe inform the user of the artifacts affordances.

Currently, materials are still generally confined in their properties. These restrictions create a small design space that still works around material constraints. With ongoing advances in material science and miniaturization of electromechanical devices, these material constraints will soon be lifted.

Within the confines of the screen and its color space and resolution, pixels are completely liberated in their expression. The development of design principles for graphical user interfaces might be interesting to consider for designing with augmented materials.

In GUIs, users and designers outgrew the skeumorphic design approach that was still tied to the affordances of the physical world. The current 'flat design' era created its own, inherently digital design language.

In 2014, Google presented their 'Material Design' framework, that devises design constraints that are not focussed on objects, but on materials as physical references. Within the world of liberated pixels, the designers of this framework claim that applying some aspects of inert materials to graphical user elements, the system can become more user friendly, comprehensible, and predictable. It would be interesting to devise a framework for designing augmented materials, similar to the 'Material Design' for pixels. How can the properties of inert materials (eg. persistence, predictability) be paired with dynamic computation without sacrifices on both sides?

Experiential Radical Elements

The radical elements presented so far were able to sense and actuate the very same modality on a physical level. This creates an interaction loop in which the human can perceive computational feedback on the very same modality as he manipulates the system. This section presents thoughts on and examples of cases in which physical feedback does not physically match, but is instead simulating by leveraging insights into kinesthetic perception and physics. While these radical elements do not actuate on the same modality which they are manipulated on, they are perceived as doing so. Utilizing these methods can help overcome technical challenges or constraints. In the analogy of the periodic table of chemical elements, these elements could be listed as elements with non-stable isotopes, as they are ephemeral and purely experientiell.
To exemplify this approach, two techniques used to simulate force feedback on touch screens are presented.

One example of such exploitation is TeslaTouch by Disney Research [Bau, 2010]. It uses the electrovibration phenomenon to create tactile sensation on a touch screen without any mechanical movement. The phenomenon is based on electrostatic

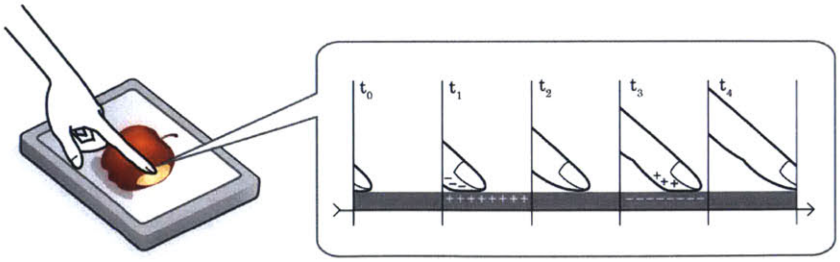


Figure 114: TeslaTouch creates haptic feedback without mechanical movements.

forces that can increase or decrease with the amount of surface friction on the surface (Figure 116). While the user has the sensation of a surface with different textures that is complemented by graphics on the screen, the actual surface is flat and shows no mechanical movement. It can be easily combined with capacitive or even pressure sensitive input sensing techniques to create an 'experiential' radical element.

Another experiential approach to this problem is the Sandpaper Method presented by Margaret Minsky [Minsky, 1995]. Instead of creating haptic textures using electrostatic forces, she uses a kinesthetic technique she calls the Sandpaper Method. With minimal lateral movements, the skin on the tip of the finger is compressed, which leads to the perception of different pressures and textures. Similar to TeslaTouch, this method can easily be combined with different touch sensing modalities. This technique is used in the Taptic Engine (Figure 112) that is implemented in the new MacBooks by Apple. It combines an actuation technique that can create the perception of a range of pressures on the finger with a pressure sensing trackpad. This creates a perceptual coupling of analog input with analog actuation of vertical pressure on the trackpad that enables embodied microinteractions.

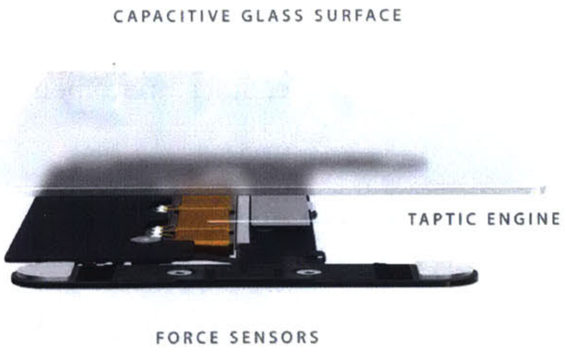


Figure 115: The Taptic engine of current MacBooks exploits the kinesthetic sandpaper-method to create a 'radical element touchpad'.

