Materiality in Suspense

Exploring radical interfaces capable of representing multiple physical property transformations to enable computational, physical material perception.

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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 Massachusetts Institute of Technology

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Abstract

Years after the inception of the Radical Atoms vision, significant advances in technology have seen to dynamic tangible interfaces that bridge the biological and micro-mechanical to enable radical physical interaction with computation. With an increasing multi-modal complexity in such interfaces, this thesis explores a new methodologies and frameworks to designing input/output coincident and physically embodied computers. New types of Shape Changing Interfaces introduce physical perception of material properties to dynamic shape with physically accurate force feedback and introduce Radical Materiality as a way to afford physical interactions with a rendered object. Finally, the Radical Reality Test is proposed as an objective for such interfaces to eventually become indistinguishable from the physical entity or behavior they are computationally and dynamically imitating.

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"The universe is full of magical things,
patiently waiting for our senses to grow sharper."

Eden Phillpotts
A Shadow Passes, 1919

Motivation

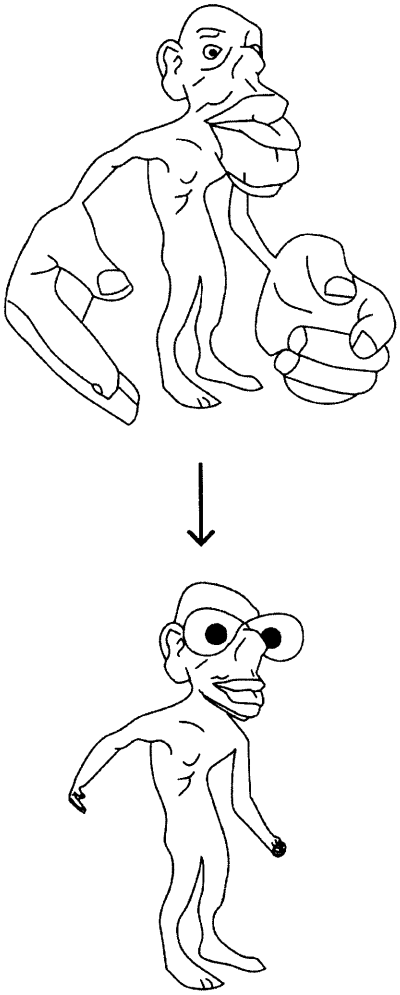


Figure 1

Top: Wilder Penfield's cortical homunculus from the 1930's represents the scaled cortical importance of various parts of your body as seen by your brain.

Bottom: Felix Heibeck's Gui-munculus of 2015 is a curious representation of the brains cortical importance when interacting with a graphical user interface today.

Computers today have a visual feedback bias. Our capabilities to develop technologies for visual feedback at a rapid pace far surpass that of our ability to rapidly create physical feedback. This has left our computers to exist in a two-dimensional plane with primarily visual representations of the digital world we manipulate. While newer advances in augmented reality mitigate this by augmenting 3D images in the physical space, the closer our visual feedback is to our reality, the greater the disconnect between this virtual reality and our computational representations.

In order to have tools that allow us to manipulate a computational world as we do our physical world, we require the same rich interaction we have with it in the first place. Shape changing interfaces allow us the ability to change not only the visual elements of an interface, but also the physical shape. This allows the user of the tool to manipulate a rapidly changing physical computer with a much closer flexibility to the interactions they would have with objects in the physical world through use of dynamic affordance.

Even here, however, we face a problem. Once again, the more realistic the physical interaction becomes, the more freedom we presume to have over this computational material and the more frustrating it becomes when we learn it is also limited. In our daily interactions with non-computationally controlled objects, we sense a lot more than the object's shape and color. We can smell the object, taste it, bend it, feel it's texture, see how it reacts to heat or combines with other objects and apply forces until it breaks.

The motivation for this thesis is to explore how we can go beyond simply rendering the shape of an object and start to

Figure 2

A material like honey exhibits not just shape but also viscosity, texture, smell, taste, adhesion and translucency

integrate material perception as a means to understand how to interact with the interface, it's limitations and its capabilities. Should we be able to successfully convince users that the shape represented has a material quality, we enable computers that are more expressive, dynamic and ever closer to the physical world we interact so seamlessly with.

This thesis is motivated by a vison for a future with Radical Atoms interfaces and is guided by a realization that in order for this to happen successfully, shape changing interfaces will need to have the ability to rapidly change both shape and material properties. It is motivated by the struggles that this field will encounter as we move ever closer to a "Radical Reality" in which we can no longer distinguish between a physical object in the real world and a rendered object in the computational, and the promise that advances in technology, a focus on human interaction and an appreciation of human expression will lead us there.

Thesis Aims

This thesis aims to identify the challenges in tangible media's Radical Atoms vision, a vision which imagines a future of computer interfaces that embed computation into physical interfaces capable of changing as rapidly as interfaces of today. In light of these challenges, this thesis aims to explore how material properties and the perception of those through dynamic, bidirectional, coupled affordances and interactions could act as a way to afford multimodal interactions.

Through this exploration, a strong focus will be made on how humans perceive computer interfaces through visual and tactile feedback. The promise of interfaces that can tap into physical perception while we interact will be explored as well, offering computers the capability to enable rich physical human experiences and expression.

Considering the multimodal nature of the Radical Atoms Vision, this thesis will propose a design methodology that allows individuals with different skillsets and backgrounds to design future interfaces that provide rich visual and physical feedback. The aim of this methodology is to simplify a broad vision into a process of discovery, creation, and validation that was used to realize multiple Radical Atoms projects.

Ultimately, validation of successful interfaces is a challenging task when the validation is a vision. This thesis aims to define a test for how successful an interface is at conveying a physical entity described as "The Radical Reality Test". Drawing on the well known Turing Test, this test provides a high level self-critical approach to evaluating the success of an interface at suspending disbelief in its users to the point where physical objects rendered by a computer appear to be and can be interacted with as if they were a real world entity.

Thesis Contributions

This thesis offers the following contributions:

1.
Identifies challenges in the Radical Atoms field and proposes a hierarchical and approachable design methodology for engineers, scientists and designers as an approachable hierarchy for the Radical Atoms Vision to enable its realization in future works.

2
Presents new physical interfaces that enable both shape and multiple programmable material properties to be recorded, represented and interacted with physically in the same computer interface.

3.
Proposes a "Radical Reality Test" to provoke and test a physical computer's ability to convincingly render, behave like and be interacted with as the material or real world physical entity it is attempting to imitate.

Thesis Outline

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

Chapter 1:
Briefly discusses the Radical Atoms vision and the challenges we face designing for and interacting with systems that implore and manipulate multiple physical states. It then proposes an approachable, hierarchical design methodology for radical atoms interfaces including physical properties, radical elements that transform those properties and radical functionality enabled as a result, such as computationally controlled physical material property perception.

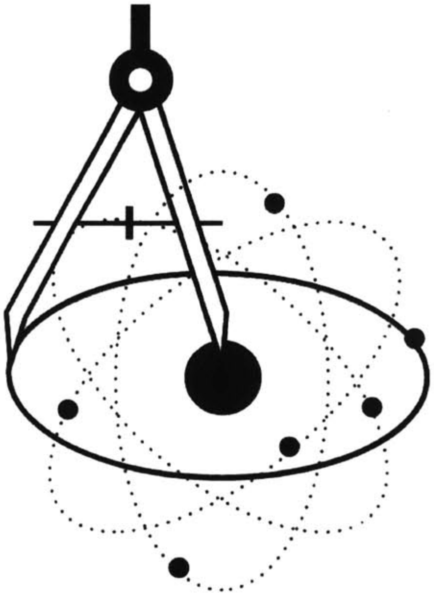
Chapter 2:
Discusses the major work of this thesis: how dynamic material properties can enable expressive interaction with increasingly complex physical interfaces and presents Materiable and inForce; computational interfaces capable of representing and recording both physical shape and material property change.

Chapter 3:
Discusses limitations and future work for new Material Interfaces building on the work and methodologies outlined.

Chapter 4:
Considers a "Radical Reality Test" as a way to objectively evaluate the effectiveness of a physical computer to convincingly behave and be interacted with like a real world physical entity through multimodal physical input and output, coincidence and physical embodiment.

Chapter 5:
Concludes the thesis with a summary.

Table of Contents



CHAPTER 1

DESIGNING FOR RADICAL ATOMS

Designing for Radical Atoms

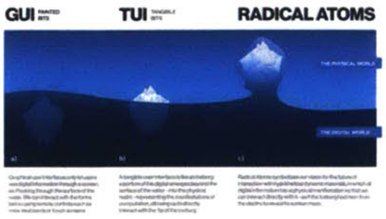


Figure 3
The "Iceberg" Metaphor from the original Radical Atoms article describes how the majority of computer interfaces have computational data "frozen" beneath the surface of a screen, while Radical Atoms envisions interfaces that can physically transform and be manipulated as a physical entity, freeing the data from it's computational limitations. 1

Radical Atoms refers to the vision of the Tangible Media Group at the MIT Media Lab. The vision first appeared in the 2012 article "Radical Atoms: Beyond Tangible Bits, Toward Transformable Materials" of Interactions Magazine [34] and describes a "vision for human interactions with dynamic physical materials that are computationally transformable and reconfigurable".

Radical Atoms envisions a future of interfaces that can transform physical properties and allow us to take advantages of the same dexterity, creative expression and sensorial experiences we have in the physical world we were born to inhabit. The vision argues that with **physical embodiment** a strong **input and output coincidence** we can leverage the physical dynamic affordance real world objects give us and our ability to assume how an interface will behave in response to manipulation through exploration of those affordances.

In this chapter the Radical Atoms vision will be explored, a revised overview outlined, some major challenges addressed and a design methodology proposed as a method for breaking down the Radical Atoms vision describing a Radical Interface composed of three distinct hierarchies to design for; Physical Properties, Radical Elements that enable the physical manipulation and representation of those properties and Radical Functionality that is enabled with a strong physical input and output coincidence.

The Focus of Radical Atoms

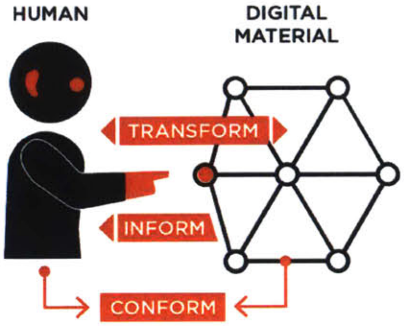


Figure 4
A simplified version of "Interactions with Radical Atoms" that outlines the three requirements: Transform, Inform and Conform.

The Radical Atoms vision can be differentiated from other research based on it's original focus - the ability to transform physical properties such as shape, texture or stiffness computationally with a further focus on this transformation for human computer interaction or, the ability for a human to perceive and manipulate an interface physically.

Because in common computer systems the screen is the main output with touch and the mouse or the keyboard is the major input, there is an inherent inconsistency in the multimodal operations of the physical system being represented and the input used to manipulate it. TUI's or Tangible User Interfaces focus on the **seamless coupling of digital and physical systems** by having the major input and output of a computer interface remain a physical one [37]. inTouch is a great example of a TUI for remote communication through physical interactions. The input and output is the same in two separate modules of the interface in different locations, synchronizing the input and output of two people in separate locations physically.

While TUI's acknowledge the importance of bidirectional synchronization of physical input and output, they usually remain specific to basic interaction or one physical property, often due to technical limitations and complexity. Radical Atoms builds on this by suggesting future interfaces should allow the manipulation of multiple properties to create a low latency multitasking computational system in which one can interact with the physical freedoms we have in the real world.

At the core of this vision and perhaps the true focus of Radical Atoms is the following two inseparable concepts:

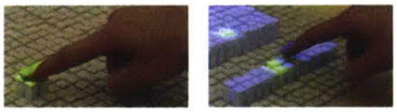
Physical embodiment + I/O Coincidence

In order to achieve coincidence in input and output of the system through physically embodied interactions, the vision states that that Radical Atoms Interfaces should fulfill the following three capabilities (see figure 4):

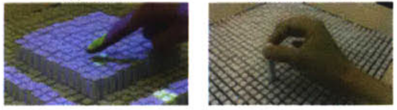
- ***Transform*** its shape to reflect underlying computational state and user input;

- ***Conform*** to constraints imposed by the environment and user input; and

- ***Inform*** users of its transformational capabilities (dynamic affordances).

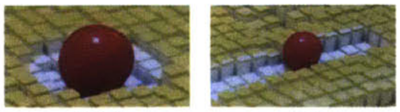


(a) Button (b) 1D Touch Track

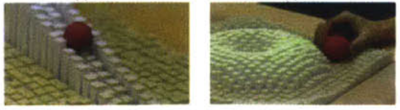


(c) 2D Touch Surface (d) Handle

Figure 6
Dynamic Affordances of the inForm Radical Atoms Interface. 1[7]



(a) Well (b) Slot



(c) Ramp (d) Surface

Figure 6
Dynamic Affordances of the inForm Radical Atoms Interface. 1[7]

Shape Change (transform), Dynamic affordances (inform) and Dynamic Constraints (conform) have been described in works like inForm [11] and Transform [35] and have enabled radical physical interaction with digital information at a lower cognitive cost [12,16] going beyond what a real world form can offer. Whether it's a physical embodiment of a person with 'Tele-operation' [17] or the ability to render and manipulate 3D computed data as a physical object [19]. In this work, real world dynamic affordance is applied to digital information that would, with a less radical interface, require a remote control (such as a mouse, keyboard or touch screen) to manipulate a purely visual representation of the physical data.

As a vision, Radical Atoms is an exploration towards truly dynamic, physical interfaces. The vision is exemplified in those works that cause a person to forget they are interacting with a computer system and thus interact with the interface as a physical entity, a material with computational intelligence.

Expansion of Radical Atoms work

Initially, the vision focused on **computationally transformable** and **reconfigurable** computer interfaces, though over the past few years this vision has expanded into biologically, pneumatically and other smart material actuated interfaces that often challenge the definition of computation itself. As the world begins to explore the possibility of rapid computation in biological forms, the Radical Atoms vision has expanded itself along with it.

The diagram below shows an updated overview of radical atoms approaches over the years and the major physical functions they have enabled as well as some possibilities for future functional research themes. Currently the major streams of research in the Tangible Media Group include dynamic shape displays, programmable materials and self-configurable systems. In the future, these streams may well combine.

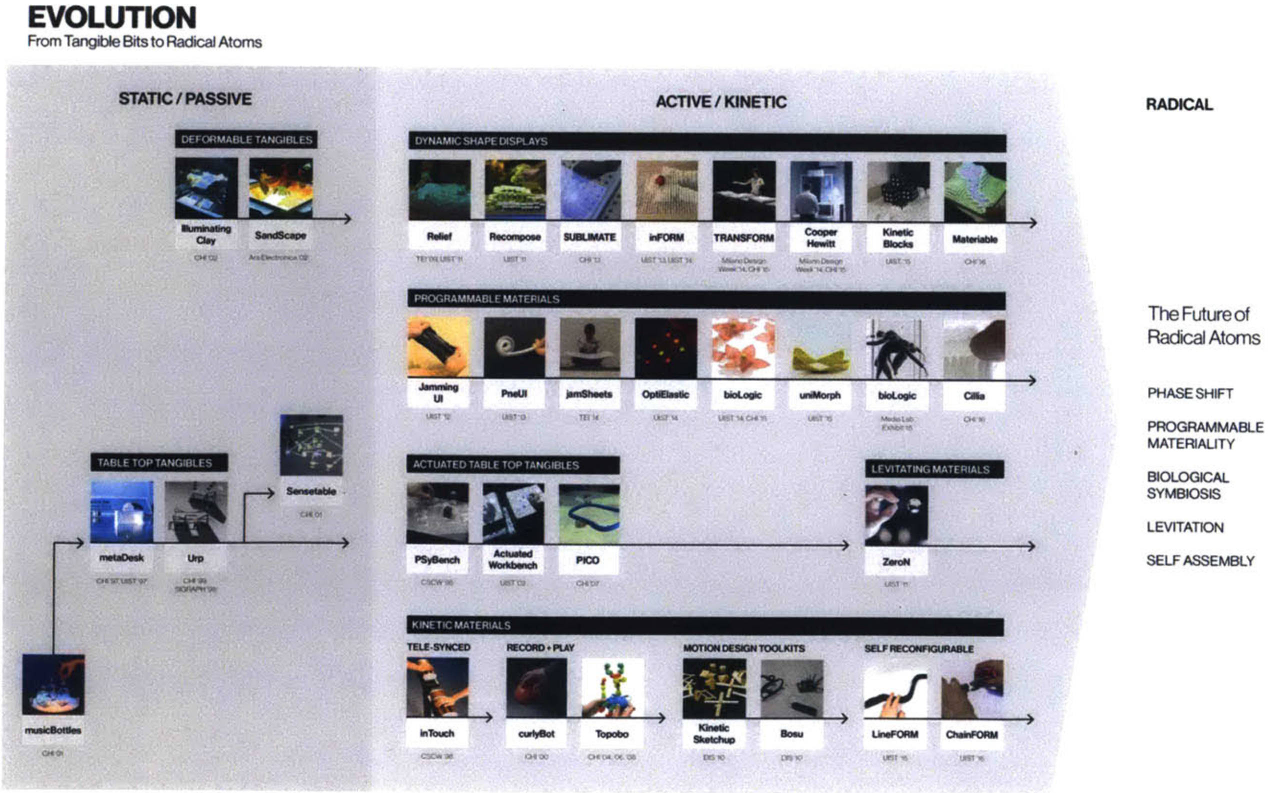


Figure 7
An updated overview showing the evolution of the Tangible Bits research vision to Radical Atoms works, including some of the most recent. 1

Major Challenges

What actually defines a Radical Atoms Interface?

