

# Receptive Skins

*towards a somatosensitive architecture*

**Chrisoula Kapelonis**

MArch II, Harvard University, Graduate School of Design, 2016  
BArch, CUNY City College, Spitzer School of Architecture, 2014

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

June 2018

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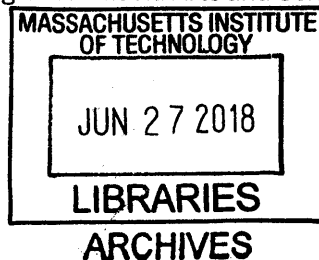
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**abstract:**

In architecture, the building skin is the primary interface for mediating the environment of the external with the internal. But today, this mediation is mechanical, deterministic, and static—often seeing the human as a generalizable and problematic input. With advances in material science however, there is great potential to disrupt these traditional manufactured environments of architecture and turn them into responsive *mediated* environments. What this thesis aims to explore is this idea of the *receptive skin*—a sensate and dynamic multi-material interface for environmental mediation. This suggests that by departing from the view that buildings are static artifacts, we may instead begin to see buildings as organic, living entities.

Through the development of a working prototype, this thesis explores how such an interface may manifest itself, through dynamic material composites, instead of mechanical and electronic means. The final prototype is a “proof of concept,” a built example of this novel design methodology, which unites material performance with sensate technologies, as a way to enable new interactions between building and environment.

**Thesis Supervisor:**

**Kent Larson**

Principal Research Scientist

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You say to a brick, 'What do you want, brick?' And brick says to you, 'I like an arch.' And you say to brick, 'Look, I want one, too, but arches are expensive and I can use a concrete lintel.' And then you say: 'What do you think of that, brick?' Brick says: 'I like an arch.'

**Louis Kahn**

**Part I**  
*Background*

## *Introduction*

The intent of this work is to understand the potentials for an active materials and their use in architecture to mediate environments. It lives at the intersections of architecture, design, phenomenology and materiality and attempts to encompass a broad cross-section of literature in order to synthesize the elements and craft a new type of relationship between people, space, and the built environment.

Part I explores the background literature surrounding the nuanced relationships between human, space and environment. It starts off in Chapter 1 by defining the concept of place, the layers of time in buildings, understanding the human experience of architecture, and discussing the relationship between body and space. Chapter 2 digs in more to the interplay between the human body and the environment, and the direct connection between the two, and how the building envelope is the interface for this dynamic. Chapter 3 explores the evolution of the envelope and how environments transformed from mediated to manufactured. It concludes by claiming the importance for architecture to be dynamic.

Part II is a study of the design space of responsive environments, and ends in the establishment of the idea of *receptive skins*. Chapter 4 outlines the definition of changing places, and break it down to dynamic and aware spaces. These culminate into the definition of a responsive environment—the ideal interplay between human, building and environment. It continues by citing examples of each, and the current state of machine-based responsive environments, and suggests the shift towards a material-based model, the *receptive skin*—a new materiality for the architectural interface.

Part III outlines the design of a physical proof of concept, and the explorations associated with it. The final proof of concept is a prototype that attempts to encapsulate a snapshot of this theory, and exercise it in practice, as a physical manifestation of a possible approach. The prototype attempts to craft a new interface for



ventilation in architecture—the respiring skin—an inflatable multi-material biologically actuated assembly for environmental modulation that actuates when certain conditions are met. The section starts from the macro space, in defining the potential for this interface, and narrows down into the specifics of the exploration: the new material model, the mediated environment, the site, the medium, the material, the behavior, and the interaction. It concludes with the visualization of the assembly and future possibilities for its implementation.

This thesis approaches architecture and materiality through the lens of a design framework, and attempts to untangle the complex relationships and find potentials for new types of human-building interface.

# Chapter 1: The Building

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## 1.1 Space

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"A house that has been experienced is not an inert box. Inhabited space transcends geometric space." - Gaston Bachelard, *The Poetics of Space*<sup>1</sup>

### defining spatiality

*Space* is the void of volume that invites occupancy. To many, it is considered to be a multi-dimensional manifestation of *emptiness*. It is the non-stuff, the everything that is not considered matter. But, this is merely the quantitative perception that defines spatiality. Space is a relatively tricky concept to describe, because in truth, the conception of space cannot be accurately described as a concept of its own accord, but is in fact, inextricably linked to the understanding of *boundary*. The container describes the contained, and it is in the mental model of the barrier that space can be accurately described. Is the space *tall*? Is this space *narrow*? Is the space *vast* or is it *small*? Even in the language used to describe qualities of spatial volume, a boundary is assumed. Spatial experience is curated by the physical elements of the boundary, and this boundary is what is known as *architecture*.

### the eye of the beholder

In the words of Louis Kahn, "architecture is the thoughtful making of spaces [...] the creating of spaces that evoke a feeling of appropriate use."<sup>2</sup> It is the medium that molds and shapes qualities of space, and enables differentiation between them.

But in the generalized understanding of space, Juhani Pallasmaa, in *The Eyes of the Skin* calls it "naive realism," and he states that space is often considered to be a "measureless, infinite and homogeneous emptiness in which objects and physical events take place."<sup>3</sup> It is only seen as a passive void, an ether of nothingness, where significance is only given to the objects and events that exist and operate within it.

In the legacy of the architectural education, it is often assumed that the concern of the architect is in the design of the aesthetic and function of the physical boundary; architecture as the manifestation of the perfect image. But, the fundamental flaw in most discussions of architecture is the failure to relate it to the reality of *experience*.<sup>4</sup>

This perception of homogeneity is detrimental to the craft and curation of architecture. It undermines the significance of the human and gives precedence to aesthetic. Anthropologist Edward T. Hall argues that the assumption that space is a neutral entity that exists as a separate entity from the human, is "one of the most destructive unconscious cornerstones of western thinking."<sup>3</sup>

This conceptual limitation leads to severe misconceptions about the core relationships between the artifact of the building and the human. In architecture, as in other forms of aesthetic art, human presence is referred to as "spectator" or "audience," a perspective that places the human in a dimension of distance apart from the artifacts—a tenuous connection supported only by the far-reaching senses of vision and audition. But the error of this view lies in the fact that architecture and art are physically situated in an environment; they do not exist in a contextual vacuum. The environment heavily affects perception. The medium of space derives its meaning not from a static aesthetic, but from the body's total response to the environment around it. In the words of James Marston Fitch, "In architecture, there are no spectators, only participants."<sup>4</sup> The experience of space is defined by human presence, and its existence is inextricably linked to the human condition.

Unfortunately, vision has been given unfair priority in the conception of building design. In academia, the image is regarded as the unspoken dominant catalyst in the crafting of architecture. Architecture has transformed into an art-form meant to please the eye, and not the body. This over-emphasis on the visual sensorium has negative consequences on the experiential immersion of architecture.

When architecture becomes a slave to the visual, the connection between human and space is disrupted. Vision has the most distant grasp of all the senses. The olfactory and aural senses bring information a bit closer to the body, in order to interface with it. Touch and taste, are the most intimate of senses, bringing the body and space interface into direct contact with the skin.

Pallasmaa claims that this vision centric approach to architecture is detrimental to the preservation of human-centric spaces. He states that "as a consequence of this biased emphasis, buildings are turning into objects of momentary visual seduction, and they are losing their sense of presence, plasticity and hapticity. They have become mere aestheticized objects that are externally viewed and marveled rather than being lived as inseparable parts of our very awareness and sense of life."<sup>3</sup>

This obsession with aesthetic architecture and the ideal image, produces spaces that are appealing to the eye, but in discordance with the body. The power of the architect to design every detail of the building leads to static, deterministic spaces—spaces that are crafted for the predicted occupant. <sup>5</sup>

The concerns of the architect should not fall heavily on the formal nature of the volume, but on the utilization of architecture to curate human experience. An architecture of experience is not static, but wholly and fully multi-dimensional and sensorial—a four-dimensional perception architecture, where the volume of space intersects with *time*.