A Toolkit for Radical Elements

This thesis presented a table of *radical elements* and discussed different dimensions of the material augmentations that they enable. The survey at the end of chapter 5 showed that this design space still has a lot of opportunities for design explorations. However, prototyping tools for most of the presented materials are currently not available.

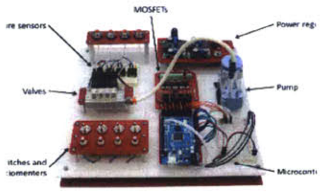


Figure 116: The Soft Robotics toolkit enables a fast entry into soft robotics by providing a basic set.

A proven approach to spreading new techniques is making a toolkit available. This allows people to enter the domain without doing most of the ground work by leveraging the toolkit's functionality. A good example for this is the Arduino platform for general electronics, or very specifically, the Soft Robotics Toolkit (Figure 116).

By designing a modular toolkit that enables the integration of most of the *radical elements* presented, one could enable a large group of people to prototype bidirectional interactions with a variety of materials and actuators.

Inspired by the structure and abstraction offered by servomotors, each *radical element* module could consist of a sensor, an actuator, and a control loop. Connecting the modules and programming them in one unified system would make prototyping of augmented material interactions very simple and would facilitate rapid iterations.

The toolkit would abstract the previously complex method of controlling these bidirectional transducers and enable digital interfacing that focusses on interaction rather than control.

metaMorph

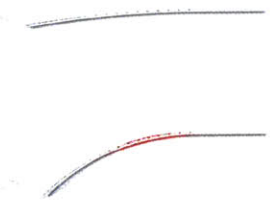


Figure 117: Polystyrene can be used to create stiffness changing sheets with a layer structure similar to uniMorph

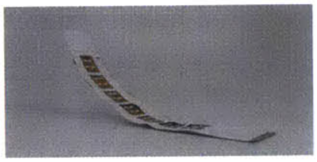


Figure 118: A first prototype of a stiffness changing thin lamp utilizing the thermoplastic qualities of polystyrene.

One of the contributions of this thesis is uniMorph, a shape-changing thin-film composite composite. While shape is the prevalent material property that is usually being focused on in HCI, stiffness is an equally important and potent property to be dynamised. Prior work in the Tangible Media Group shows some applications of particle and layer jamming. However, none of them have attempted to combine shape actuation and stiffness change. Future work could explore an alternative way of dynamically changing a material's stiffness. Thermoplastic polymers have the ability to be deformed above their glass transition temperature. Similar to the uniMorph's shape actuation, this temperature change can be induced by means of a heating circuit that is composited with the thermoplastic. Due to its great availability, polystyrene, a cheap material used in food packaging and general plastic products may be a good material. When heated up to 95°C, the polystyrene performs a phase change from hard to soft. This is usually utilized by uniformly heating up the material and then pressing it onto a form to impress a new shape to the material. However, when compositing it with an active heating element, one can easily soften only specific areas.

Since all three dynamic properties share one stimulus, they can be controlled with the same control-structure. This allows for a composite that can change all three properties.

Conclusion

This thesis postulates the importance of integrating computational qualities with the physical world. Specifically, it considers the role that augmented materials can have in the new type of interactions emerging from this. In order to truly integrate bits and atoms and enable not just transformations, but also conformation to the human body, materials have to facilitate bidirectional interactivity similar to how the physical world interacts.

This thesis presented a list of bidirectional transducers called *'Radical Elements'* that are able to facilitate sensing and actuation on the same modality. Materials with this transducing quality can truly mediate digital information in a comprehensive way.

The uniMorph composite exemplifies how a new radical elements can be created from simple materials. It enables easy fabrication of thin-film shape-changing interfaces and enables interesting applications by facilitating direct integration of electronic components into the material.

Finally, this thesis presented a framework for microinteractions with augmented materials. The framework draws on the interactions that we have with inert materials and creates a taxonomy of augmentations that extend this behavior.

Hopefully this thesis will inspire and guide development towards a future in which we can manipulate bits by interacting with atoms and truly integrate the qualities of physical materials and computation.

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