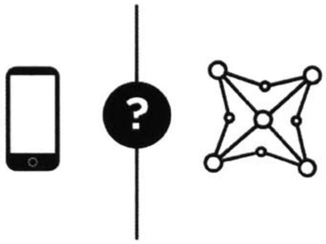


Figure 8
Under vision driven research, it becomes increasingly difficult to justify the novelty of a new system without scientific justification. This thesis calls for a more thorough definition of Radical Atoms.

While the Radical Atoms vision has been clearly defined with a series of important explicit concepts (I/O Coincidence, directionality, computation, the ability to transform, conform and Inform physical properties, etc.) it is not entirely clear that a Radical Atoms Interface of the future should ultimately incorporate all of these elements together. It is technically difficult to incorporate all of these elements in one system as for many approaches, the technical capabilities of the chosen technology (actuators, sensors, biological cells) are limited in speed, strength or ability to create a bidirectional system for direct manipulation. However, because Radical Atoms itself is a vision, it is important to state the goal and define how we can go about achieving this, or parts of this in order to continue to identify what research needs to be done to justify it.

A need for Latency Coincidence

The original Radical Atoms Interactions article [34] states the importance of configurability (computation) with human hands. The speed at which our hands can move creates quite a limitation for many approaches. While it is assumed that this speed should match that of a visually output focused system like a touch screen, for many physical systems this is not always the case. Many projects have focused on a more gradual interaction space, for example, the environment or biological state. In bioLogic, a nato-bacteria based approach for actuation, the reaction is no where near as rapid as direct manipulation - however, for I/O coincidence in the case of the sweat changing garment, it does not need to be. In this case, the input is the amount of sweat the body releases and the output is a physical shape change in a garment to balance this sweat level creating a bidirectional loop. While the interaction is gradual and seemingly unintentional, bioLogic proves an extremely beneficial computer for this application space as there is no need for electronics or complex systems. In many cases a direct physical reaction might not be necessary.

What is relevant, however, is that the speed of the system matches the required speed of the task. With the inForm shape display [11], the system should respond immediately to touch to allow for the direct manipulation of a model by hand. The speed of any individual transformation in a Radical Atoms Interface should therefor be directly coupled to the speed of the physical interaction required. The issue is that computers today can perform multiple tasks and incorporate more than one method of interaction in the same system and at varying, very rapid speeds. Currently the only Radical Atoms approaches capable of variable speeds and tasks are those that are electro-mechanically actuated, though several attempts are being made to combine programmable materials and electromechanical actuation, for example with the recent work of Cillia [28] which vibrates 3d printed nanostructures of hair to create complex actuation and sensing.

The difficulty in designing for multiple physical properties

A system capable of multiple physical interactions, rendering multiple material properties such as shape, smell or texture and capable of performing multiple tasks as a traditional computer does will need to consider the appropriate speed of physical transformations to match the expectations the user has of a real world material for each individual physical property change. Designing appropriate transformations, behaviors and tasks for such a system becomes an incredibly difficult process as designers need to consider what to do for each particular sensorial experience.

Considering the work in this thesis has faced exactly these challenges, the importance to 'divide and conquer' approaches for the future design of highly multimodal Radical Atoms interfaces has never been more important.

A Hierarchical Design Methodology for Radical Atoms

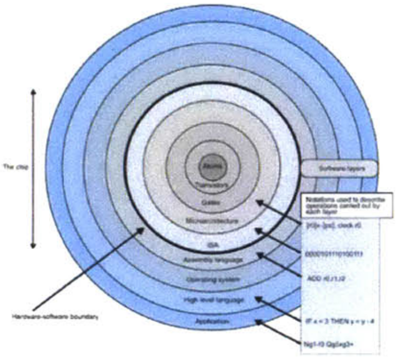


Figure 9
The Computer Hierarchy visualizing computers from the transistor to the assembly language, operating system, high level language and eventually the application that the user sees.
Alan Clements 1

Whether it's the software hierarchy of an operating system based laptop device or the cellular hierarchy of the human body, complex systems are defined in a comprehensible model that allows us to build and design for them without needing to deeply understand lower level functions, for example the common programming hierarchy [7] shown in Figure 9. When a well designed model of a system has multiple parts with calculation we refer to this as "Computation". The Radical Atoms vision, however, does not define a clear hierarchy for bidirectional I/O coincident machines capable of manipulating physical properties. While many projects have defined hierarchical control systems specific to the work, these usually change from project to project and not all consider the importance of **I/O coincidence** and **physical embodiment**, the core of Radical Atoms.

The purpose of this section is to extend the common computer hierarchy and break up any Radical Atoms works into three major hierarchies that together form a "**Radical Interface**". Beginning with '**Radical Elements**' that behave as bidirectional transducers of physical properties to the "**Radical Physical Properties**" derived from combining radical element and ultimately to the "**Radical Functionality**" that we can enable as a result of this bidirectional physical interaction with the interface.

A Radical Atoms Interface

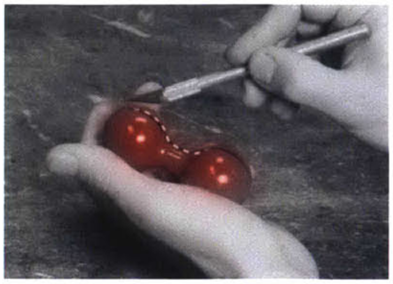


Figure 10
Perfect Red is a film describing a conceptual Radical Atoms Interface composed of a programmable material.

For the purpose if this design methodology, a Radical Atoms Interface is composed of three major hierarchy levels between the computer (a system capable of logical operations) and the actor manipulating the interface (the human) [41]:

- ***Radical Elements***
  Transducers of physical properties at a designers disposal to create a bidirectional interaction loop with the interface. [14]
- ***Radical Physical Properties***
  Real world physical material properties simulated via the patterning of Radical Elements, that humans are capable of sensing and perceiving with low cognition.
- **Radical Functions**
  New functionality or capabilities enabled by a convincing physical interaction with computationally controlled Radical Physical Properties.

The purpose of this methodology is to categorize inventions and allow designers, engineers and scientists to approach Radical Atoms Interfaces at any hierarchy:

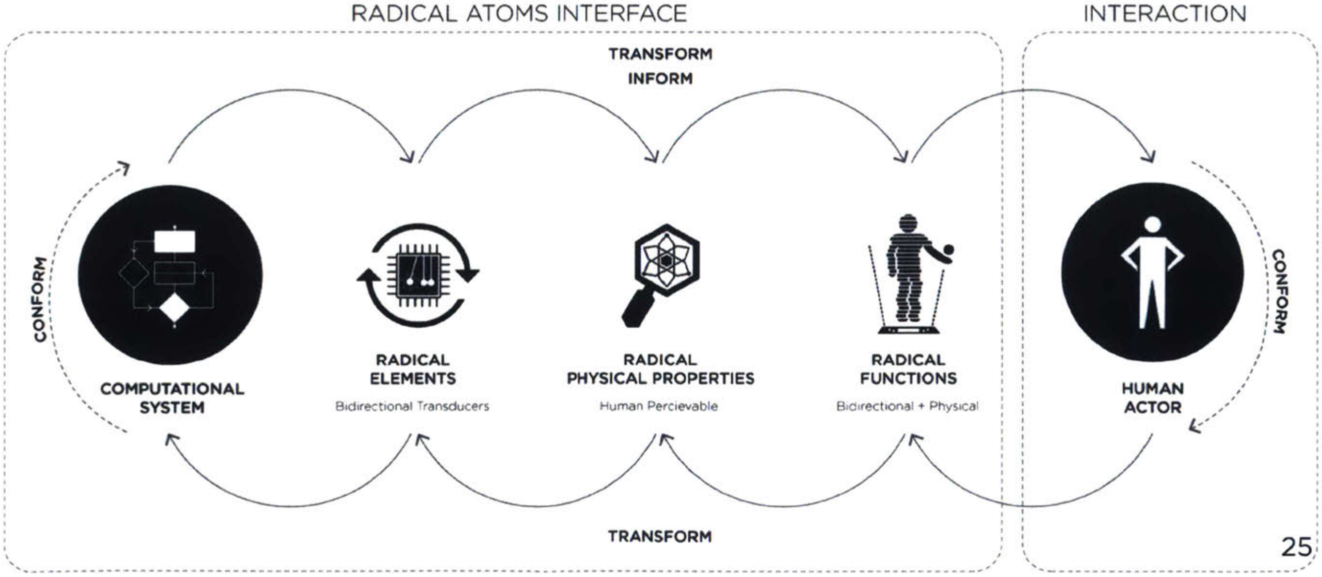


Figure 11
A hierarchical design methodology in the form of a control loop describing the requirements for Radical Atoms

Radical Elements

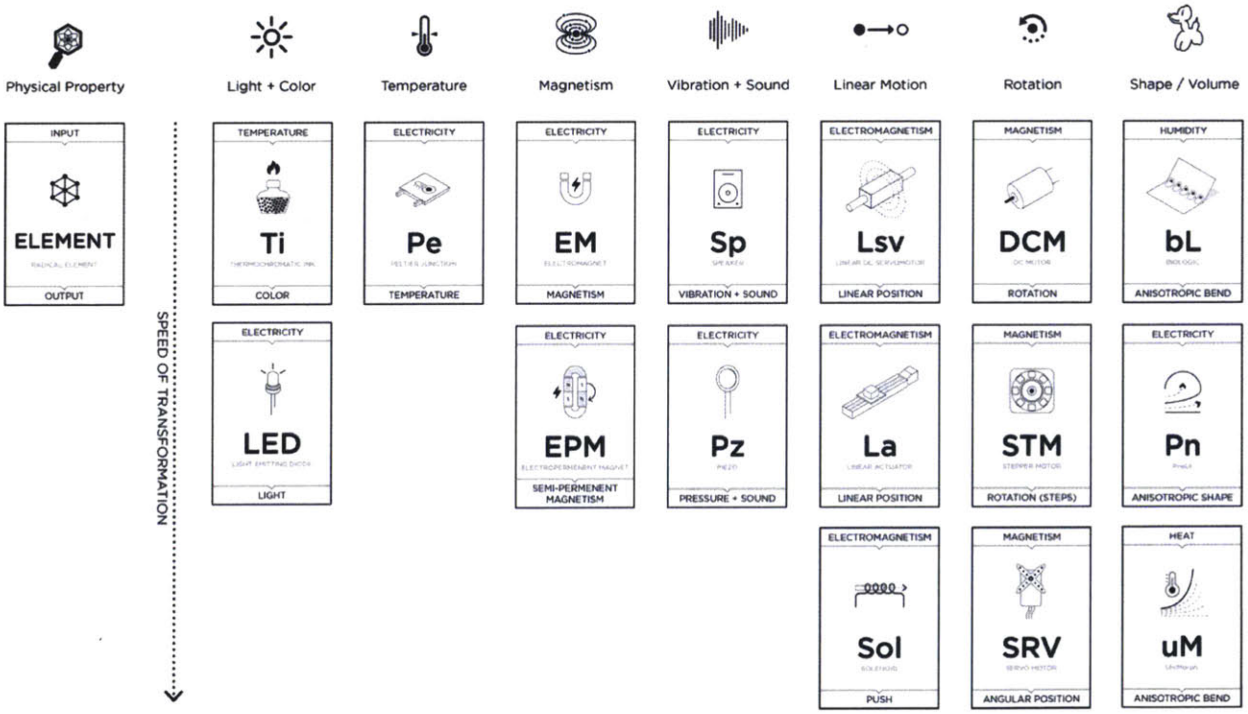
Figure 12
The Faulhauber's "quickshaft" actuator (LSV below) is a linear servo motor capable of turning electricity into very rapid and precise linear motion. The inForce interface described later in this thesis combines this with force sensors to create a variety of "Radical Physical

The core concepts of Radical Atoms must be prevalent when considering which technologies to take advantage of in a system capable of bidirectional interactions:

I/O Coincidence + Physical Embodiment

In order to actually build a Radical Atoms interface, we require a technology that can transduce physical properties as an input and output, or build a convincing perceptual model of them, between the human and the computer (Inform, Transform, Conform). Felix Heibeck in his 2015 Masters Thesis refers to such technological elements as "**Radical Elements**" [14]. The following is an updated version of Heibeck's table of Radical Elements to include the inputs and outputs of the element and some elements used in the work of this thesis. It includes possible elements such as a servomotor (rotation transformation) or an electromagnet (magnetic).

Figure 13
Radical Elements are hardware elements designer can use to transduce physical properties



Radical Physical Properties

Figure 14
A Radical Physical Property is a simulation of a real world physical property that is computationally variable via Radical Elements.

There are thousands of defined physical properties in physics, for example, the stiffness or flexibility of a material, it's breaking point or it's ability to stick to another object (adhesion). Each of these properties have a mathematical definition that can be computationally simulated and often are in visual feedback based computer simulations of physical data [26]. In the real world we use our senses interacting with an object over time to measure physical material properties and build a proprioceptive model of it's materiality.

A **Radical Physical Property** is the physical representation of these real world properties through an interface comprised of bidirectional physical transducers, Radical Elements. While the Radical Element itself does not always physically change an actual real world property, a combination of elements together can create a computationally reprogrammable proprioception of shape, texture or flexibility, for example. Some properties have already been explored in work like Jamsheets (stiffness [29]) or inForm (shape [11]). The following is a table of real world physical properties that we can perceive and could be or have been (highlighted) represented with I/O coincidence and physical embodiment in a Radical Atoms Interface.

Figure 15
Physical properties we can perceive, that could be simulated by a Radical Atoms Interface, categorized by state

LESS ENERGY ········> MORE ENERGY

EASY TO PERCIEVE ········> HARD TO PERCIEVE

SOLID	LIQUID	GAS
Stiffness	Viscosity	Compressibility
Shape	Cohesion	Expandability~(Smell)
Elasticity	Adhesion	Taste
Colour/pattern	Mass	Temperature
Flexural Modulus	Density	Pressure
Plasticity	Taste	
Texture	Reflectivity	
Taste	Refraction	
Smell	Temperature	
Temperature	Evaporation	
Creep (Deformation)	Surface Tension	

Radical Functions

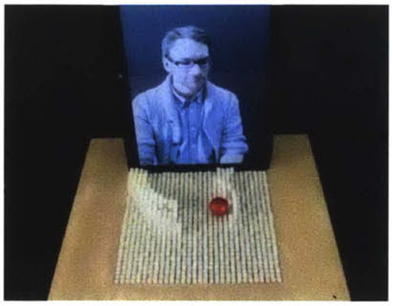


Figure 16
By computationally varying "Shape" on the inForm shape display, we can represent and interact with a physical person at a distance. We call this "Teleoperation"

When we combine, pattern and chain Radical Elements we enable '**Radical Functionality**' through the human perception of physical change in response to our physical interaction with those elements.