### **space vs. place**

"In memorable experiences of architecture, space, matter, and time fuse into one single dimension, into the basic substance of being, that penetrates the consciousness " - Juhani Pallasmaa, *An Architecture of the Seven Senses* <sup>6</sup>

Pallasmaa believes that the built environment and its urban context are “instruments and museums of time.”<sup>6</sup> Buildings are not static conditions, but fluid, ever-changing mechanisms, that are only understood through time. And it is in this flow of time that the creation of human experience, creation of *place*, is enabled.

*Place* is the crossing of *space* with *human experience*.

The word *place* describes the human-centric experiential relationship that a person has with a particular space over time. A relationship that exists not only from the synthesis of the architectural elements, but also from repeated interaction and the formation of memory. The dynamics of this relationship are constantly remapping because there is a direct and significant connection between the medium of space and the *human*.

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## 1.2 Human

---

### an architecture of the human

Martin Heidegger’s understanding of the relationship between the human condition and space is that there is an existential connection between the two—a powerful connection between the acts of “building, dwelling and thinking.”<sup>3</sup> He believes that there is no separation between human and space, but instead, that they coexist as one another: “When we speak of man and space, it sounds as though man stood on one side, space on the other. Yet space is not something that faces man. It is neither an external object, nor an inner experience. It is not that there are men, and over and above them, space...”<sup>3</sup>

The meaning of architecture emerges from this intersection between person and space. The person’s sense of self shapes the spatial experience.<sup>3</sup> And because of this, *architecture is inherently human-centric*. It is through the first person perspective that the mental model of place is generated through the “perceiving and experiencing self.”<sup>3</sup> The human is always at the center.

### **the perceptive participant**

Buildings are not just physical manifestations of shelter. They are “mental meditation”<sup>3</sup> between the self and the world.

“[The house] is an instrument with which to confront the cosmos” - Gaston Bachelard, *The Poetics of Space*<sup>3</sup>

Architecture not only houses the body, but it inhabits the mind as well. It curates the human experience of the world, and it itself evolves in accordance with the human condition. Even the most foreign of spaces can be grown into and molded by the mind.

The “perceiving and experiencing self” is the embodiment of human consciousness. But there are varying philosophies surrounding the definition of this self-centric relationship. Gabriel Marcel claims that, “I am my body,” whereas Wallace Stevens states, “I am what is around me,” Noel Arnaud claims, “I am the space, where I am,” and Ludwig Wittgenstein concludes that “I am my world.”<sup>3</sup>

The spatial world is constructed around the self. And the understanding of self, is filtered through the reception of inputs from the outside world into the body. One does not simply observe that a room is cold, but instead they *feel* cold, through the communication between touch receptors on the skin transmitting that information to the brain. The experience of self is structured around the sensory and corporeal centers of *the body*.<sup>3</sup>

### **the immersive medium**

All the information that a person receives about their environment is perceived through the senses, and is processed by a brain that has been shaped and molded by years of experience in environments both similar and distinct. Input from the body’s senses triggers a cognitive response that defines one’s understanding of place. A cold, dark place elicits a different response from one that is warm and filled with sunlight, even if the objects contained therein are identical. The spatial experience is best understood as the synthesis of sensory information

translated into cognitive perception. Only that which can be sensed can be perceived, so it is the sensory environment that mediates experience. Space is the medium of sensory immersion.

Because architecture is the most immersive medium, and it envelops the entire body, the qualities of space that filter in as sensory inputs are mapped to the entire body, not to merely just a zone. Pallasmaa claims that “qualities of matter, space and scale are measured equally by the eye, ear, nose, skin, tongue, skeleton and muscle”<sup>6</sup> in what he understands as the seven realms of sensory spatial experience. Architecture rings our ears, brushes our skins, entices our eyes, cools our tongues and invigorates our noses. It is felt through the bones, and its gravity tugs on the muscles. The experience of architecture, by nature, is *multi-sensory*.

In the Renaissance, the five senses were understood in hierarchical formation. Vision was considered the highest, and touch the lowest. And each of these senses were mapped to the image of the elements; vision to fire and light, hearing to air, smell to vapor, taste to water, and touch to earth. But in reality, all the senses perform as an integrated system.

Anthropologist Ashley Montagu even goes as far as to say that each and every one of our senses is an iteration of touch and skin. He proclaims that “[The skin] is the oldest and most sensitive of our organs, our first medium of communication, and our most efficient protector [...] Even the transparent cornea of the eye is overlain by a layer of modified skin[...] Touch is the parent of our eyes, ears, nose and mouth.”<sup>3</sup>

The skin is the architecture of the body. And touch is its communication interface. In the words of Pallasmaa, “Home and skin turn into a single sensation.”<sup>6</sup>

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## 1.3 Body

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### **body and building**

This relationship between building immersion and the relationship to body extends beyond the human, and into the material of architecture itself. The relationship is bidirectional: building affects human, which affects building. Often the building is seen functionally as a place of refuge, of shelter, meant to house and protect the occupant. A container to house the living. But the relationship between this description of container, *the shell*, and the body is much more interconnected.

In the past, buildings were shaped by the mechanics of the body. Houses of mud were formed by the palm, caves were carved by the hand and tool, and the material of huts was only as large as the arms could handle. The builders of the past shaped their buildings with their own bodies. These limitations and capabilities of the body directly affected the realized manifestation of the built environment. And as a result, the body was the catalyst that crafted the form and space of the envelope.

In the ancient world, the body was often represented by the symbol of the shell. The body was believed to act as an envelope that contained the soul, a similar relationship to that of the body of the mollusk and its shell.<sup>1</sup> The shell, aside from just performing as physical shelter for the creature, also acts as an extension of the mollusk's flesh—a second skin that simultaneously shapes the body while the body shapes the shell. This anecdote could well be used as a parallel to describe the relationship between the human body and the building as its exoskeleton.

In simple terms, the building acts as an extension of the body. Pallasmaa likened this relationship to the "pleasure of curling up...an unconscious association between the images of room and the womb..."<sup>3</sup> Just as the womb is a space of comfort and shelter that is shaped by the body, so too is the architectural shell.

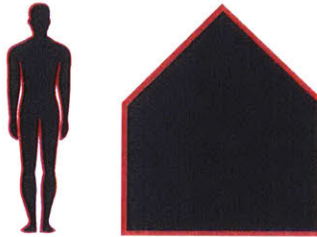


### building as organism

Buildings, similar to living organisms, are composed of a series of layers that works together like organs in a body to achieve homeostasis. The systems of a building are similar in function to the operations of an organism. Complex living beings possess a series of biological mechanisms that allow them to execute the processes that allow them to live. And these processes have counterparts to the systems that exist in the body of a building. Below are a few examples of the parallels between the organs of each.

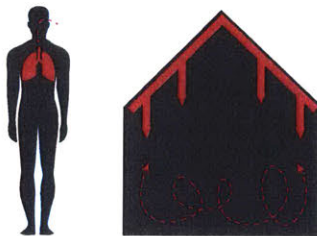
**The Skin:** the boundary - a barrier and a filter.