A Radical function includes the interaction we have with the system, the computation the system performs to control multiple Radical Elements, the manipulation of the Radical Elements in response and the perception of the physical changes the system performs over time.

Examples of Radical Functions in various works of the Tangible Media Group include Teleoperation - the ability to remotely interact with real physical objects or people and have that entity reflected physically, Dynamic Affordance - the ability to physically afford how an interaction will dynamically adjust the interface, or Inter-Material interaction where both the user and the interface can manipulate real world physical objects.

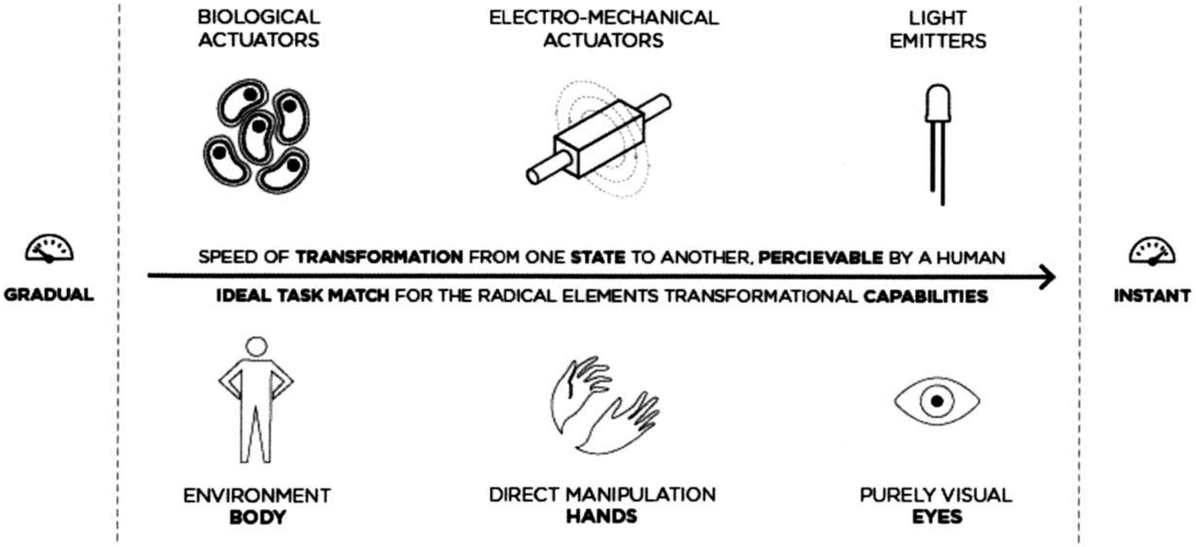
Figure 17
Physical properties we can perceive categorized by state of matter

Interaction, at the correct Speed

Due to the importance of physical I/O coincidence, one of the major technical challenges mentioned before in this chapter is that of latency in some Radical Elements. Due to the nature of physical transformations taking time, designers need to consider the coupling of the elements to appropriate perceptions of the user.

For example, most biological actuators have a slow effect; they are currently not ideal for direct manipulation. A light emitter, usually rapid in it's transformation, is often used in Radical Atoms works. However, it only provides visual feedback and should be used with discretion. Our hope is that science will further push the boundaries of biological actuation such that one day we can build systems purely from these radical elements, Technological limitations of strength and speed today suggest in order to explore the possibilities of direct manipulation, a mechanical actuator coupled with a processor provides the strongest bidirectional control loop.

Figure 18
Suggested matching of Radical Elements to methods of Interaction.



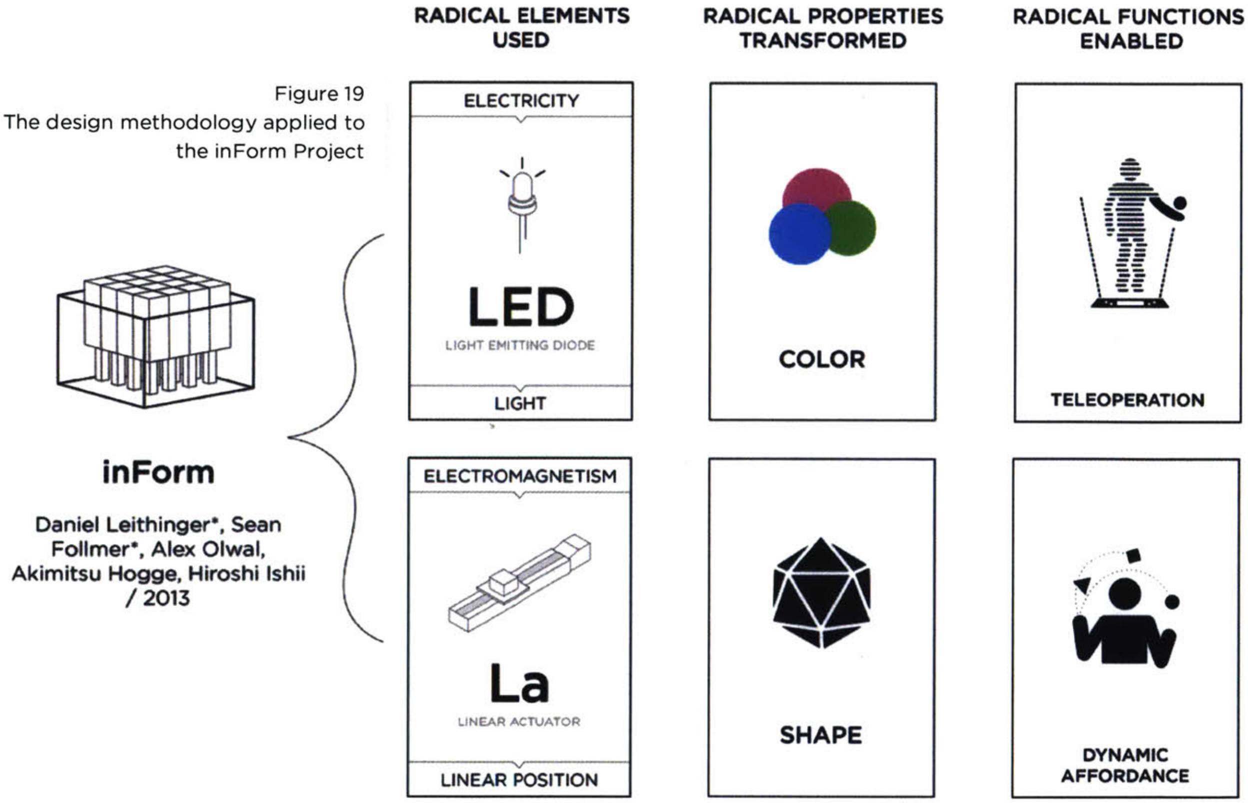
The Design Methodology applied to Radical Atoms Works

Additionally, this methadology also allows us to break down various works into a digestable format for those who wish to learn how the system functions. We can split various projects into this heirachy to understand how to design for them, what we can improve and how we could, in future work, combine different functionality derrived from this research.

inForm

inForm [11] combines light and linear position radical elements mechanically in a pin array that together creates rich shape and color output perceivable through direct manipulation and gesture control.

Figure 19
The design methodology applied to the inForm Project

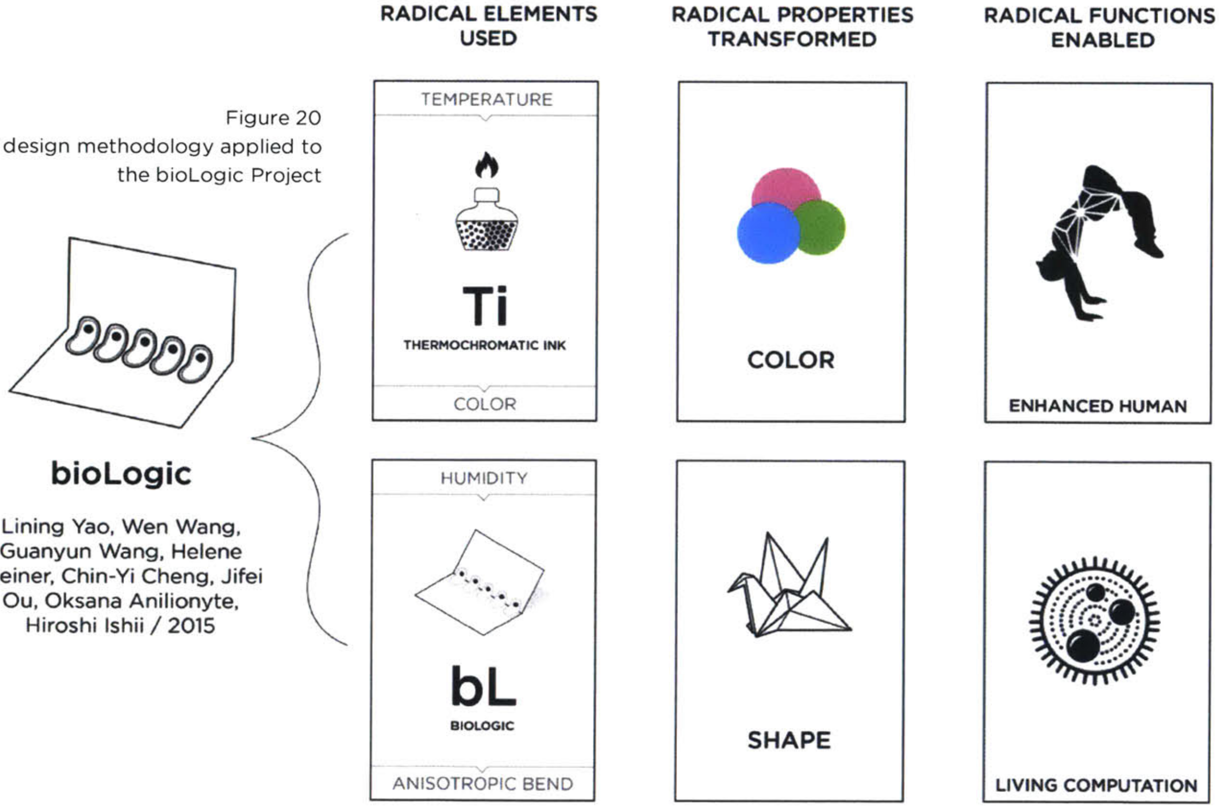


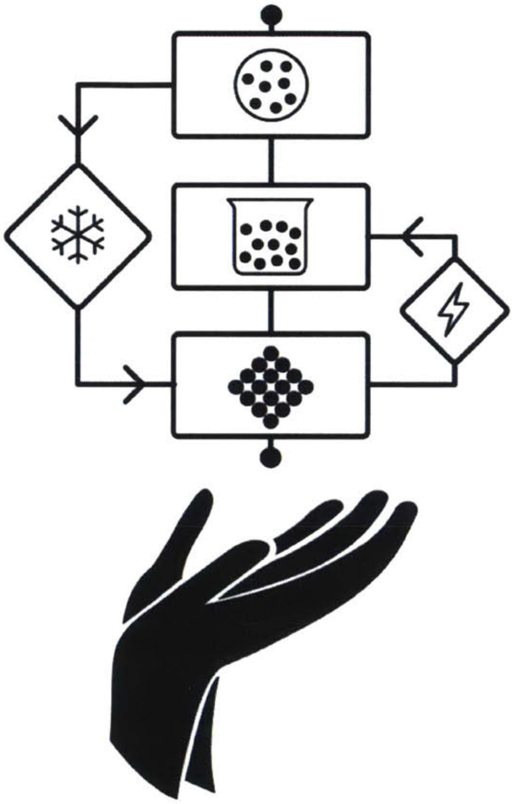
bioLogic

bioLogic [40] combines thermochromatic ink and custom natto-bacteria onto a flexible fabric positioned such that the garment can fold it's shape and sometimes also it's color in response to humidity.

Because the change is gradual, however, at the time being this work is best suited for interactions that happen gradually such as wearable clothing. Ideally, the Radical Elements in future could be combined in other ways to provide the capability for intentional interaction or direct manipulation.

Figure 20
The design methodology applied to the bioLogic Project





CHAPTER 2

RADICAL MATERIALITY

Radical Materiality

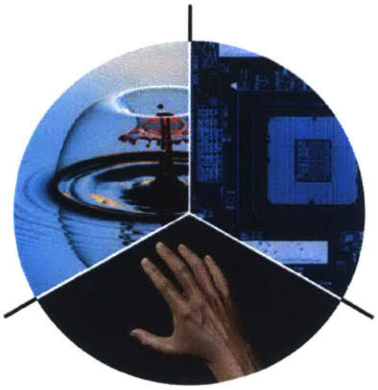


Figure 21
The aim of this thesis is to create a physical interface capable of rapidly and drastically changing perceived material properties in response to direct manipulation.

Sources beginning from top left:
1) liquiddropart.com, Corrie White,
2) Chip, wallppaperscraft.com
3) 3D Hand, Leap Motion

As we continue to develop new physical ways to manipulate computational information these systems move closer to a world we understand through our own lifelong sensorial experience of it - our real physical world. Systems like Tangible Media's shape changing displays have drawn upon the benefits of the physical affordance of shapes and dynamic affordance of moving physical shapes. Unlike our physical world, however, a shape display allows its physical form to change immediately, like the touch screen can change its visual output immediately. While a shape changing interface proves extremely powerful in many types of physical interaction, the physical world we inhabit has a plethora of affordances that we perceive while interacting with an object.

Chief among them for this thesis, is the power of material property perception. A child can understand that a ball of clay is malleable and a block of concrete is not, that water and paint will soak into their clothes and honey will be difficult to remove from their hair because it is adhesive. These rich affordances of material properties have yet to be explored in an interface that can rapidly change between them, because it is technically difficult to change an actual material property as rapidly as we can change light produced from a light emitting diode or the position of the pins in a shape display.

The following work in this thesis explores how we can achieve the radical function of material property change and how affordances of these material properties could drastically change the way we interact with physical interfaces, giving way to material interfaces where physically rendered objects actually feel like the material they are representing.

From Physical to Computational, and back again, immediately.

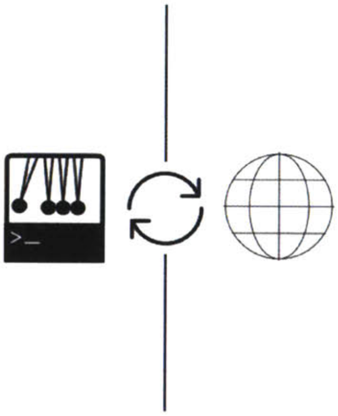


Figure 22
To strengthen the 'illusion', the transition between what is physically perceivable and the simulation must be rapid and accurate

In the real physical world, a material like sand does not lag mid air when dropped, a flexible material does not remain rigid as it tries to compute how to bend and a body of water does not appear as a two dimensional image on a flat screen TV. Any Radical Atoms interface capable of rendering material properties needs to process the physical input and the physical output such that the manipulator perceives and interacts with it as a given material. In order to get this desirable speed, resolution and opportunity for strong physical perception, we began our work using Shape Changing Interfaces, specifically shape displays, which have proven the ability to rapidly change shape.

Rendering Material Properties on Shape Changing Interfaces

Shape changing interfaces have been a recent realm of research in the HCI field [21,34] Shapes of 3D digital data or even remote real objects can be rendered and manipulated in physical form, dynamically using various types of shape changing interfaces [12,25]. While shape, color and animation of objects allows us rich physical and dynamic affordances, our physical world can afford material properties that are yet to be explored by such interfaces. Material properties of shape changing interfaces are currently limited to the material that the interface is constructed with. In our work, we aimed to represent various material properties by taking advantage of shape changing interfaces' capability to allow direct, complex and physical human interactions.

The Materiable and inForce projects also draw upon the vast research of physics simulations in computer science which allow for the computational simulation of physical properties and research in Shape Changing Interfaces. These works explore how to take direct physical interactions with the system, compute and simulate the appropriate material behavior response and represent the result physically in a bidirectional loop with Input and Output coincidence.

The result for both systems is an early representation of multiple physical properties in one interface to varying degrees of realism and sensing. For Materiable, the system represents the shape of the material accurately while inForce increases this realism and range of tangibility by incorporating accurate force sensing, force output and recording through inter-material interaction.

Shape Display to Material Shape Interface

The Materiable project was the first attempt to create a perception of multiple material properties dynamically through direct physical manipulation of the interface. Without implementing any new hardware to Tangible Media's inForm and TRANSFORM displays, this approach applies a framework for bidirectional coupling of the dynamic interaction we have with a material property to the shape changing interfaces ability to physically render an appropriate behavior. While Materiable is not able to render physically accurate haptics and force feedback to simulate a materials physical forces, we were able to render material property behaviors to a level in which participants in a user study began to interact with variations of material properties as if the shape display's pins were actually a responsive material.

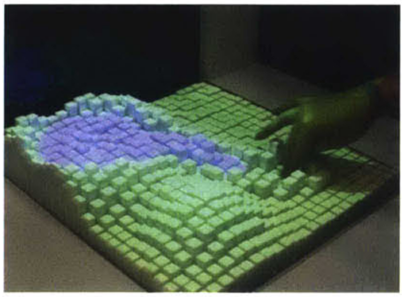


Figure 23
Materiable: A Material Shape Interface.

Shape Interface to a true Material Interface

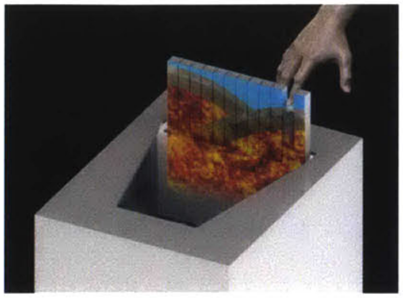


Figure 24
inForce: A Material Interface.

With the successes and learnings of the Materiable project, we began to explore what it would take to create a true "Material Interface" - that is, an interface which was able to render and directly couple the forces a person applies to the forces that would be expected of multiple given material properties in the same interface as a display can represent more than one color.

The inForce project incorporates extremely precise, fast and low profile motors (Faulhauber's "Quickshaft" Linear DC-Servomotors [9]) and a pin with embedded sensors to create a force control feedback loop for each individual physical pin (the 'Radical Element'). This feedback loop allows the interface to create variable forces in a 3-dimensional space and allows for interactions rich in physical force feedback.

The added benefit of this system is that it can both record and represent physical force. This potentially allows the Material Interface to scan both the shape of a physical object and its material properties, and then represent that same object as a digital physical rendering with perceptually the same material properties as Radical, computationally controllable ones.

The application space for this interface is vast. Material interactions mean a much broader possibility for physical affordance, the ability to rapidly change between logical and expressive operations, the ability for true Inter-Material interaction as well as a rich tactile interaction space for augmented and virtual reality displays.

Related Work

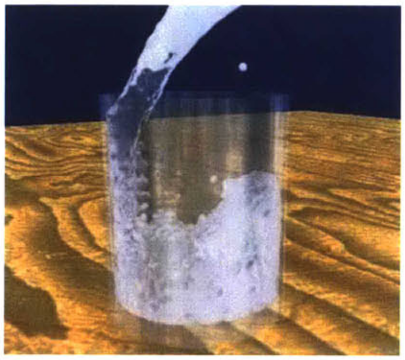


Figure 25
Particle-Based Fluid Simulation for Interactive Applications

Müller et al., SIGGRAPH 2003

Various research has been conducted for simulating and representing material properties in multiple fields. In the field of Computer Graphics, researchers have developed algorithms for simulating how objects with different material properties behave differently with external force or gravity [4,13,24,26]. Although every year advancements in their research has shown us astonishingly realistic simulations, they remain limited to the medium of visual feedback, displays and screens.

Towards the goal of representing virtual objects in users' hands, various haptic devices have been proposed to provide the sensation of different material properties [27,31,33]. Researchers have utilized haptic systems to replicate elasticity of organs for medical applications [2,8]. However, works in haptic devices either remain in flat static surfaces or require additional wearable/hand-held devices that target sensations to specific parts of the body [23].

Figure 26
Jamming User Interfaces: Programmable Particle Stiffness and Sensing for Malleable and Shape-Changing Devices

Follmer et al. UIST 2012

On the other hand, in some research, the actual properties of physical materials are controlled computationally. This approach enables us to interact with different ways of interaction using any parts of our body. For example, jamming techniques have often been used to dynamically change stiffness of the interface and connect this change to content represented on the jammable material surface with projection [10, 29]. Also, recent 3D printing research enables us to replicate objects to have both various shapes and elasticity by controlling their micro structures [32].

While these research areas always require physical control of force feedback or air pressure, there has been an approach to create an illusionary haptic sensation by providing visual feedback according to users' action, named "pseudo haptic effect" [21]. With the theory of human perception that we perceive objects not only through haptic feedback but with a mix of multi-modal sensory feedback, this technique conveys sensation of virtual objects only by visual effect in reaction to a user's motion [1]. For example, this effect is applied to GUI systems where users can perceive changes in rendered textures, such as friction, by observing the way their mouse cursor slows down across the image [20,38]. The necessity of cross-modal design in haptics to consider not only the touch sense but also other sensory modalities have been emphasized [22].

In contrast to prior work, Materiable introduced a novel interaction technique to represent material properties with shape changing interfaces inspired by pseudo haptic effect, which changes shape according to the direct manipulation from the user. In the Materiable project, the material is perceived as immediately responding to the user's physical interactions and allows for a bi-directional feedback loop, much like one would expect with real physical materials and common computational devices. In addition, this approach doesn't require any hardware to be attached to the human body. Users can use any part of their body or even other existing physical tools and materials to interact with rendered material properties in order to explore their limitations, feedback and capabilities in the same way one might do so with a real material in the physical world. With this technique, we aimed to push the capability of shape changing interfaces beyond rendering the shape alone.

If Materiable allowed for the perception of material properties through dynamic visual and physical shape behaviors, the inForce Material Interface extends this work by implementing a rapid force feedback control loop to create a richer multimodal perception of material properties through physically accurate forces - the way we generally sense material properties in the actual physical world. The rapidly updating control loop of the inForce interface allows the rendered object to exhibit forces that would be expected of a stretchy material, a rigid material or a super elastic material in response to real world physical forces of touch or otherwise. This means in addition to human computer interaction, the interface can also record, respond to, and manipulate real world materials that fit within it's range of forces. This is considered "Inter-material" interaction.

As computationally controllable interfaces, Materiable and inForce open up the possibilities of material affordance within the realm of human computer interaction. While shape changing interfaces have deeply explored how physical affordances of shape alone can be used as a way to comprehend a computational objects movements and enable rich expressive interactions with computation, the ability to afford a rendered objects material properties could allow an individual to recognize how to interact with the object, for example kneading a flexible material like clay or gluing more rigid objects together with an instruction. In order to achieve this perception, we needed to construct a physical simulation of these properties and implement this on a shape changing interface capable of providing physical feedback.

Rendering Perceivable Material Properties of Deformable Materials

Physical Material Properties

Considering a strong focus on human computer interaction in this work, this thesis will explore those physical material properties that are perceivable through human interaction with an object. While specific physical properties were selected for both the inForce and Materiable projects for validation and focus, these interfaces are not at all limited to these properties. The goal of Materiable is to see if we can make these material properties "Radical", that is, computationally controllable and physically perceivable as the real world properties.

Creating a physical perception of Material Properties

In order to achieve this, the Materiable project focuses heavily on learnings from traditional computer simulation of physical systems and implements these on a shape changing interface. The novelty here is the combination of real physical output that translates to visual and haptic feedback as well as spatial recognition of the shape. We believe that by dynamically changing the physical behavior of the interface, we could create a perception of these material properties strong enough to discern the differences in various simulated material examples.

Materiable

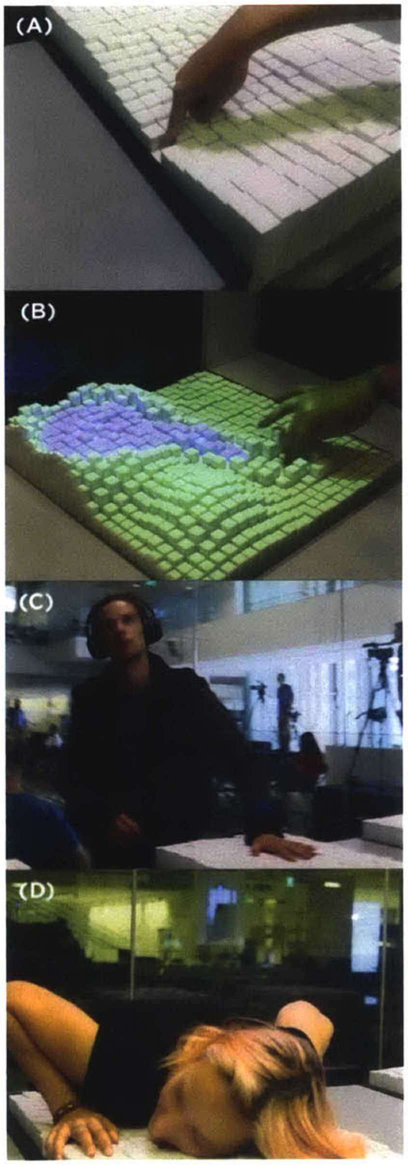


Figure 27
Materiable Project

A) Example of a direct input as a distrusted human-material interaction B) Implementation of multiple material properties responding to direct input C) Participant gazes into the distance while trying to feel and identify the rendered material D) A user study participant using their body to feel the rendered material.

In the Materiable project, we proposed an interaction technique to represent material properties using shape changing interfaces. Specifically, by integrating the multimodal sensation techniques of haptics, our approach built a perceptive model for the properties of deformable materials in response to direct manipulation.

As a proof-of-concept prototype, we developed preliminary physics algorithms running on pin-based shape displays. The system can create computationally variable properties of deformable materials that are visually and physically perceivable through shape. In our experiments, users identify three deformable material properties, namely flexibility, elasticity and viscosity, through direct touch interaction with the shape display and its dynamic movements. In this project, we describe interaction techniques, our implementation, future applications and evaluation on how users differentiate between specific properties of our system. Our research shows that shape changing interfaces can go beyond simply displaying shape allowing for rich embodied interaction and perceptions of rendered materials with the hands and body.

Overview

In this project, we explored methods to represent dynamic human perceivable material properties through shape changing interfaces, where the shape and nature of the material is directly deformed by the user. Specifically, by controlling the shape of interface according to users' direct physical input, we assume that users can perceive of various material properties through physical deformation. To be concise, in this section, 'rendered perceivable properties of deformable materials' is often referred to as 'rendered material properties' (Radical Physical Properties) to differentiate between those perceived in the real world, and those we can computationally control. We implemented two main types of material emulations, deformable solid and liquid, using basic physics simulation algorithms on a pin-based shape display in combination with direct physical input detection algorithms (See Figure 28). We propose applications that utilize the display's ability to render multiple material properties at the same time, or to render shapes in response to input. We also conducted preliminary user studies to evaluate how well our technique expresses the given material property and to investigate if users can distinguish specific properties.

Radical Physical Properties explored in Materiable

For the purpose of this project, we specifically focused on the mechanical material properties of flexibility, elasticity and viscosity which are perceivable through human touch and observation. *Flexibility* is a measure of a solid's ability to be bent or flexed by a given force and is the inverse of stiffness. *Elasticity* is a measure for a materials ability to resist a distorting influence or stress and to return to its original size and shape when the stress is removed. Lastly, the *viscosity* of a fluid is a measure of its resistance to gradual deformation by shear stress or tensile stress. It is informally referred to as the "thickness" of a liquid.

The Materiable Method

With Materiable, we attempted to measure the displacement of a user's direct manipulation as touch input, translate this through physics emulations and have the shape changing interface render a dynamic deformable solid or liquid that behaves relative to the calculated physics of this input. One can feel and view the simulation from any angle and direction interactively. As with any real-world material, the user is connected to the simulation through a dynamic physical experience. Our goal was to convey deformable material properties recognizable as actual materials in the physical world even under the constraint of the interface's unvarying materials. Thus, our proposed approach enables shape changing interfaces to represent dynamic shapes and material properties at the same time.

Figure 29 shows the interaction framework we proposed. The shape changing interface detects the user's direct physical input using built-in sensors and changes its overall shape with actuators according to a physics emulation that is computed in real time. The deformation is provided to users as both visual and haptic feedback.

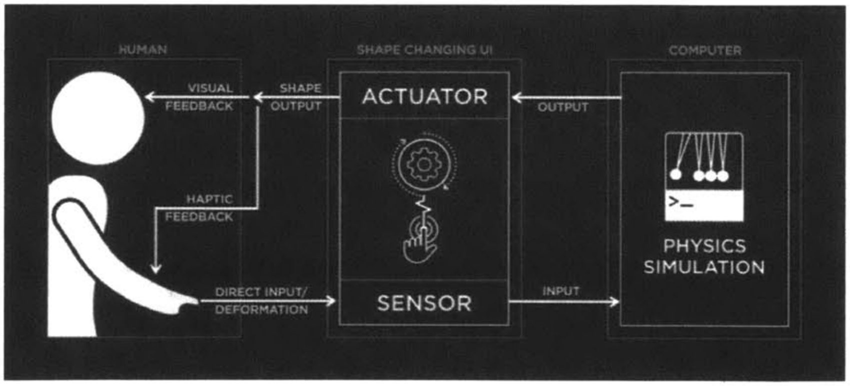


Figure 28
Interaction framework to represent material property using shape changing interfaces.

In order to interact with the rendered material on shape changing interfaces, a user can use any part of their body to touch and manipulate the rendered material property as shown in Figure 30. Users can also take advantage of other physical tools or objects to manipulate or test the simulation though this work does not explore this directly.

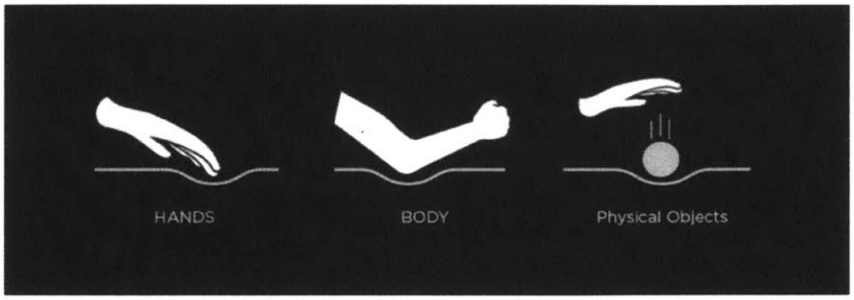


Figure 29
Different ways to feel and interact with the rendered materials we proposed.

Technical Implementation

As a proof of concept, we implemented a prototype system to represent material properties using two pin-based shape displays.

The TRANSFORM system [35] consists of three shape displays, 16 ⇥ 24 pins each, which extend up to 100 mm from the surface, and cover an area of 406 ⇥ 610 mm. Actuation speed is 0.644 m/s and each pin can exert up to 1.08 Newton's. The shape display hardware uses custom Arduino boards that run a PID controller to sense and move the positions polystyrene pins through motorized slide potentiometers (See [12,35] for details). The TRANSFORM system was used for the user study.

We developed application examples on a smaller shape display [18] consisting of 24 ⇥ 24 actuated pins on a 434 ⇥ 434 mm area. While using similar actuators as the TRANSFORM system, the higher resolution and square form factor was better suited for prototyping more complex applications. This shape display also has a projector mounted to provide graphic feedback on top of the surface of pins.

Our software is written in C++/OpenFrameworks and communicates information with the shape display over USB to RS485. Pin height data is sent and received as a gray-scale image with a 7 bit resolution.