**organism: (skin) building: (skin)**



**Respiration:** the process of taking in fresh air and removing the bad

**organism: (lungs) building: (HVAC)**

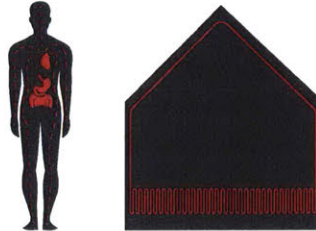


**Structure:** the mechanism for supporting the body

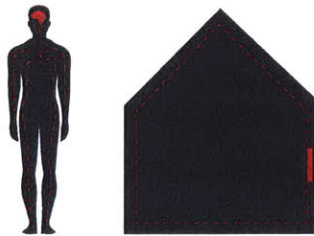
**organism: (skeleton) building: (structure)**



**Circulation:** circulating the good liquids and disposing of the bad  
**organism: (circulatory) building: (plumbing)**



**Metabolism:** electric circuitry  
**organism: (digestive) building: (electrical system)**



These architectural organs mimic the processes that exist in the organism, and are necessary for the longevity and sustainability of the building's lifespan. But the most interesting part of these organs, is not their function, but where they reside. Unlike in the organism, where the internal organs occupy most of the space within the body, in architecture, these are all embedded into the periphery, the exoskeleton.

### layers of time

Similar to the mollusk shell from the earlier example, the architectural exoskeleton is made up of a several layers operating on different time scales. As the mollusk grows, the material of its exoskeleton grows in tandem. Tissue from the body in contact with the shell secretes proteins and mineral to form the next layer of the shell. Scientific American<sup>7</sup> likens this relationship to "laying down steel (proteins) and pouring

concrete (mineral) over it." As the seashells grow, they evolve from the bottom up, by adding material at the margins over time. Thus, the composition of the mollusk shell results in a series of layers reflecting different time scales of construction. The building exoskeleton behaves in a similar way as well.

The academic perception that buildings are singular, static objects is fundamentally false. Frank Duffy summarized this argument by claiming the following: "Our basic argument is that there isn't any such thing as a building. A building properly conceived is several layers of longevity of built components."<sup>5</sup> Buildings, like the mollusk shell, built by layers of material that are shaped by the presence of the human body.

Stewart Brand interprets and expands Frank Duffy's concept into one he calls, *shearing layers*. His concept takes the systemic layers of architecture's outer shell, and understands their longevity as layers of time. To him, the building exists not as a single unit at a moment, but as a choreography between various layers of varied life.

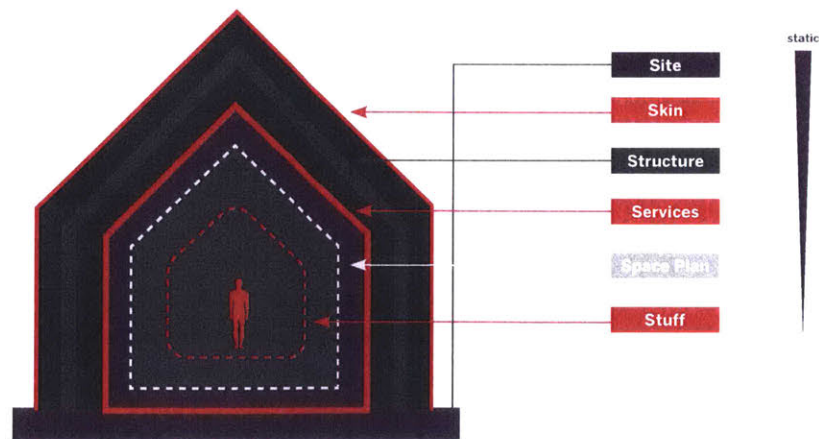
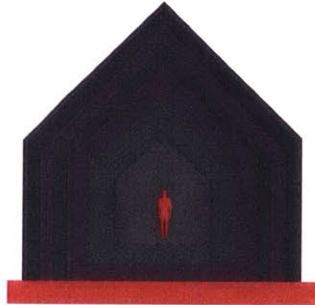


Figure 1. Stewart Brand's Shearing Layers

These shearing layers are organized in succession of time, from the one with the longest duration, to the most fluid part of the experience.

**Site:** The site is the urban location of the building, and the geographical context. This layer outlasts all, and according to Duffy is "eternal."



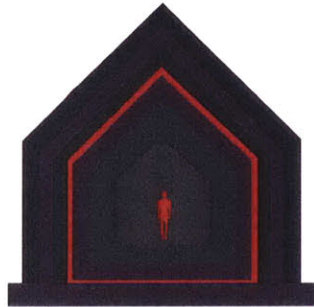
**Structure:** The structure composed of the elements that hold a building up, and act as support for the body. This includes the foundation and load-bearing elements, and they could last anywhere from 30 to 300 years.



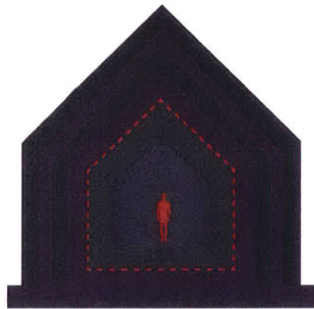
**Skin:** The skin in this case, is considered to be the exterior envelope, the barrier between the exterior elements, and the interior conditions. Brand estimated that these surfaces change every 20 years or so.



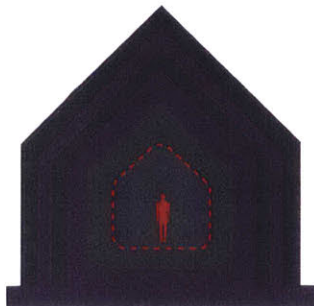
**Services:** This layer is where the HVAC, electrical system and plumbing exist. It also includes moving parts such as elevators and escalators. This layer wears out around every 7 to 15 years.



**Space plan:** The space plan encompasses walls, floors and ceilings; the interior layout. In commercial settings this is replaced every 3 or so years whereas sleepy homes could take 30 years.



**Stuff:** Here is where all the kinetic pieces of the interior exist - objects such as furniture, phones, pictures, lamps, tissues. This is the layer that encompasses all things that twitch.





### towards a process architecture

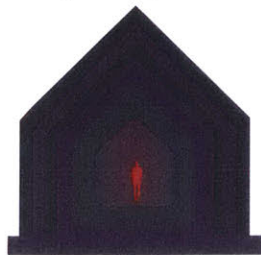
Stewart Brand's concept of the shearing layers encapsulates an understanding of the building as layers of permanence, and it further exemplifies the argument that the spatial experience depends on the relationship between time and the input of the human. Buildings are living, and take a life of their own. And similar to the process of cell replacement in the body, and how different organs replenish and replace cells at different rates, the building is constantly refreshing and morphing into a different version of itself as a function of dwelling.

Brand questions this philosophy of a static architecture, an architecture of finality upon completion, and with his theory, proposes an alternative approach to design, an architecture that instead, is molded by its users; "an architecture of improvisation."<sup>5</sup>

The conversion will be difficult because it is fundamental. The transition from image architecture to process architecture is a leap from the certainties of controllable things in space to the self-organizing complexities of an endlessly unraveling and unraveling skein of relationships over time. Buildings have lives of their own." - Stewart Brand, How Buildings Learn<sup>5</sup>

Brand describes this approach as akin to a term used often in the fringes of biology called, *ecopoiesis*. What ecopoiesis describes is the process of a system making a home for itself. He compares this to the process of dwelling, and the potential for the dwelling and the dwellers to shape and reshape themselves until there is a "tolerable fit"<sup>5</sup>—human as catalyst for spatial transformation.

But this diagram, though extensive in its reach, neglects to encompass one of the most fluid, and experiential layers of architecture, the layer in which body and building actively engage in this phenomenon of ecopoiesis and the most temporal layer: *the environment*



## Chapter 2: The Environment

### 2.1 Inside Out

#### the external environment

Environmental experience is perhaps one of the most constantly changing layers of a building. This layer of experience, according to James Marston Fitch, is a synthesis between various elements of the environment.<sup>4</sup> Out of this composite, the factors that affect the human body directly are of immediate concern: *thermal, atmospheric, aqueous, luminous, sonic, world of objects, and spatio-gravitational*. These fluctuations, similar to Brand's shearing layers, also have varying degrees of longevity and cycles, all acting at different scales. The conditions of these external environmental factors change continuously at varying degrees, from the minute, to the day, and even across the year. Each factor possesses its own cyclical rhythm with respect to the others.

**Thermal** - The transfer of heat and temperature fluctuations. Temperature changes consistently throughout the day, and slowly moves in a linear fashion up or down. The thermal factor changes abstractly from colder to warmer as the sun rises and sets, and cycles in a larger scale from overall colder in the winter to overall warmer in the summer.

**Atmospheric** - The atmospheric condition encompasses movement and composition (chemical and physical). This includes air and particle makeup. Generally speaking, the atmospheric composition changes slowly because it is more contextual, like site.

**Aqueous** - Amount of moisture and lack thereof. The fluctuation of moisture is mostly dependent on cycles of climate, and atmosphere and can change over a few hours to days to seasons.

**Luminous** - This is the presence of light within an environment. The daily cycles of light change to reflect day and night, and overall, change incrementally with the seasons. But the presence of clouds and other obstructions also have micro effects on light conditions at any given second.

**Sonic** - The sonic factor is a confluence of presence and movement. This changes drastically from minute to minute depending on the existing conditions of the site, for example, the presence of birds vs. presence of cars, cities vs. country side.

**World of Objects** - Reflects the organic and inorganic objects that are in the environment such as trees, animals, street lamps, microorganisms, insects, etc. This layer is constantly changing for objects that move, and almost static for objects that don't.

**Spatio-gravitational** - Remains mostly constant and encompasses factors such as gravity and physical spatial qualities.

These external environmental factors are elements that are not aside from the body; they are experiential. The body's daily experience with these fluctuations is similar to a fish in water—fully immersive and submerged. Even more specifically, as Fitch proclaims, "The body's dependence upon this external environment is absolute - in the fullest sense of the word, *uterine*."<sup>4</sup> But, unlike the womb, this external natural environment does not allow for optimum conditions for the person. The external environment has direct parallels to functions within the human body that handle the interface between the inside and the outside world.<sup>8</sup> Before birth, this was a function that the womb afforded the fetus, but once the human is born the process exists as a series of internal functions. And this existence takes place on two levels; *metabolic* and *perceptual*.<sup>4</sup>



### **the internal environment**

There is a distinct differentiation between the metabolic process and the perceptual mechanisms of the body. Mainly, the metabolic process is the fundamental basis for operation, and the perceptual mechanisms only come into play *after* the metabolic is satisfied, as interpretations of sensorial conditions. Below are the distinctions between both processes.

***Metabolic Process:*** This process in the realm of homeostasis, provides basic chemical transformations that allow the body to live. Most of life's fundamental processes exist at this level, such as circulation, digestion, and thermoregulation. The metabolic process is the precursor to perceptual, and acts as the material for life to continue. In fact, when minimal metabolic thresholds are crossed, loss of consciousness is usually the first reaction to serious environmental stress. Environmental disturbances to this system exist when the environment drops below the minimum, or above the maximum thresholds for living.

***Perceptual Mechanisms:*** This process encompasses all the mechanisms of sensory perception. Similar to how the metabolic process is the material to living, the perceptual mechanisms are the material basis of aesthetic. This set of processes includes the visual, auditory, gustatory, olfactory, haptic and proprioceptive senses. Each sense acts as a filter, "to handle the essential commerce between the body and its atmospheric environment."<sup>8</sup>

The confluence of all these systems provides equilibrium inside of the body by controlling the relationship between internal and external states—a remarkably stable and consistent existence within the body.<sup>8</sup> But in order to understand the regulation, it is first important to understand the direct relationship between the body's inside and the environmental outside.

### i/o (inside-outside)

There is a complex and direct relationship between the previously listed environmental factors, and the internal processes of the body. Each separate factor has a bearing on at least one or more of the bodily systems. The relationship is uterine. For example, modulations in temperature directly affect the metabolic system, and the perceptual systems of the tactile sense. The body needs a range of temperature in order to survive (metabolic), and then the tactile system responds to the differences in temperatures between that range to produce a mental model of the thermal environment (perceptual-tactile). Below is Fitch's seminal diagram for understanding the components of this relationship.<sup>8</sup>

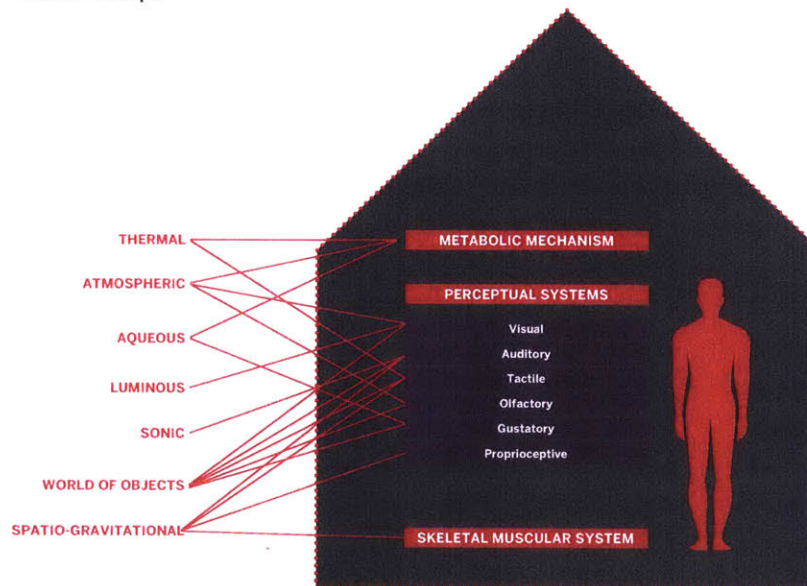


Figure 2. Fitch's diagram from *American Building and the Forces that Shape it*

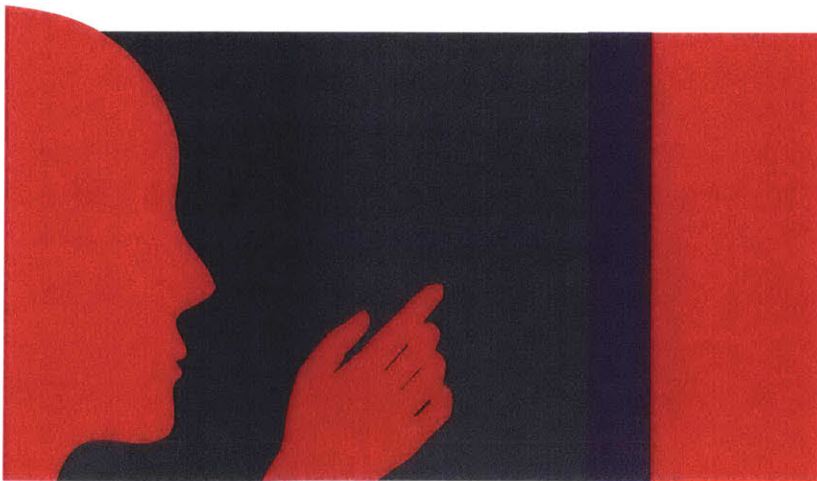
The body is constantly bathed in this homeostatic exchange, and constantly reacting to the stimuli from the environment with beautiful regulating consistency. Unfortunately, in the normal state of the natural external environment, this consistency is not the case. These environments can very often vary from being biologically sound to uncomfortable, or even hazardous to life. The homeostasis of the body can only operate within certain limits that are established by the body as a whole<sup>8</sup> and not below or above that or else stress is caused.