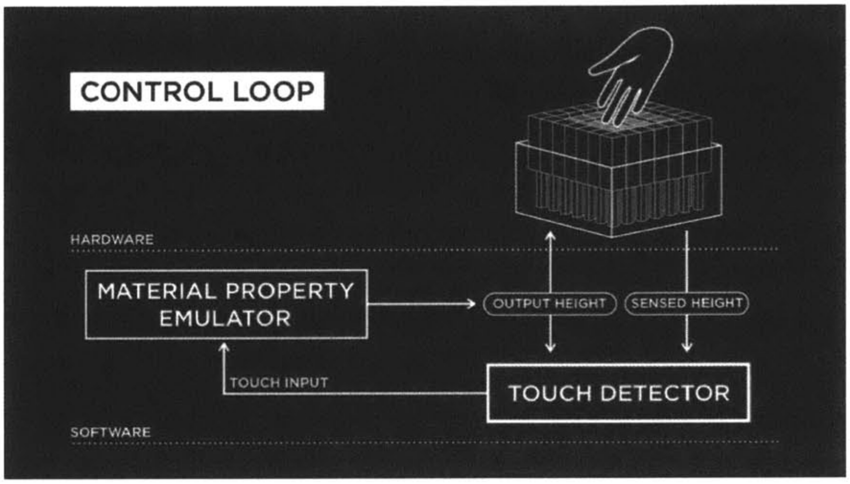


Figure 30:
Materiable System Control Loop

The software for our system can be mainly divided into 2 parts; material property emulator and touch detector (see Figure 31). Certain material properties are simulated in the emulator, then the output shape data is sent to both the shape display and the touch detector. While the shape display renders the shape, it detects the measured height at the same time and passes it to the touch detector. The touch detector detects if each pin is pressed by comparing the output height and measured height. We describe each part in detail below.

Material Property Emulator

The goal of our material property emulator is to loosely approximate the physical behavior of various materials. It was desirable for the material behavior to be realistic in appearance, but it wasn't crucial for the system to be physically accurate. The algorithm presented below outlines the process for emulating two example models, although many more models may be possible in the future. We named our models "Deformable Solid Model" and "Liquid Model." Figure 33 shows the equations used for each model, and Figure 32 gives an overview of the variables we chose.

General Simulation

We represented each material as a two dimensional grid-cell approximation. For each cell, we store its height information as well as its current vertical velocity. Each grid cell in the model maps to a pin on the shape display.

Figure 31:
Variables used and selected variables modified in the user study

Variable	ρ	i,j	a	d	v	t	Δt	k	b	s	c	h
Deformable Solid Implementation	Height	Cell at row i, column j	Acceleration	Dampening Term	Velocity	Time	Time Step Size	Spring Constant	Depression Factor	Elastic Factor	n/a	n/a
Liquid Implementation	Height	Cell at row i, column j	Acceleration	Dampening Term	Velocity	Time	Time Step Size	n/a	n/a	n/a	Wave Speed	Cell Width

	Deformable Solid	Liquid
❶ Compute acceleration for each cell	Ai $a_{i,j}(t+\Delta t) = -k\rho_{i,j}(t) - dv_{i,j}(t)$	Aii $a_{i,j}(t+\Delta t) = \frac{c^2}{h^2}(\rho_{i-1,j} + \rho_{i+1,j} + \rho_{i,j-1} + \rho_{i,j+1} - 4\rho_{i,j}) - dv_{i,j}(t)$
❷ Integrate	Bi, ii $v_{i,j}(t+\Delta t) = v_{i,j}(t) + a_{i,j}(t+\Delta t)\Delta t$ $\rho_{i,j}(t+\Delta t) = \rho_{i,j}(t) + v_{i,j}(t+\Delta t)\Delta t$	
❸ Apply ad-hoc constraints	Ci $\rho_{i,j}(t+\Delta t) = b\frac{\rho_{i-1,j} + \rho_{i+1,j} + \rho_{i,j-1} + \rho_{i,j+1}}{4} + s\rho_{i,j}(t+\Delta t)$	Cii No Constraints

Figure 32:
Physics algorithm as steps (two-dimensional representation).

Figure 33 shows a 3 step process the algorithm undergoes for every cell in the model. This process shows how the cell's velocity and height are computed for the next time step. Here we will give a brief overview of each step in the process.

1. The acceleration for each cell is computed. This acceleration is where we account for any forces on the cell, including spring forces and dampening forces.

2. We perform Euler's Method to integrate the acceleration to get the cell's next velocity, as well as to integrate the cell's velocity to get its next height.

3. Ad-hoc constraints (see Figure 33 Ci) are applied to the cell's height or velocity. This is where each cell may have height or velocity recomputed.

Each mode has its heights rescaled and translated in order to meet the 0 to 255 value range of the shape display's input value for pin height. For input from the touch detector (described later), an impulse value is added to the shape display's touched pin's corresponding cell's velocity. Below, we describe how each mode computes its governing forces and which constraints are applied.

Deformable Solid Model:

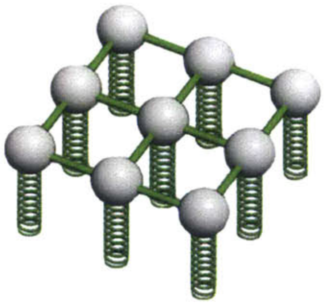


Figure 33
The deformable solid model represented here as a spring simulation

The Deformable Solid Model attempts to emulate the physics behind real world objects like a soft foam or the springs in a mattress. These solids may spring back rapidly after a deformation or slowly return back to their resting state.

The governing forces behind each cell in the deformable solid model is a spring force towards their origin position as well as a dampening force, as shown in Step 1 on Figure 33 Ai. The spring force simply uses Hooke's Law:

$$a = -k\rho$$

Here, the height is the distance from resting state and k is the spring constant. The dampening force pushes against the current velocity scaled by the dampening term d.

With just these forces presented, each cell is simply an over dampened spring acting independently of the other cells. So in Step 3, we recomputed the cell's current height as a linear combination of its current height and the average of its adjacent neighbor cell heights (see Figure 33 Ci). *b* and *s* scales the average term and the current cell height term respectively. The averaging term coupling cells to their neighbors so that they're softly connected. At the boundaries, for cells at corners and walls, we simply use the average of their surrounding 2 or 3 neighbors.

With the ad-hoc constraint in place, the model simulates a believable foam or mattress surface, depending on how the parameters are tuned. We discuss some of the values we choose for these variables later on in this section.

Liquid Model:

The Liquid Model emulates the physics behind any kind of fluid filled container. Previous work [15] refers to how one can extend the 2D height field model to have an adaptive 3D surface with splashing. Since we're limited to a two-dimensional height field display, we use a two-dimensional height field liquid model.

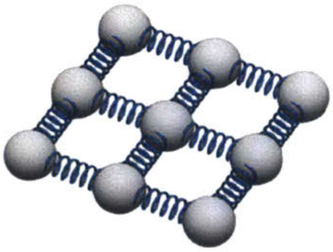


Figure 34
The liquid model represented here as a spring simulation

For the liquid model's governing forces, we employ the Shallow Water Equations and a dampening force. The Shallow Water Equations approximate the full Navier-Stokes equations under the two dimensional height field model [5]. The acceleration for each cell is computed using the density of adjacent cells using the equation seen in Figure 33 Aii. Here, *c* is the wave speed and *h* is the cell width. We again included a dampening factor of *d*, which controls the rate at which waves disappear.

For further stability, we subtract the average density of all cells from each cell density, and constrain each → to between -255 and 255. Subtracting the mean keeps the average density at 0, so we can arbitrarily add or remove velocities to cells (such as when a user presses down on a pin) without the total volume of the liquid changing substantially.

Touch Detector

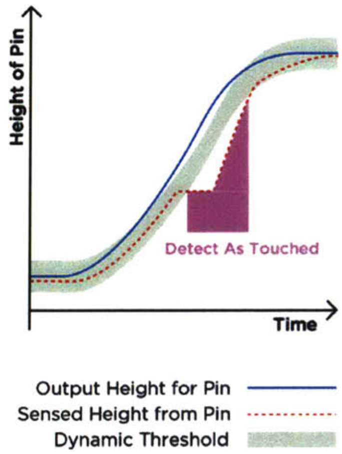


Figure 35
Example Image of Touch Detection Processing

The touch detector algorithm is designed to detect users' physical input by comparing the measured height and the predicted height based on output for each pin. The graph on Figure 36 shows an example of the relationship between input and output height value and a dynamic threshold which is derived from the predicted height for a pin. To predict the height, the delay between when the value is sent and when the pin reaches a given target height is considered to calculate the dynamic threshold. When the actual measured height is not within the range of the dynamic threshold, the algorithm distinguishes it as touch detection. Accordingly, the difference between predicted height and measured height is given to the material emulation algorithm as a force added to rendered materials.

Due to the low positional accuracy of our linear actuators, our prototype initially registered false touches when the output height value changed rapidly. Therefore, we disabled touch detection for 0.3 seconds following rapid changes to output values. Touch detection accuracy could be improved with appropriate algorithms and characterizations of individual motors and pin frictions. As a result of our implementation, it took approximately 0.45 seconds for software to detect physical input after pins were actually pressed.

Radical Functions

In the Materiable project, we demonstrated possible Radical Functions (applications) that utilize the capability of our technique to render dynamic shapes and material properties at the same time on shape changing interfaces; a pin-based shape displays in this case.

Explorative Display

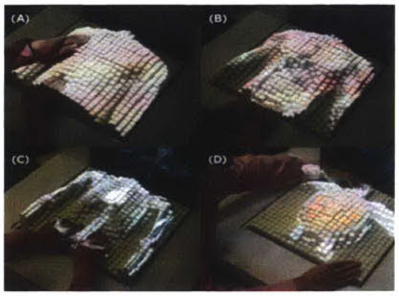


Figure 36
Enhanced experiences with anatomy and biology with juxtaposed rendered material property interactions (A: Body, B: Anatomy, C: Xray and D: Turtle).

In this application, we introduced our system as a tool for exploring the material properties of objects or anatomical forms through physical manipulation (see Figure 37). In an online furniture store, one might get a sense for how flexible a sofa or mattress might be before purchasing the item. In education, children can explore various anatomical forms of humans or animals to get a sense of their flexibility. They can also understand how materials may combine in chemistry to form viscous materials. Finally, in the field of medicine, we can explore different anatomies and render variable flexibility for the materials that make up that anatomy. This can potentially aid practitioners in understanding patients' medical data but also the patients themselves who can have concerns explained to them with a rich, physical experience.

Landscape Design + Simulation

Designing complex models such as a landscape or city usually requires the knowledge of complex software and of how different structures and features may interact with each other. With rendered material properties in combination with the ability to directly manipulate 3D shapes, novice users can create and simulate land formations in the same way they

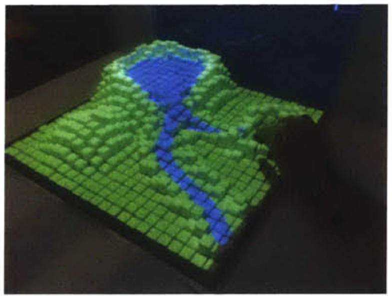


Figure 37
Manipulating and simulating landscapes with flexible, elastic and viscous rendered material properties.

might play with the materials usually used to create models (Figure 38). Prior work such as "Illuminated Clay" [30] allowed users to create land forms with the same affordances as a sand pit. Here, rendered material properties allow the combination of multiple rendered materials that can each be manipulated in different ways. For example, one might create a body of water by deforming a solid behaving material and allowing a viscous material to flow into the container. By extension, a user could also interact with the rendered material to test complex scenarios such as a tsunami or earthquake, invoked by manipulating the interface with considerable force.

Material Properties as Interaction Cues

Figure 38
Various material properties inform how a user can manipulate the 3D Data in a city design application. Here a viscous material property suggests the body is deformable, and then, keeping the same volume as a viscous body, the form can be manipulated and deformed

In our physical world, we interact differently with materials based on our assumptions of their various properties. These material properties, if emulated in shape changing interfaces, could prove useful for enhancing the way we interact with physical data. For example, CAD applications are split into solid modelers, which involve boolean and parametric operations on "solid" parts which cannot be directly manipulated by the main input while surface modelers usually render the model only as a surface to be manipulated and deformed as a mesh. With the ability to switch between perceived material properties, we envision leveraging human perception to inform the way one may be able to manipulate a form or even to represent the material the form is intended to be constructed with.

Here, the percept of material properties informs the way a user can interact. A more liquid or viscous rendered material property might afford a surface model approach where deformations are direct and local (Figure 39) while a more flexible or elastic rendered material property informs a surface that can be distorted. A more solid body could inform a parametric approach where relationships between parts are structured and deformations global according to guided boolean functions. These more structured and global operations could be performed with gestures or another form of interaction leaving direct manipulation through physical touch to deformable content. While we see this as exciting in the field of CAD, the same percept of material properties could be used in various other ways we interact with information by applying the physical metaphor of how "malleable" the information is in other computational paradigms.

Evaluation of Materiable

User Study

We conducted a preliminary user study to evaluate if participants could perceive differences between various rendered materials. 10 participants, from the age of 22 to 35 took place in this user study. There were 5 men and 5 women with no known perception disorders. Our user study was split into a qualitative questionnaire (see Appendix 1) and a quantitative rating test (see Appendix 2). For each experiment, users were told to focus on their observations of what they see while interacting with the shape display.

For the user study, we prepared 3 sets of material properties to experiment (flexibility, elasticity, and viscosity) for the participants to interact and perceive. The sets of material data we created for experiments were defined based on the variables in equations described beforehand (see Figure 32). Specifically, we chose to vary the elastic factor *s* for flexibility and the depression factor *b* for elasticity both from Deformable Solid Model. The dampening factor *d* from Liquid Model was selected for experimenting viscosity. We assumed that each variable would affect users' perception of flexibility, elasticity and viscosity respectively. For each variable, we picked 4 different values and a neutral value which was set as reference point for quantitative experiment. The values were selected based on our prior test that manipulated the variables in our underlying mathematics simulations to create the broadest human perceivable variations. Figure 40 shows the variables and their detailed values adjusted in the experiment.

In both tests we also observed how participants interacted with the rendered material properties. Participants were told they could interact in any way that made sense to them and were shown ways to interact with their hands; using one finger, multiple fingers or palm to press. At the conclusion of both experiments, participants were asked whether they focused on what they saw or felt to discern the rendered material properties of the simulations.

Figure 39:
Table of simulated models and variables used in the evaluation.

Evaluated Material Property	Flexibility	Elasticity	Viscosity
Used Model	Deformable Solid Model		Liquid Model
Varied Variable	b	s	d
Values for each Variable ([...] as the neutral value)	0.8, 0.88, [0.92], 0.96, 0.99	0.0005, 0.002, [0.007], 0.01, 0.012	0.0005, 0.001, [0.002], 0.003, 0.005

Describe and Identify Material Properties

As for the qualitative questioner, participants were first asked to identify variations of material properties for each emulation. After describing the simulation users were asked to identify one material, if any, that the simulation made them think of.

Rate Material Properties

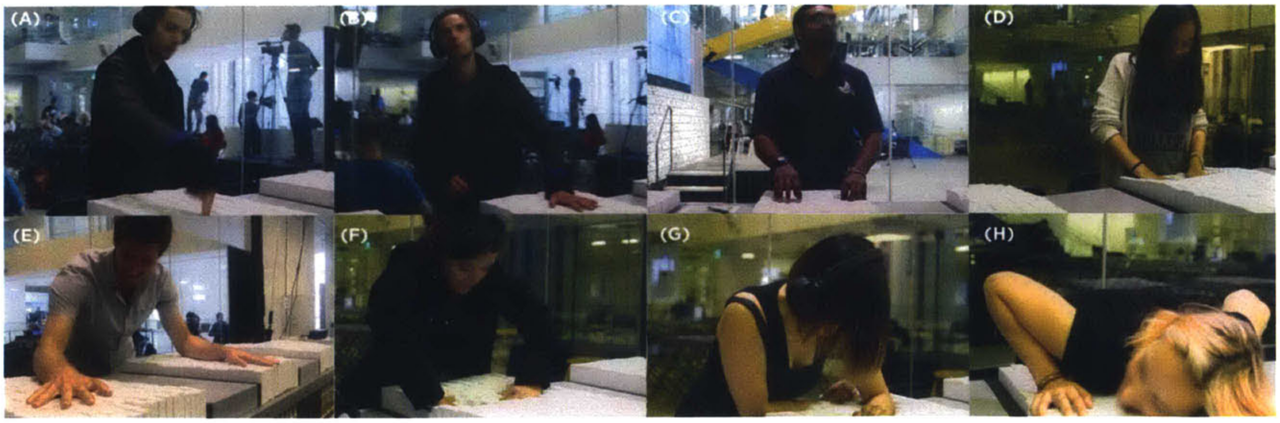
In the quantitative test, we had users rate perceived material properties between 1-10 (10 to be most flexible, elastic or viscous) for each material properties. Each user tested 3 kinds of material property and 4 different values each as listed in Figure 32, thus 12 times in total. Before rating each property, users had to experience neutral material which was told to be five in ratings. We randomize the order of each material properties that user perceive and rate. In this experiment, users were asked to wear a set of headphones playing white noise to have participants focus on the perception of the simulation and not the loud noises produced by the moving pins.