In regard to this modulation, Fitch claims that "the body has wonderful mechanisms for adjusting to the external variations, e.g., the capacity to adjust to enormous variations in the luminous environment or the adjustability of the heat-exchange mechanism of the skin. But the limits of adaptation are sharp and obdurate. Above or below them, an ameliorating element, a 'third' environment, is required."<sup>4</sup>

### **the third environment**

This "third" environment, proposed by Fitch, is the introduction of an external instrument to regulate this relationship between the constant internal condition and the fickle external environment. And this instrument also happens to accurately describe the container of *the building*. He claims that the human needed to invent architecture in order to become human, and tame the world of volatility into a new type of environment. According to Fitch, it is the seminal task of architecture to impose itself between man and the natural environment, and "remove the gross environmental load from his shoulders."<sup>9</sup>

With the birth of this "third" environment, a new kind of space is created between the skin of the human and the skin of the building: the interior environment. Pallasmaa states that, "[c]onsequently, architecture is communication from the body of the architect directly to the body of the inhabitant."<sup>6</sup> Skin to skin communication is the environmental interface.



## Chapter 3: The Skin

### 3.1 The Envelope

#### from skin to skin

*Skin* is a special kind of material *boundary* that acts as both a barrier and a filter, to exchange physical signals between exterior and interior. In the realm of the human body, the skin, as described by Neri Oxman, “acts simultaneously as a structural membrane, and an environmental filter and barrier.” It protects the body from the harmful elements of the environment, while allowing the necessary inputs to filter through the material and sustain life and experience. The building skin operates in a similar fashion, with the intention to mediate the relationship between the body’s internal environment and the exterior elements, providing a third space often referred to as the interior architectural space. According to Michelle Addington, “[t]he exterior walls of a building were mediating elements, negotiating between the needs of the body and the extant environment.”<sup>9</sup> It is in the interplay between the materials of the exterior wall that this mediated atmosphere is accomplished — with the building envelope as architecture’s *interface*.

#### envelope as interface

An interface is a point in which two systems meet and interact—the perfect analogy to describe the behavior of the building envelope and its interaction with the outside and this third environment. Fitch proclaims that “the ultimate task of architecture is to act in favor of man: to interpose itself between man and the natural environment in which he finds himself, in such a way as to remove the gross environmental load from his shoulders.”<sup>9</sup> With this, he elegantly concludes that the role of the building envelope is to act as an artificial second skin to the human body. In his text, “The Aesthetic of Function,” he breaks down the elements of the environment, and describes the building interface at the granular level as inputs and outputs. Below is the diagram that illustrates the building-environmental interface.



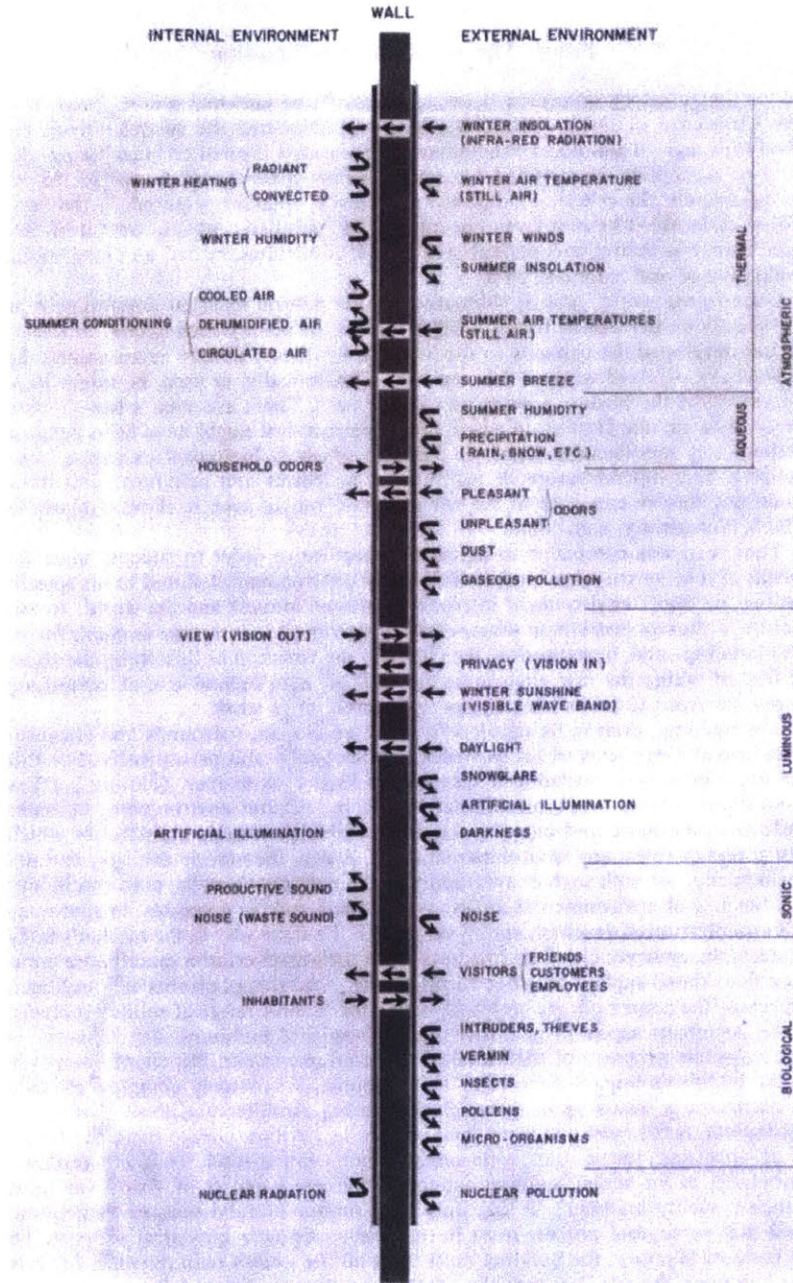


Figure 3. Fitch's envelope diagram from *American Building and the Forces that Shape It*

This diagram has significance in the understanding of the building envelope as interface because it describes all the granular relationships (in the abstract) that an envelope strives to mediate. For example, it is undesirable for the summer humidity to break the barrier, but a summer breeze is invited in. It is also important to bring natural sunlight in, but keep artificial night illumination out. The envelope controls the reception of architecture to inputs from the environment, either as rejected components or accepted inputs. These nuances between rejected and accepted inputs is where the envelope starts to perform less as a static, single-dimensional wall, and more as a permeable skin; as both a boundary and a filter. And the success that this envelope has in mediating the interior environment is the “ultimate determinant of man’s animate perceptions, and wellbeing.”<sup>9</sup>

### ————— *3.2 The Altered Interior* —————

#### **the mediated environment**

This expectation for the envelope to perform as a mediating interface for environment stems back even to the construction of vernacular architecture. These elements of environmental modulation were physically embedded in vernacular architecture—having a more direct effect on form and materiality than even local and regional culture did. For example, Addington describes that buildings in low-pressure climates possess similar roof slopes, and solid-to-void wall relationships, regardless of geographical location or continent. The same consistency presented itself in the vernacular of high pressure climates as well, where the envelopes had similar thermal-mass materials. These laws of heat transfer were facilitated by the material boundary of the building, and this boundary—the envelope—was where the transfer would take place. Addington concludes that “‘envelope’ becomes coincident with ‘boundary’ which then becomes implicitly coincident with ‘mediation.’”<sup>9</sup>

But, as more complex environmental technologies were invented, this “third environment” was slowly starting to separate itself from the envelope and from a relationship with the exterior environment. With the advent of technologies such as HVAC around the late 19th, early 20th centuries, the concept of comfort was introduced through the building systems. This slowly freed the building from its role as environmental mediator, and instead turned it into a sealed container to keep comfort inside, the total decoupling of exterior and interior environments. In vernacular architecture, there was a symbiosis between interior and exterior; they were treated as one entity. But, “[t]he use of environmental technologies set the stage for the substitution of the interior environment with an altered and reconfigured environment that was distinguished from the exterior by its level of conditioning. The more it was conditioned, the more independent it became from exterior conditions. It became a manufactured rather than a mediated environment.”<sup>9</sup>

#### **the manufactured environment**

The concept of the manufactured environment was brought upon by the shift from envelope as permeable interface to envelope as container. The introduction of building systems that controlled the interior environment spurred a shift to environments that were manufactured and generated from the inside rather than filtered from the outside. Mechanical and electrical systems removed excess heat, HVAC cooled and ventilated, and overall comfort became a programmable entity completely decoupled from the envelope. This paradigm shift towards tunable systems completely recast the envelope from its role as a permeable boundary of exchange, to one of discontinuity. This allowed architecture to seek experimentation in new materials that were previously not conducive to modulating environments. “The sleek glass facades that were the iconic representation of Modernism were possible only because the building siting and materials could be decoupled from the interior environment.”<sup>9</sup>

But the initial intentions of the introduction of environmental systems such as HVAC actually emerged from a desire to bring a closer

connection between interior and exterior. In the early 19th century, there was a concern about the toxicity of interior conditions in buildings. The increased overcrowding in cities along with more knowledge about air chemistry led to a paranoia about the human contamination of air. It was believed that body odor was a result of rotting skin, and that the carbon dioxide we breathed out was toxic. As a result, ventilation with air from the outside was seen as the only solution to control the spread of illness and death. This led to more permeable facades, with larger openings to let the air in. This was further propelled by the spread of tuberculosis, where fresh air was seen as a helpful measure against the disease.

Unfortunately, ventilation proved not to have an effect on the prevention of disease, and with the spread of the 1918 flu epidemic, fears about disease laden air coming from the exterior emerged. As a result, building openings were closed shut, almost “hermetic” and HVAC manufacturers sold a promise that their systems provided manufactured environments that were more pure than nature could produce.<sup>9</sup>

This paradigm shift led to an impermeable envelope that acted as a barrier to the exterior, and isolated the interior. This view that the building envelope contains the interior environment and repels the exterior privileges the aspiration for the interior to be a homogeneous, and ideal environment. “But keeping in the nice warm air (or the nice cool air in hot seasons) meant also keeping in all the moisture that human, kitchens and bathrooms constantly exhale.”<sup>5</sup>

### **the homogeneous input**

The “hermetically sealed” interior, one that was conditioned from the inside-out, spurred the quest to understand the physiological relationship the body had with transient thermal behaviors. A measure known as the Predicted Mean Vote (PMV) compiled a series of polls that asked people to determine what they determined to be “satisfactory” conditions, which helped define set conditions that were determined to be the most “neutral” (not too cold, not too warm). The American



Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) determined that the definition of thermal comfort is “those conditions in which 80% of the occupants do not express discomfort. This meant that the conditioning of the interior environment was based off of measures of conditions that one would not notice. Addington added, “[u]ntil the 1970s, the homogeneous interior environment lived up to its one criterion – it was not noticed. There was so much thermal inertia in the large volumes of air circulating inside the building that the body was subordinated to its surroundings: the interior environment drove the body’s heat exchange rather than the reverse.”<sup>9</sup>

The problem that arose from this neutral stance on conditioning, was that the thermal relationship between body and space was in tension, especially as the HVAC manufactures went from high thermal inertia systems, to low inertia ones. This led to the production of environments that started to negatively affect the body’s health and comfort. Any shift in the thermal environment such as standing up, or the glare of sunlight, would deeply disrupt the neutrality of the “ideal” environment and cause significant variability. What this meant, is that the building, instead of acting like an extension of the skin, started to view the body as a “generalizable yet problematic input.”<sup>9</sup>

### *3.3 Performative Spaces*

#### **the performative envelope**

High performance buildings were introduced as a solution to this variability, because it was thought that the inability for the HVAC system to maintain this neutrality was a result of poor envelope. The performative envelope emerged as a result. Building functions were pushed onto the walls, and compressed into the envelope, in the assumption that buildings were returning to a state of envelope as mediator. Double skin walls, smart glazings, adjustable louvers, and sensors were added to the container in order to manage the relationship between exterior to interior environment. But, the performative envelope is really “a tautological twist”; most of the technologies are only necessary because of the decision to have a fill

glass facade. "Rather than mediating between interior and exterior, the performative wall is compensating for the environmental penalties wrought by a material choice."<sup>9</sup> Addington continues, "[i]f the advent of HVAC enabled the application of the Modernist glazed facade, then the contemporary glazed facade demands additional technologies and systems so the HVAC systems conditioning the interior environment can function adequately."<sup>9</sup>

### **the interior condition and the body**

This privileging of the building as a primary determining factor for environmental mediation is inherently detrimental to the wellbeing of the human. Throughout the entirety of the 20th century, there have been numerous investigations in trying to understand the complex relationship between the human body and the interior environment with respect to thermal and luminous factors. The body's heat exchange responds to its surroundings in two ways: through convective exchange between the skin and the surrounding layer of air which is a few centimeters thick, and the second, an exchange between the body and the heat sinks and sources in a room. These realizations have led to the development of an incredible array of new materials and technologies to support these nuances. But none of these have led to the re-imagination of the purpose and function of the building envelope. And neither has the growth of building-borne illnesses attributed to any changes, even with many illnesses coming directly from overly sealed building envelopes and poor HVAC systems. The mantra that still prevails in this building-centric model is "Build Tight, Ventilate Right."<sup>9</sup>

According to Addington, there is the potential for "a rigorous application of current knowledge regarding local heat transfer coupled with existing technologies could easily manage the thermal needs and sensations of each and every body, and [can] do so with orders of magnitude less energy use; yet the field of architecture will not relinquish its hegemonic privileging of the building as the primary determining factor."<sup>9</sup>

Manuel Kretzer takes this even a step further by claiming that our inability to favor the human results in an augmented reality of living. "We have modified our environment so radically that we must now modify ourselves in order to exist in this new environment. We can no longer live in the old one."<sup>2</sup> What is necessary now, is to turn away from the assumption that architecture is static, and that the human is meant to respond to the conditions presented to them. Instead, we should look towards a model for building that is *receptive* to the human.

### **the case for dynamic spaces**

Decoupling the human from its relationship with the environment is a problematic approach to architecture. People increasingly spend a significant amount of their days indoors. Humans who live and work in urban places spend 90% of their time in enclosed spaces, and approximately 15 hours per day at home.<sup>2</sup> The effect that our interior environments have on our well-being is significant. And these environments are currently blind to the majority of the activities of the human in their space.

In the crafting of these interior environments, the architect designs for the human in the abstract - not merely the person at rest, but often for the person at work. But the problem with this generalization is that the architect designs spaces on a series of assumptions about the nature of human behavior. People are not predictable, yet buildings are built on a foundation of deterministic assumptions about activity. This causes extreme discordance between the predicted use of a building, and the actualized use, which causes tension between human and space. For example, in respect to environment, the needs of the human engaged in an activity done within buildings varies depending on the action. For example, a person at sleep requires a very different set of environmental conditions than a person at work. And yet building systems have yet to account for these variations.