Results of Materiable Approach

Perception of real world materials

In a qualitative questionnaire experiment, participants were quick to identify rendered material properties in more dynamic simulations. Many participants described the deformable solid implementation with a high depression factor and elastic factor as "trampoline material" and were quick to identify "water" as their best guess for the liquid implementation with low dampening and high wave speed.

Figure 40:
Participants, without direction, chose to deform the rendered materials with hands, bodies and even their faces to "feel" how they behaved, despite a lack of accurate haptic feedback..



Interestingly, despite being told specifically to "observe" the simulation "visually," all participants described what they "felt" while describing a simulation. While we did not test specifically for tactile perception, at the conclusion of the study 8 out of the 10 users stated they were prioritizing their perception of touch over sight when asked to describe, identify and rate the rendered material simulations (see Figure 41).

Perceiving Specific Material Properties

Figure 42 shows average scores of participant's responses in our quantitative experiment for flexibility, elasticity and viscosity.

We have shown through these tests that we can directly influence perception of material properties by varying our corresponding algorithmic parameters for flexibility, elasticity and viscosity. Most participants vocalized the difficulty of rating flexibility due to the way they had to interact with the shape display pushing with a downwards force which is not an interaction they are used to doing with real world deformable solid materials. Despite this concern with interaction, participants were still able to correctly identify flexibility as a property of the simulation. Viscosity was the most successful property for all participants in terms of the speed of their responses and the accuracy of their rating. We feel this correlates directly to the very active nature of the simulation which depending on the way the participant interacted with it and the level of dampening would have the simulation remain active for a longer period of time than the deformable solid implementation. Preliminary results suggest there is a correlation in the quantitative data we have gathered, however, a more comprehensive user study involving more participants would help to quantify this correlation and further explore specific correlations between perceived material properties and our algorithmic variables.

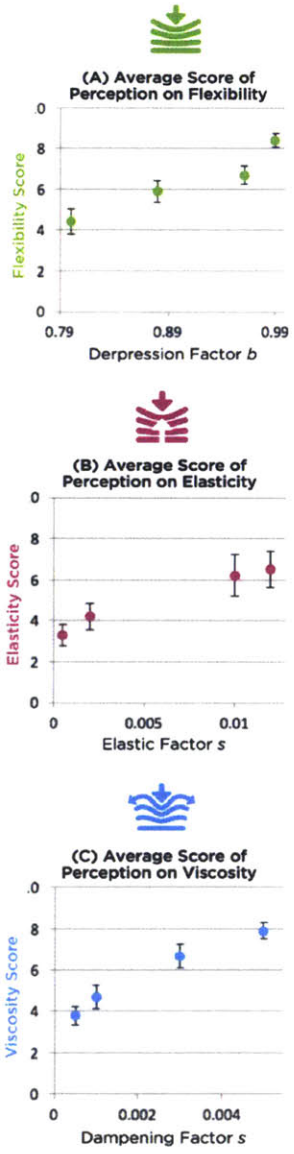


Figure 41
Results of quantitative user study
(bars represent standard errors)

Limitations of Materiable Project

Due to 2.5D movement on current shape displays, some simulated material properties are easier to identify than others. The interactions we have with real world materials are very complex and are not restricted to an array of linear forces. Not all material properties will make sense to simulate on shape displays, for example, any form of gas would be extremely difficult. A deformable solid material is usually grasped to gauge its flexibility, not pushed. Thus, we had to make do with the limitation of the shape display's vertical displacement. Although many people perceived our liquid emulation as water, the user's hands are not immersed in the rendered liquid.

We were also limited by the type of sensing and actuators we built into our current shape displays. The Materiable project was only able to assume forces with displacement so while the variations were distinguishable to users, the force feedback did not actually represent real world materials. While participants noticed a change in resistance for various materials, this was likely due to the motors moving with them in response to their input and does not accurately represent the forces we would like to represent with 'Material Display'. A desire for much more accurate representation of force and a strong coupling of bidirectional, accurate force feedback is what lead us to begin the inForce project.

inForce

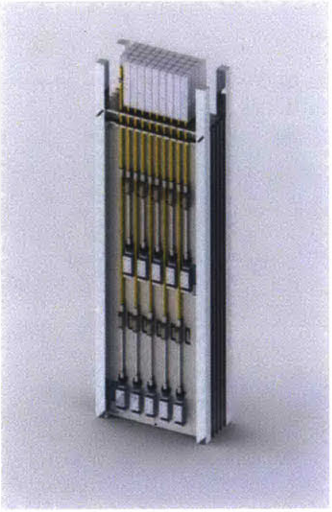


Figure 42
inForce Prototype 2

A rendering of the inForce Material Interface

In this project, we proposed a rapid bidirectional control feedback loop to accurately represent the physical forces of material properties using shape changing interfaces. Specifically, by taking advantage of state of the art linear actuation, integrating localized sensing in an array of pins and implementing techniques from the Materiable project, our approach builds an accurate perceptive model for the properties of deformable materials in response to direct manipulation with accurate force feedback.

As a proof-of-concept prototype, we built a new type of material interface with the ability to represent and sense variable forces across the array of the material interface's pins. The system can create computationally variable properties of deformable materials that are visually and physically accurate to those found in real world objects. As of writing this thesis, this work is yet to be published and is a work in progress, thus evaluation for the project with users is yet to occur. This section describes our technical achievements and our hypothesis of the system's capabilities and possible application spaces.

Overview

inForce began with a desire to focus on the bidirectional limitations of the Materiable approach to rendering dynamic material properties. While Materiable could represent the dynamic behavior of material properties in response to assumed forces, the forces were not being accurately sensed or represented in the interface and thus users were deriving a proprioceptive model of these properties based on the dynamic movements of shape that occurred. The inForce approach however is derived from a singular motivation

- how accurately can we actually represent the physical forces of real world material properties?

The interface implements a drastic change in hardware used in shape displays of Tangible Media or related work and thus required building a new completely new architecture from scratch. At every level of the project strong consideration was made to the requirement of Radical Atoms - that the interface **embody** physical properties and provide a **bidirectional** interaction.

The result is an extremely engineered system that can represent and record variable forces, shape and color of a material and thus opens up the possibility for a lot more material properties to be explored, recorded and in addition how dynamically rendered objects of the same shape and different materiality can behave with real world physical objects. (inter-material interaction)

Method

With inForce, we measure both the displacement of a user's direct manipulation as well as the force they are applying to each individual pin. We then compare the position of the pin to a 3 dimensional force map of the rendered material or object, translate this through physics emulations and have the material interface calculate the appropriate force and behavior to apply to the pin at any given moment. With a desired force for the given position, pins moved by a localized PID loop (for speed) on a microcontroller which moves the pin relative to the touch input to create the desired force. One can feel and view the simulation from any angle and direction interactively. As with any real-world material, the user is connected to the simulation through a dynamic, accurate physical experience. Our goal here is to convey deformable accurate Radical Physical

Properties (simulated properties) and build a perception of actual materials from the physical world even under the constraint of the interface's unvarying real world material properties. This proposed approach enables a powerful bidirectional loop between interaction and the rendered objects to represent dynamic objects and material properties of those objects through force feedback all in real time.

Figure 44 shows the interaction framework we developed in the Materiable project, applied to the inForce. The shape changing interface detects the user's direct physical input using built-in sensors and depending on material properties of a rendered object, changes its overall shape with actuators according to a physics emulation that is computed in real time. The deformation is provided to users as both visual through color and shape of the object as well as physically through the shape and dynamic forces generated by the interface.

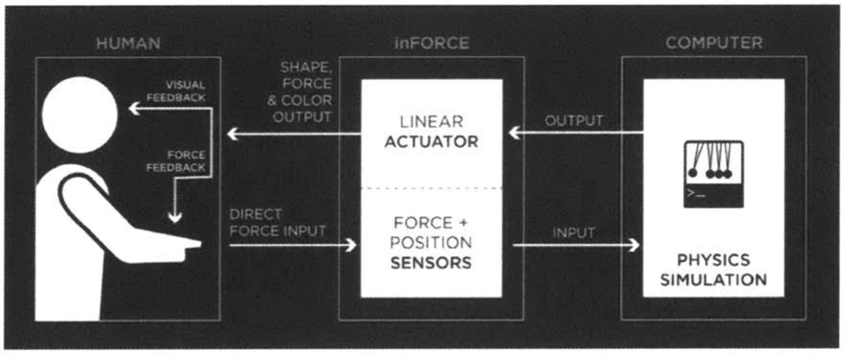


Figure 43
This is the interaction framework developed in the Materiable project modified to include the enhancements of the inForce Material Interface.

Technical Implementation

This interface excels in both sensing and actuation in comparison to other systems like inForm and TRANSFORM. [11,35]. We developed two prototypes to determine how advanced the interface's technical implementation should be in order to create an accurate force feedback loop. The first prototype implemented stronger, more accurate motors and the second prototype advanced the method of sensing and control over the first.

Prototype 1 - Hardware

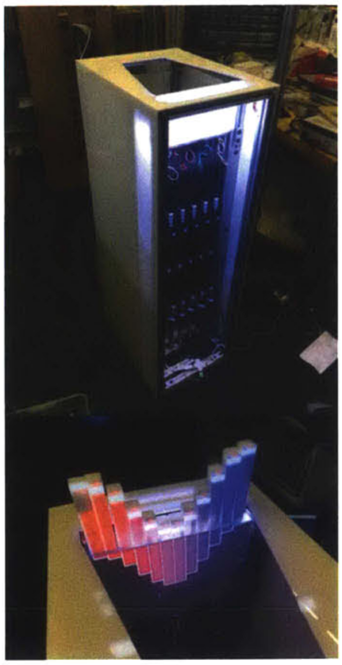


Figure 44
The first prototype of inForce using force sensors within the pins to render force feedback on a 12x1 pin array

For the first preliminary prototype, we developed a 12X1 pin array system as a proof of technical capability and technical exploration (see figure 45). The prototype included Faulhauber's Quickshaft Linear DC Servo Motors [9] which are capable of over 1000 positions for each 127mm travel distance and behave more like a magnetic stepper motor. This means the motor is continuously locked in position and by default, provides greater resistance to other systems which traditionally implement an off the shelf DC linear actuator and potentiometer combination. The motors can also move more rapidly than other systems (up to 1 meter per second) which translates to a very rapid refresh rate and change of physical state.

For sensing, the first prototype included standard FSR's inside each pin which also included a spring allowing the pin to remain in contact with a finger as it pushes the pin down. This gave us a constant force to feed into a PID loop where the target was to keep the force of the FSR constant with a given force. This PID control loop is the foundation of our technical implementation and is the most important consideration for accurate force feedback.

In order to demonstrate applications for the first prototype, we included a projection onto the side of the pins. This allowed us to experiment with section cuts of 3D data like medical data or landscapes and test the system's ability to represent different forces at different heights in a two dimensional plane.

The sensing capabilities of the first prototype were nominal in comparison to the hardware we used for actuation and in addition to this, all of the computation for the control loop managing the position of the motors was performed on a computer creating a latency in communicating positions back to the system. We also found FSR sensors to be highly inaccurate for sensing forces due to an embedded hysteresis in the sensor and a drop in accuracy when the forces are in the larger range.

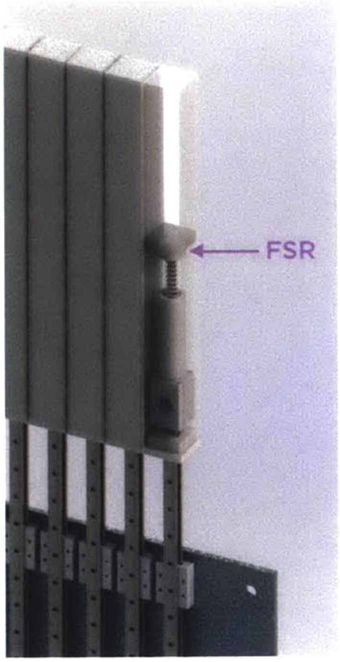


Figure 45
Pin design of the first prototype including a force sensing resistor and a spring with known constant

Despite these flaws and differences in what we wished to be an accurate, bidirectional and rapidly updating control loop, the first prototype of inForce demonstrated what we could improve through an implementation of various application examples including medical data, landscape manipulation and an example of tectonic shifting plates that through direct manipulation of the plates, would cause a volcano to erupt.

We learned the importance of rapid updates in the control loop and the importance that the quality of our sensing needed to match the capabilities of our actuation, further highlighting the importance of a bidirectional loop in tangible interfaces not purely based on the type of input and output, but also a match in quality of that output.

Accurate Force Representation with a Rapid PID control Loop

Related work highlights the importance of localization of the sensing of a system to it's actuation. The da Vinci Surgical Robot is a system that can provide very accurate real time force feedback and achieves this to a speed of one kilohertz by keeping the communication between the sensors and the servos used in the system in a single thread localized to one processor [6]. Authors also argue that if a separate thread is created between the actuator and sensor, the feedback data will be out of synchronization and effect controller performance.

On top of inaccurate sensing of force in the first prototype, having the processing for the PID control loop running on a separate processor resulted in exactly this problem. Considering the goal of this work was to create the most accurate representation of force feedback in a shape changing interface, we began construction of a second more advanced system.

Prototype 2 - Hardware

One of the biggest challenges in the design of the second, larger prototype was selecting a type of sensing that would both be accurate, require low processing, provide rapid communication, very low friction and all fit within a very small profile of the interface's pins.

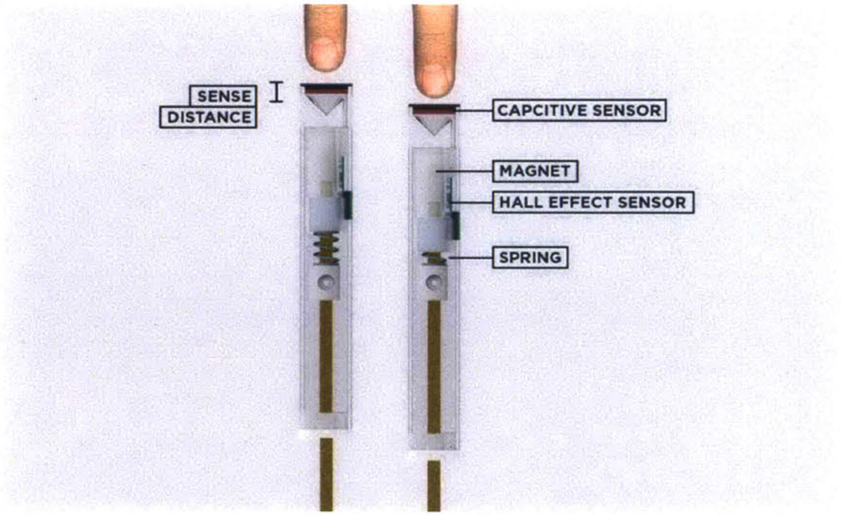


Figure 46
The second pin design incorporating a custom hall effect, spring and capacitive sensor arrangement

After testing multiple sensing methods, we designed our own custom sensing with a hall effect sensor. We also increased the spring constant to reduce an undesired elastic effect in each pin from the first prototype. The idea here is that when we wish to render a rigid material, the pins should not displace. At high forces this requires the PID loop to move the pin in an upward direction to mitigate the difference in force applied. By increasing the resistance of the spring, this effect becomes difficult to notice.