In regards to daily living done indoors, what's even more significant is that the activities that the human often perceives to be a natural part of their life, are mostly "unnatural." For example, a person sitting at their desk for a couple of hours, typing away on their computer, is a quintessential example of an "unnatural" activity. This "normal" task of working, strains the eyesight, negatively affects posture, and puts the human in an abnormal amount of stress, even though these are the activities that are considered "natural." Often, these repetitive and fractionalized patterns of unnatural activities result in processes that are unhealthy, and sometimes dangerous to wellbeing, yet they are unnoticed by the individual.<sup>4</sup> The rhythms of daily living indoors no longer correspond to the rhythms of the natural world. Kevin Lynch says that as we "spend more of our lives in interior environments, we are deprived of many natural clues to the passage of day and season,"<sup>10</sup> cues that over evolutionary time have shaped the circadian rhythms of our bodies. Instead, we operate in tension with these cycles and adapt to the stagnant environments created by these building systems.

Addington gives the example of the child at school as a way to demonstrate the tension that exists between the child's body and the experience of their environment in an interior space. He proclaims that the child's physical growth and intellectual development should be "steady and parallel" throughout the day, as high at the end of the day as in the beginning. But in reality though, he claims that this is impossible because energies flag as the day goes on, and nothing but play, food and rest can be restorative to them. The question he poses for architects is "how should the classroom intervene in his favor? How to manipulate his external environment that his learning advances with optimum speed so and minimum stress?"<sup>4</sup>

The child's requirements for peak operation are dynamic, and are directly related to its dynamic relationship with the space of the classroom. What Addington brings to light, is that spaces need to be dynamic and responsive to the body, not in reverse.

"It should be immediately apparent that the child's requirements are dynamic and imply a dynamic relationship with his classroom. No classroom should confront the child with a fixed set of day-long environmental norms, e.g., 72° F air, 50 per cent humidity, 60 foot lamberts at desk top, 45 decibels of sound. Far from being held at some fixed level, the probability is that environmental conditions should be continually changing. But this change cannot be casual or statistically indeterminate (if change alone were all that was required, the class could be held in a nearby meadow). It must be a designed response to the child's changing requirements. The child may well need less heat at 2 p.m. than at 9 a.m. At day's end he may need less humidity and more oxygen; he may require more light and a different color; he may need a chair that gives a different posture or sound levels higher or lower than the morning. Whatever the requirements are, they could only derive from the child himself, in the experiential circumstances of study."<sup>4</sup>

What Addington is proposing, is the need for responsive environments; a turn towards crafting *liquid* architecture.

# **Part II**

## ***Design Space***

## Chapter 4: Receptive Skins

### 4.1 Changing Places

#### static architecture

In order to head towards this “liquid” architectural state as described by Michelle Addington, it is important to first understand how architecture came to be **static**. Static architecture is architecture that does not respond to contextual conditions such as environmental changes and human behavior. It remains frozen in time—frozen in the moment the architect drew their last line. It is an architecture of permanence.

This permanence draws its influence from the Modern movement, where the architect became fully in control of design. With full creative control handed to the architect, buildings became about a perfect image, as opposed to a perfect experience.

“Inherent to the Modern movement is the German idea of gestalt — totality. It’s Bauhaus. It’s a terribly powerful word that was interpreted by architects as the power to determine every detail of the building. And you cannot touch anything once it’s there.” Architects of this persuasion want your light switches and toilet stalls, desks, and fire stairs to reflect the same pervasive aesthetic as the roof line and lobby. If your life is out of sync with that, too bad.”<sup>5</sup>

What happened to architecture at this time was two-fold: architecture became about satisfying the vision of the architect, and buildings became “completed” artifacts—spaces that were considered finished even before occupancy. Preference for the image superseded the needs of the user. The synthesis of these two factors contributed to the privileging of a permanent and static architecture.

“Architects think of a building as a complete thing, while builders think of it and know it as a sequence — hole, then foundation, framing, roof, etc. The separation of design from making has resulted in a built environments that has no ‘flow’ to it — you simply cannot design an improvisation or an adaptation”

Static spaces are easy—they are easily controlled. But the transition from a static to a process architecture means relinquishing full control from the architect, and allowing for buildings to be shaped by external forces: “Buildings have lives of their own.”<sup>5</sup> It is a search for an architecture that is not finite upon completion, but can be changed by context—an architecture of the human.

### **after static architecture**

In order for the built environment to be in tune with the cycles of human living, it needs to be in constant flux. Kas Oosterhuis, a professor of architecture at TU Delft, points out that the dynamic processes that occur during the construction of a building, should not end at the moment of completion. Rather, they should continue and evolve in accordance with occupancy. He proposes an idea he calls “Hyperbodies,” which are “programmable building bodies that change their shape and content in real time”— an approach that will lead to an architecture which “[can] no longer remain static” but finally “become liquid”, not only as a metaphor, but as a real time behavioral condition.<sup>2</sup> This approach to architecture takes into consideration the previously ignored factor of *time* and the fluctuations of living. It demarcates the evolution of a system that goes from inert to active, essentially architecture that molds itself around environmental condition, and subsequently gets molded by it. In order to achieve true responsiveness to people and changing conditions, environments must be both *dynamic* and *aware*.

**dynamic:** An articulation of active structures to create particular kinetic and ambient effects. The impetus for change is based on a directed and intentional action of the occupant. Typically there is a deterministic output from the input.

**aware:** An understanding of spatial conditions with a focus on understanding user and built environment. Typically the input is received from a sensor infrastructure.



## 4.2 *Dynamic Environments*

### **dynamic environments**

Dynamic environments express themselves through the characteristic of change. They are spaces that are programmed to shift and evolve through their flexibility. These can be spaces that fold and unfold, move around, change their atmospheres or physical characteristics, all triggered by simple inputs such as manually operated transformations. Dynamic environments utilize dynamic systems in order to behave in a kinetic fashion.

### **dynamic systems**

Dynamic systems are the infrastructure put in place to enable spaces that shift. They have a multitude of manifestations. Below are some examples of categories and systems that pertain to them. This thesis chooses to highlight examples of systems that are self contained and automatic, and not only dependent on manual human actuation.

**digital systems:** screens, projections, e-ink

**mechanical systems:** louvers, kinetic furniture, HVAC

**material systems:** pneumatics, SMA, thermo-chromic pigments

### **actuation**

Actuation means "to incite or move to action." The result of dynamic systems, and the translation of this behavior results in actuation. The types of actuation that can exist in dynamic environments is multi-fold and varies dependent on the medium and system that incites it. Below are some examples of the categorization of actuation.

**actuation of environment:** thermal, luminous, aqueous

**actuation of form:** shape-change, inflation,

**actuation of property:** color, texture, stiffness

**actuation of movement:** drag, lift, rotate

### ori systems

One precedent of a commercially produced dynamic environment is *Ori*,<sup>11</sup> a kinetic, unfolding wall that is made up of a series of moving parts. The project originated from a prototype called *CityHome*,<sup>12</sup> a project that came out of the City Science group at the MIT Media Lab. The project was designed with a desire to fabricate a platform that would allow a small space to have the same functions a larger space would — “living large” in a small space. In order to achieve this, the project examined the separate programs that existed within a home, and how these different “rooms” could unfold from within a wall to turn a bedroom into a closet, or a living room into a kitchen.



The project uses a series of horizontal motors to actuate this wall, and move it across the floor to allow spaces to grow and shrink. Concurrently it also has motors to open and close pieces of furniture such as a bed, and a desk. And all of these changes are enabled through the touch of a button on the side of the unit.