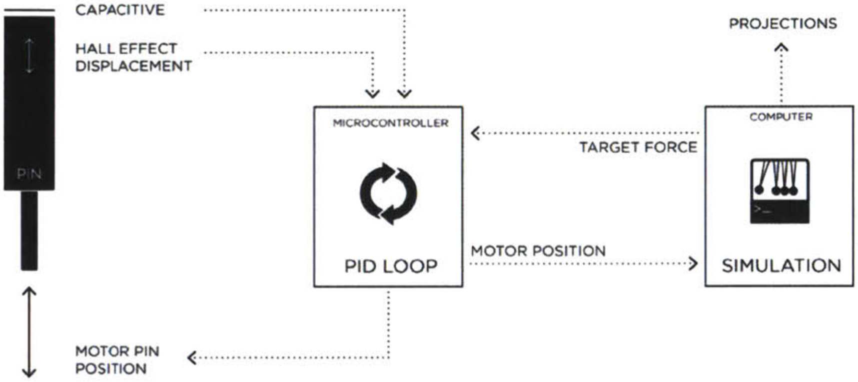


Figure 47
The second pin design incorporating a custom hall effect, spring and capacitive sensor arrangement

This custom designed sensing method gave us an accurate representation of displacement of the spring, which when compared to the known spring constant of the spring inside each pin gave us an accurate force for each pin applied to the finger. We also added a capacitive sensor to each pin to discern for some applications, whether the force being applied was coming from a human hand or neighboring pins.

Figure 48
A rendering of the inForce Material Interface

Figure 48 shows how this control loop behaves with our custom sensor combination. In order to speed up the frequency of communication in the PID control loop, we also localized processing to one teensy microcontroller for each 5 pins. This removed the bottlenecks we were facing in the first system where there was a noticeable latency in the force feedback. Having the control loop communicate with the motor controllers directly through a CAN interface drastically improved the frequency in which we could update the pins position.

Software Implementation

The inForce physics algorithms and applications are computed in C++ running Open Frameworks. Currently, we are implementing various applications that each require different physical simulations. Like the Materiable project, we implemented a spring lattice algorithm to render properties like flexibility, elasticity and viscosity. Unlike the Materiable project, however, the refresh rate of this system means a much better representation of shape while the force sensing and feedback results in an accurate haptic feedback that matches the desired forces of the property embedded in the simulated material.

As of writing this thesis, the software implementation is still in progress. We aim to implement algorithms to also record material properties of a given object for flexibility and elasticity, as well as the objects shape, such that we can represent this object in digital space.

Applications

For the inForce project, using our first prototype, we demonstrated applications taking advantage of the Radical Function of force representation for dynamic material properties. Upon the completion and publication of this work, our goal is to implement the ability to record and represent objects (Material Scanning) into the system giving us a much wider capability for various application domains.

Manipulating Section cut Data

In our first prototype, we showed how section cut shape data such as medical data or tectonic systems could be represented

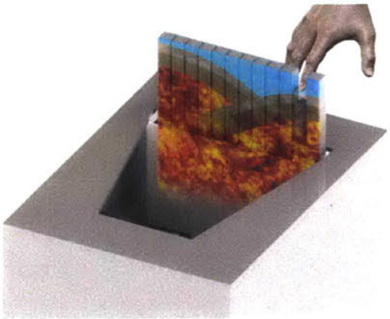


Figure 49
inForce Prototype 1, manipulating section cut data while feeling material property force feedback.

with force feedback. Here, users of the system could both feel and manipulate physical representations of such data adding a dimension of physical experience to direct manipulation. The added benefit of projecting on the side of the 3D model allows for the exploration of 3D data enhanced by a physical, bidirectional force feedback loop between the material properties represented and the section cut data presented.

In the second prototype, we will be implementing this in 3 dimensions allowing you to traverse 3 dimensional data while viewing the section cuts of that data from the sides of the pins.

3D Physical Data Exploration

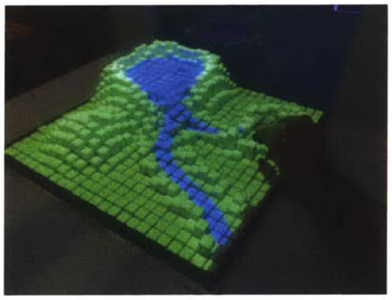


Figure 50
Manipulating and simulating landscapes with flexible, elastic and viscous rendered material properties. inForce will enable this with the addition of rich force feedback

Like Materiable, inForce allows for the direct manipulation of 3 Dimensional data sets. For a person using Materiable to sense the data inside the object, it would require the shape display to change its shape. Unlike Materiable, however, inForce can give this feedback through physical differences in material properties as one pushes through the model. For example, a Medical practitioner could locate the source of a tumor or a particular bone in a data set by "feeling" for it and then having the interface configure itself to that point to represent the data more appropriately.

Materiality Scanner

Because the inForce truly has a bidirectional feedback loop for shape, forces and color, it can both represent and record the shape, material properties and color of a given object. We are currently building in an algorithm derived to measure multi-material 3D viscoelastic data of a transtibial residuum (a leg) in collaboration with Arthur Petron from the Biomechatronics group at the MIT Media Lab.

With this implemented, we hope to be able to scan objects within inForce's force range and then represent the same object as a physical, interactive rendering, essentially replicating the object in digital space.

This type of functionality will prove incredibly useful for CAD Design, Teleoperation (in which the objects rendered at a distance will also feel like the material they are made of) and material science where combinations of real world materials can be explored.

Teleportation and Replication

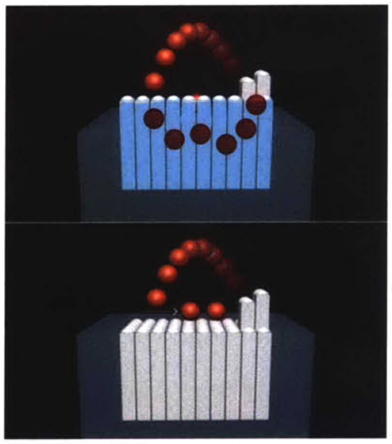


Figure 51
The rapid moving pins here can help teleport objects from one place to another through digital space (the projection) while 'inFusing' the object with other material properties

Because of the inForce's pin array configuration, it has the ability to hide and move objects within the array out of sight from an observer. By combining this effect with the projection mapping on the side of the array, we hope to be able to perceivably suck the object into digital space, show impossible physical behaviors of the digital version, and then eject and perhaps duplicate the object in a different location. This will express the physical capabilities of the inForce to distort physical perceptions of an object's actual material properties.

With the help of inForce's actuators, we can bring inert materials to life. We call this capability 'inFuse' taking advantage of the concept of inter-material interaction. The novel addition of this system is that due to its ability to replicate the physical properties of the object and duplicate it, we can have inter-material interaction with a duplicates of the real physical object and the original object itself.

Technical Evaluation

Represented in figure 53 is an evaluation of inForce's ability to represent varying forces in the controlled setting of having a rigid bar covering the pins. The figure demonstrates how quickly the interface can represent a desired force. Our system has response times of about 100,000 to 900,000 us (0.1 - 0.9s) though most responses are around 300,000us (0.3s.).

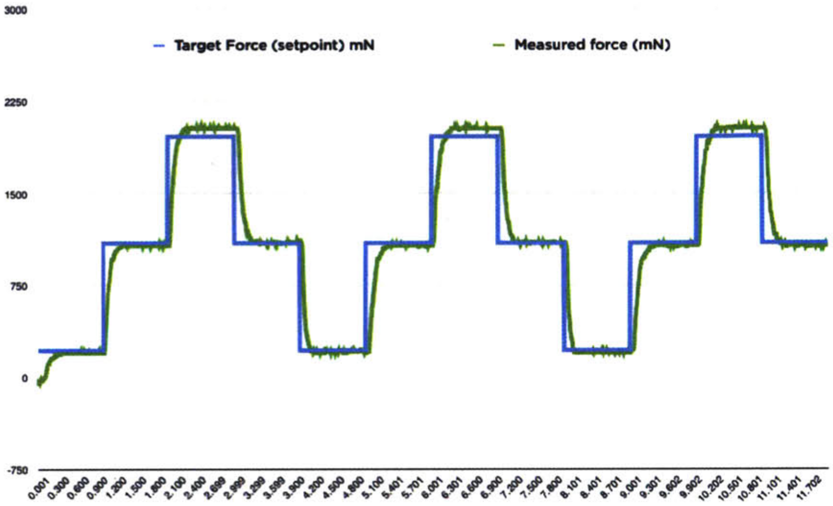


Figure 52
Highlights the error between Target Force and Actual Force which decreases over 0.3 seconds as the motor reaches the target force .

This means within 0.3 seconds, we are representing the force that is intended by the simulation for the given position of the motor. While the motors are within a steady state with the required force, they remain within range of this force by approximately 0.1 N. The entire PID Loop for each motor is updated every 1.25ms or at 800hz, 200hz shy of the da Vinci surgical robot , which according to the documentation of requirements outlined related articles [6] is accurate for physical simulation interaction.

We are confident with this control loop that for publication, we can successfully achieve both rapid shape and force feedback output in response to direct manipulation of the interface as well as the ability to record material properties of objects placed on the surface of the pin array.

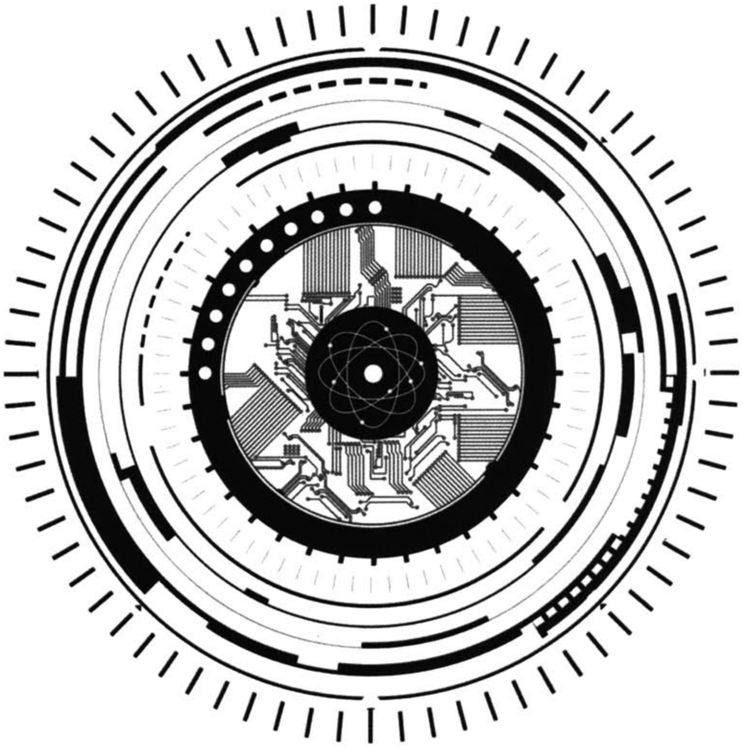
Limitations of the inForce approach

Like all interfaces that array linear actuators, we are still limited to vertical interaction. Unlike other prior work such as inForce or Transform [11,35], with embedded sensing we can allow the pins to move upwards in response to touch. This is inherent in the PID loop where should we allow the interface to do so, pins will "stick" to fingers interacting with it. This allows us to, as opposed to prior work that requires gesture input to do so [3], we are able to add and subtract from a shape through direct manipulation alone.

We are still, however limited in horizontal input, which for an interface with such rich opportunities for dynamic feedback would be ideal. Having horizontal sensing for each pin would enable 2.5D manipulation of 2.5D data and would strengthen input / output coincidence with the objects being manipulated.

Currently, we manipulate the color of the interface with projection mapping. As we did with sensing, embedding this color change into the physical pins themselves would be ideal and could, given the speed of the motors also provide some interesting opportunities to go beyond rendering deformable materials like solids or liquids and extend the perceptions we have developed to gasses or plasma.

Ultimately, we feel this interface, with it's modular pin design, offers a huge opportunity for expansion and various types of input and output modalities to be explored. We will continue to develop its capabilities even further with future work.



CHAPTER 3

FUTURE WORK

Future Work

Publication of inForce

Currently, the inForce display is in need of user testing and evaluation beyond the technical evaluation included here. As of writing this thesis we know it to be capable of the Radical Functions described, however, these must be completed for publication and evaluation.

New Research on the inForce Architecture

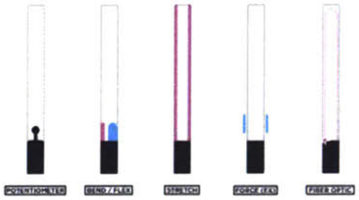


Figure 53
Various pin designs with embedded electronics that could enable new research with the inForce architecture

In addition, the strong forces and speeds that the quickshaft motors can function with, mean this display could be used for a lot of different research other than force feedback. We have designed the system to be modular so that different pin configurations with different localized input and output can be explored. Such possibilities include pins that include LED lights moving rapidly to render a 3D volumetric POV display or pins made of soft, flexible material and directional sensing such that one can move past the vertical limitations of this type of interface for interaction and be able to manipulate rendered objects horizontally.

inFuse

Figure 54
A rendering of inForce Juggling an inert object.

While Materiable explored flexibility, elasticity and viscosity - the inForce interface will be able to represent a lot more material properties such as adhesion or surface tension. In addition, because of the strong sensing and actuation feedback loop, we envision being able to 'inFuse' new material properties to inert materials placed on the interface. Throwing a bouncy ball at the interface might have the interface rapidly slow down the ball such that it does not bounce at all, rigid objects can become super elastic with the addition of force from inForce's pin array and heavy objects as light as a feather. This type of manipulation could be useful in simulating physical behaviors without the actual objects at hand.

Radical Material Affordance

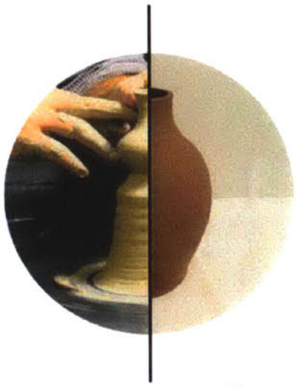


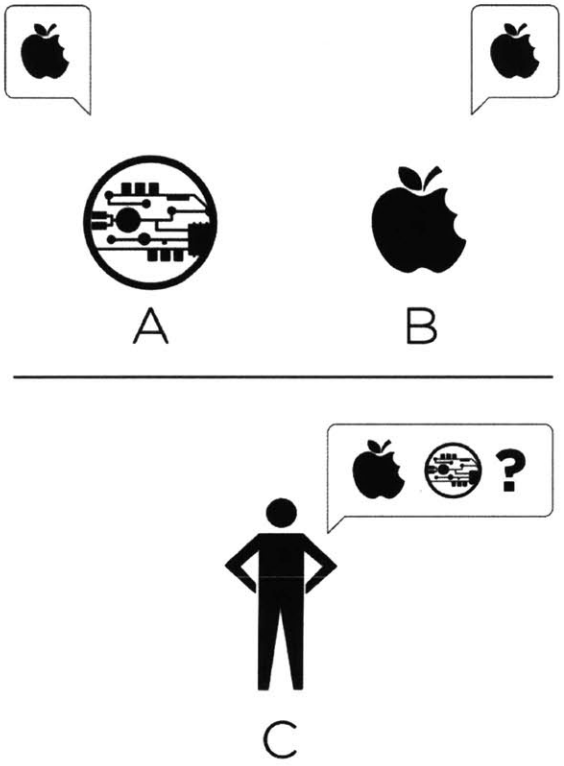
Figure 55
Material properties can afford how we should interact with them. This pottery example could translate to computational information and how one may interact with it.

We envision material exploration from the focus of human computer interaction will give designers and researchers the tools to assess how affordances of material properties could be implemented in a repeatable computer interface and guide physical interactions.

With the ability to perceive material properties, the material itself will guide the user in how to manipulate, what can or can't be manipulated and the capabilities of the computational information. This type of affordance could enhance everything from the mundane action of copying and pasting restricted files, the representation of physical architectural models to the enhancement of the entire computer interface at large.

As the complexity of this behavior expands, it is important to research and design for this with a focus on human interaction. These transformations should be focused, intentional and bidirectional as the Radical Atoms vision suggests.

Ultimately we see this as a step towards an ultimate Radical Atoms interface where the line between computational and physical is blurred such that one is not perceivably different to the other.



CHAPTER 4

THE RADICAL REALITY TEST

The Radical Reality Test

"A computer would deserve to be called intelligent if it could deceive a human into believing that it was human,"
Alan Turing, 1950

Since the original Interactions article describing the Radical Atoms vision, multiple metaphors have been derived (the iceberg for example) to explain the goals of the vision. There are other visions, for example Artificial Intelligence, that have an explicit goal for the computational system. This chapter will explore a well defined goal, the Turing Test, as inspiration for a constructive test to evaluate how effective a Radical Atoms interface is at being "Radical".

The Turing Test

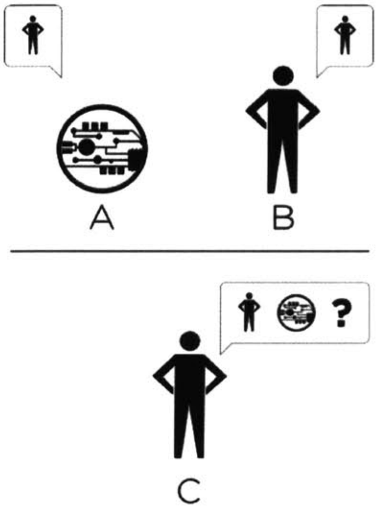


Figure 56
The Turing Test depicting A) The Computer, B) a Human and C) a human

In "Computing Machinery and Intelligence" [36] (now one of the most cited works in philosophical literature), Alan Turing describes "The Imitation Game" or "The Turing Test" as a means to assess a machine's ability to exhibit intelligent behavior equivalent to, or indistinguishable from, that of a human:

"It is played with three people, a man (A), a woman (B), and an interrogator (C) who may be of either sex. The interrogator stays in a room apart front the other two. The object of the game for the interrogator is to determine which of the other two is the man and which is the woman. He knows them by labels X and Y, and at the end of the game he says either "X is A and Y is B" or "X is B and Y is A." The interrogator is allowed to put questions to A and B" [36]

Turing further describes how while a machine has many more capabilities than human, such as the ability to rapidly derive answers to algebraic questions, it is not in the machine's interest to "boast" these capabilities, but rather to imitate the responses a human would give.

Figure 57
The Amazon Echo includes "Alexa" a natural language product that can understand speech, complete tasks and speak in a natural human voice that would pass the Turing test.

Image: Amazon

Originally, the test was designed under controlled circumstances (Turing suggests an elevator setup where the computer and human could only communicate through speech). In many cases, machines have passed the Turing test. Whether it's the automated answering machine that has you under the impression it is human before you shamefully stop describing your day or the chat bot helping you with your internet service provider, systems today frequently pass the original test. With devices like Amazon's Alexa and powerful language processing, we are already seeing machines that are extremely convincing in their 'humanity' and ability to hold a meaningful conversation with speech.

The reason for this constraint, Turing argues, is that it would be impossible with technology in the 1950's to imitate the physical qualities of a human being, in particular the materiality of a human's skin:

"we should feel there was little point in trying to make a "thinking machine" more human by dressing it up in such artificial flesh" [36]

Today, however, the test has become so powerful, it has spread widely through philosophy, popular culture, theory and research and is the foundation for what many would consider to be the deciding factor for a physical artificially intelligent machine or sentient robot. With advances in materials, computation and our ability to control them, it may well be possible replicate the materiality of human skin, if not imitate it in a similar test, the Radical Reality Test.

A Test for Radical Interfaces

The hypothesis of this thesis revolves around the concept that we do not need to actually change the real world material properties of a physical computer to convince a user that it has those material properties. Very few Radical Atoms works today actually change these properties and instead frame a **combination** of materials as a new material that simulate such properties [29,39] (Radical Physical Properties). The work in this thesis, Materiable and inForce, are both examples of interfaces that can convince users of material properties even with a low resolution display. As we combine, miniaturize and make more efficient the Radical Elements we use to construct such interfaces, the question of "What is real?" becomes increasingly prevalent.

From Metaphor to Programmable Matter-Reality

The traditional focus of Tangible Bits and Radical Atoms, and in fact all computer systems, is to derive metaphors from physical interactions we are familiar with (affordance) to the computational system. Often these are designed on a case by case basis. However, with interfaces like inForce and Materiable, it becomes clear that such systems can surpass this function by function approach.

In order to truly go beyond the capabilities of actual materials we have in the real physical world and develop interactions with new, computationally radical materials, we first need to convince users of the system that it behaves as a well known, perceivable material with all of the affordance that such a material provides. Thus, A Radical Atoms Interface would deserve to be called Radical if it could deceive a human into believing that it was a physical entity other than it really is.

The Radical Reality Test

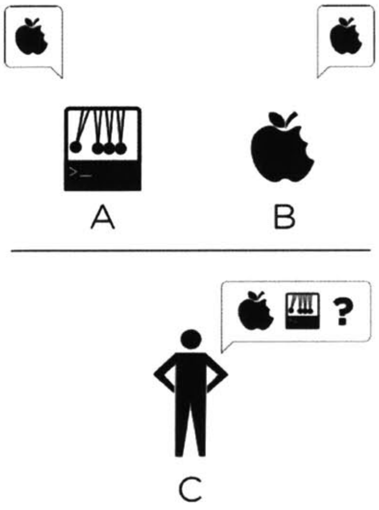


Figure 58
The Radical Reality test as a game in which player C, the interrogator, is given the task of trying to determine which is the real object or material and which is the simulation - A or B?

The Radical Reality test (see Figure 59) is heavily influenced by Turing's Imitation Game. In this "Game", the computer attempts to simulate the physical behaviors, affordances and responses to interaction that a real material has.

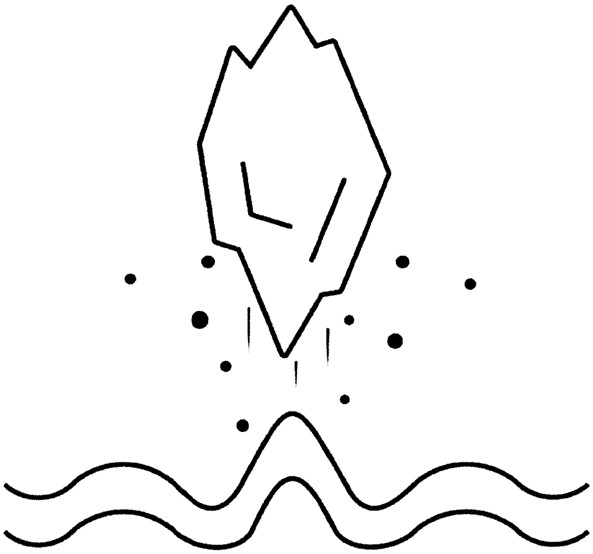
Imagine a ball made of red rubber (B). The ball has real world physical properties; for example, it is flexible, elastic and is red. It also behaves with other materials around it in a predictable manor (inter-material interaction). If the red ball (B) hits concrete with force, it bounces. If it hits water, the force is dissipated as waves in the surface of the water and thus it does not bounce.

In order to pass the Radical Reality test, the computer (A) will need to replicate the physical material properties of the bouncy ball (flexibility, elasticity, color, texture) as Radical Physical Properties, allow for the same physical interaction we can achieve with the red rubber ball (grasping) and behave as expected with other materials (bounce off concrete for example).

Like in the Turing Test, where Turing describes the ability for the computer to "boast" with mathematical solutions, the simulated bouncy may also have the capability to levitate - but this would not be in the computer's favor as the object would not behave as expected and the user (C) would know which is which.

Potentially the limitations of our technology may never allow a computer to completely surpass this test, as is with the Turing Test and a physical sentient robot. However, different fields of research (material science, augmented reality, radical atoms) are moving towards computers that cover all of our senses. My presumption is that these fields and the "Radical Elements" they use to build the illusion of materiality could soon merge into interfaces capable of convincing people of their realism are close.

Thankfully, unlike the Turing test where the goal is to question the nature of a computer's intelligence, this test remains a little humbler with a focus on human computer interaction. If we can surpass the physical reality we inhabit with an interface that passes this test, we can build Radical Atoms Interfaces that are truly exceptional in their capabilities and express ourselves with others through them without boundaries.



CHAPTER 5

CONCLUSION

Conclusion: There's so much more to Touch, than Touch.

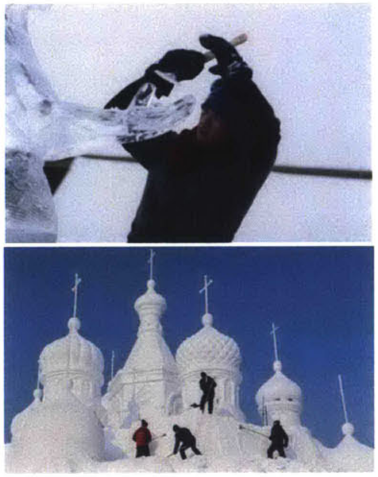


Figure 59
Top: St Andrews Day Ice Sculpture, Sandinyourey, The sculptor uses a very accurate perception of the material properties, and physical affordance in the ice and the tool to create a masterpiece . Photo by Thomas Wood and SIYE Halifax

Bottom: Jingyue Snow World festival in Jingyuetan National Forest in China's Jilin Province, photo by Caters News Agency

The current trend of computation is to blur the line between physical and computational interfaces. Whether it is a virtual reality headset or the projection of interfaces onto physical objects, there is a strong desire to have the two worlds combined.

Unfortunately, many of these fields are lacking in their consideration of physical feedback and how important this is to the way we navigate the physical world around us.

This thesis has covered the vision of Radical Atoms, described an approach to designing systems that focus on providing rich physical feedback and the importance of I/O coincidence and physical embodiment in such a system.

Materiable and inForce represent new types of multimodal material interfaces capable of rendering material properties through direct physical manipulation. This thesis has explored the possibility of incorporating material properties into future Radical Atoms interfaces opening up the field of Material Interfaces that can represent much more than purely the physical shape of an object. Through this work, we have proven that individuals manipulating such interfaces without direction, perform methods of interaction that are uncommonly seen with visual systems imploring their hands and body for interaction and confirming the realism of the physical interface before them.

Finally, this thesis has explored "The Radical Reality Test", an explicit goal for interfaces that wish to combine the physical and the computational as a provocation and drive for interfaces that implore the Radical Atoms vision to such an extent, that they are indistinguishable from reality.

Radical Atoms and specifically, interfaces capable of transforming, conforming and informing users of physical material qualities of the interface have a long way to go before being able to pass such a test without controlled parameters. However, it is clear to this author and many others who explore physical interaction for computation that there is a lot more to touch to explore than simply touching a screen or remote control. The world is full of physical wonders, patiently waiting for our technology to grow sharper.

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The MIT Media Lab

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Appendix

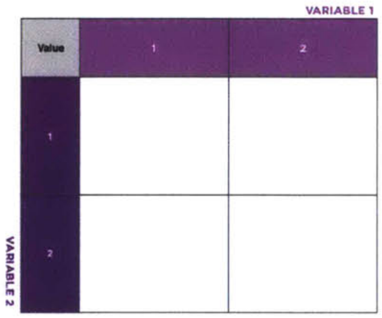
Appendices

Appendix 1:

Materiable qualitative questionnaire

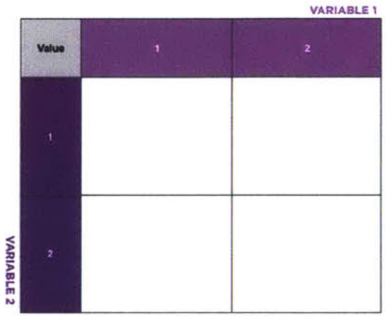
USER 0

Flex Solid: How would you describe this Material?



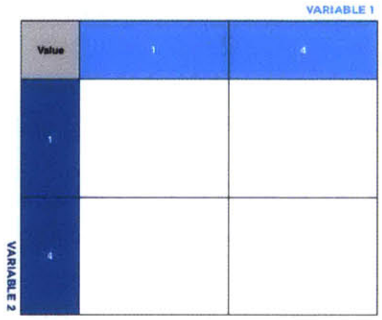
Value	1	2
1		
2		

Flex Solid: What Material does this remind you of?



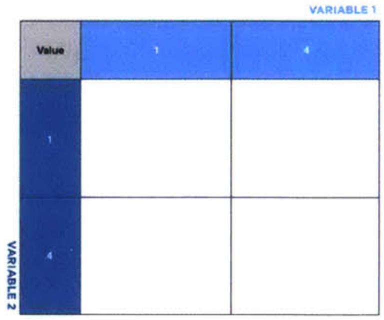
Value	1	2
1		
2		

Liquid : How would you describe this Material?



Value	1	4
1		
4		

Liquid : What Material does this remind you of?



Value	1	4
1		
4		

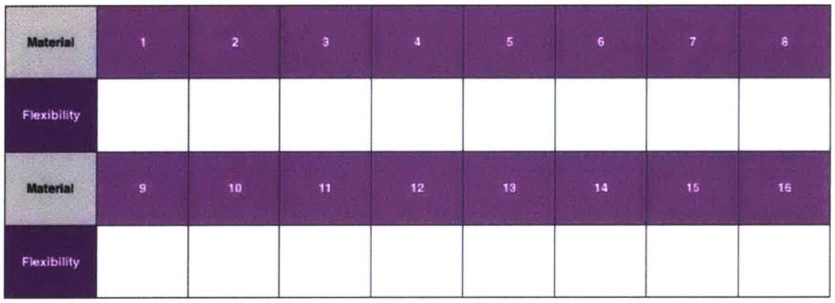
Appendix 2:

Materiable quantitative rating test

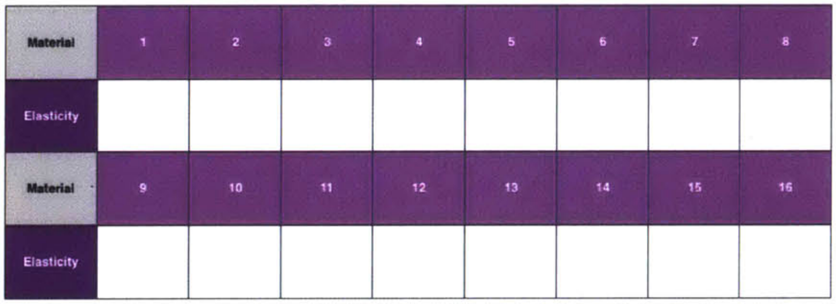
Flexibility: The ability for the material to be bent or flexed
Paper is **more** flexible than **Copper**

Elasticity: The ability for a material to return to its initial shape after an applied force or deformation
Rubber is **more** elastic than **Aluminium Foil**

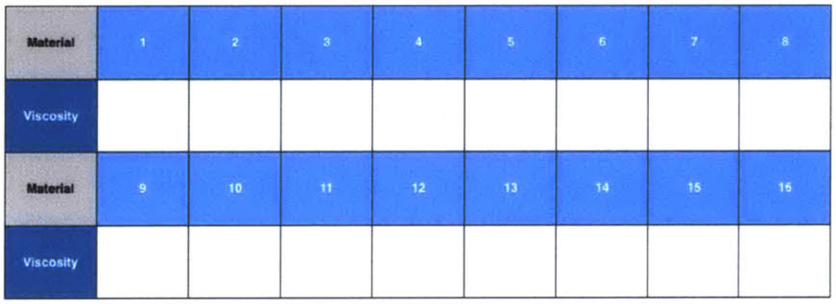
Viscosity: The state of being thick, sticky, and semifluid in consistency, due to internal friction.
Honey is **more** viscous than **Water**



Material	1	2	3	4	5	6	7	8
Flexibility								
Material	9	10	11	12	13	14	15	16
Flexibility								



Material	1	2	3	4	5	6	7	8
Elasticity								
Material	9	10	11	12	13	14	15	16
Elasticity								



Material	1	2	3	4	5	6	7	8
Viscosity								
Material	9	10	11	12	13	14	15	16
Viscosity								