Figures 3 & 4. Photographs of iterations and in situ of Ori Systems

*Ori's* work utilizes the dynamism of mechanical systems in order to facilitate spatial choreography between what is an otherwise static space. The project allows for the seamless continuity between spatial programs.



Figure 5. Photograph of Ori in use.

### 4.3 *Aware Environments*

#### **awareness**

The second property that defines post-static spaces is the state of awareness. "Awareness is the state of knowing about the environment in which you exist; about your surroundings, and the presence and activities of others."<sup>13</sup> It is the synthesis of components that form an understanding of existing conditions. With acute awareness, spaces can start to understand the status of the human, and the status of the environment. The capturing of this information is useful because *knowing leads to understanding*.

### **sensors**

Mark Weiser talks about awareness as a major subset of the term he calls 'ubiquitous computing.' He says that "[s]ensor technology plays an important role in dedicating computers to a small subset of 'understanding the world around us' (a key element of intelligent behavior)."<sup>14</sup> Sensors are the tools that are used to capture the data about the conditions of the space. They are electronics or materials that capture information about certain inputs. Some of these inputs are elaborated on below:

**environmental:** thermal, luminous, sonic, atmospheric, aqueous

**presence:** occupancy, location

**activity:** moving, talking, walking

### **information**

The importance of sensors is their ability to capture data points in order to fuse them into interpretation about condition. Weiser continues his ideas by stating that "[b]y widely deploying and interconnecting sensor-based tiny computers, one would be able to integrate environmental data (location, temperature, lighting, movement, etc.) and use this information to produce smart behavior of computers and computerized physical objects."<sup>14</sup> This dimensional shift from 'data' to 'information' requires the interpretation of many data points, and signatures of conditions.

### **placelab**

An example of an architectural project that is driven by principles of awareness is the *PlaceLab*.<sup>15</sup> This project was motivated by a mission to design and build "living labs," spaces that were built for the study of human behavior in situ. The site of the lab was in an apartment that was situated in Cambridge, MA, where volunteer subjects would agree to live for varying time periods. The house was retrofitted with sensors that were hidden from view and passively collecting data. It was through the use of these distributed sensors across the environment, that researchers were able to collect a substantial amount of information about daily living, and create insights derived from that data.

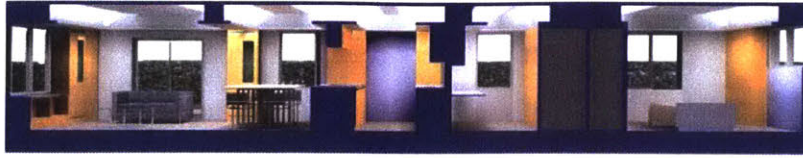


Figure 6. Rendering of PlaceLab space

The sensors were hidden, and installed in places such as cabinets, under chairs and on tables. This allowed for a more holistic gathering of data points because it allowed the human subjects to operate as they normally would, without the constant reminder they were being monitored. These sensors were used to develop insights about future interface applications for use in the home in tandem with learning more about human behavior. The type of sensors are displayed below:

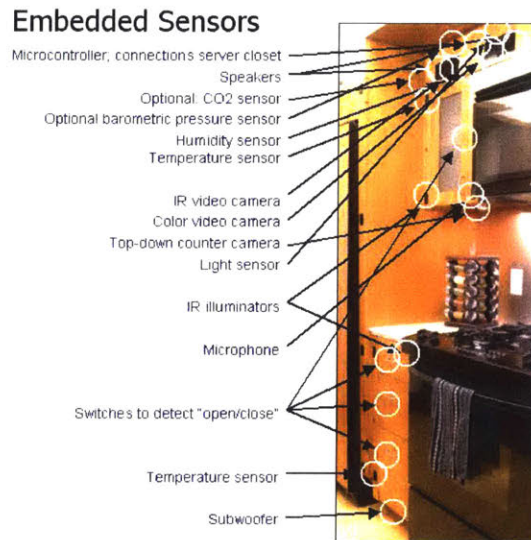


Figure 7. Diagram of sensors and components in PlaceLab

### changing places

These two types of spaces, dynamic and aware, embody the philosophy of **changing places**—fluid spaces that abandon the approach of static architecture, and embrace and architecture that molds itself around changes in context. This approach leads us to a direction of architecture in process, as opposed to a completed artifact. The synthesis of these two types of changing places—aware space and dynamic space—is known as a **responsive environment**.

## 4.4 *Responsive Environments*

### **responsive environments**

The marriage of dynamic and aware spaces produces what is known as *responsive environments*. These environments, because of the combination of knowing and doing, can receive inputs that trigger behavioral outputs. For example, when the temperature in a room increases, the HVAC system responds with cold air. The sensor communicated the status of the current environment, understood it as above a set threshold, and reacted accordingly by introducing chilled air until a thermostatically preset temperature is reached.

*In short, dynamic + aware = responsive*

Responsive spaces enable the choreography between human, environment, and space, in a way that static architecture can never achieve. It enables experiences that can support the dwelling of human, and allow itself to be a real extension of the body—architecture as womb. Responsive spaces form a symbiotic relationship with the human, through the interaction between three components: *sensing*, *computation* and *actuation*. On one level, this resembles a basic model of human behavior: the body senses information, the brain determines an appropriate response, and the muscles translate that response into physical action.

### **sensing, computation, actuation**

Responsive spaces are dependent on the synthesis of sensing, computation, and actuation in order to respond to stimuli. The current infrastructure of this model are typically manifested as separate components serving one goal: sensing information is received through sensors, the computation of this information is processed by a computer, and the actuation is achieved by a separate machine. Mark Weiser describes the relationship between sensing, computation and actuation as follows: “By widely deploying and interconnecting sensor-based tiny computers, one would be able to integrate environmental data (location, temperature, lighting, movement, etc.) and use this



information to produce smart behavior of computers and computerized physical objects."

*sensing*

Sensors act as abstracted human senses—programmed to receive certain kinds of inputs and send those signals to the processor. Sensors can take many forms: analog sensors, digital sensors, cameras, microphones, etc. These components are specialized to receive only specific signals, such as audio, temperature, color, and are blind to other inputs that are not in their protocol. This is the limitation of singular sensor input—the inability to pull more information from the environment—and why *sensor fusion* is more in line with the ways our bodies receive inputs. *Sensor fusion* is the conglomeration of multiple sensor inputs to build a more holistic model of reality. Our bodies do not receive sensory inputs independently from one another, but simultaneously, and as a result, can allow us to understand reality more accurately. For example, the act of cooking depends not only on visual inputs, but on olfactory, auditory, somatosensory and gustatory. It is in the fusion of these senses that the human can understand when to intervene in the process. And the brain is the processor that synthesizes together all these inputs. In responsive environments, this idea of "brain" manifests itself into *computation*.

*computation*

Computation is the processing of inputs to enact the corresponding outputs. It is the centralized model that possesses the logic for every input and every output. Computation in the responsive system acts deterministically—every single relationship is mapped, and any input has a corresponding reaction. This transfer of information is expressed as a series of digital signals, flowing from the sensing components to the actuating components. As signals from the sensors stream through the electronics, they are processed through the model of predetermined logic, and then signals are sent to the actuators to produce the resulting action.

### *actuation*

Actuators in responsive spaces, are akin to being compared to the muscles. They are the physical manifestation of transformation, and receive their information from the output of computation. The output of the actuator is dependent on the physical construction of its actuation, and the translation into material. Sensors listen to spaces, that information is processed through computation, and the actuator listens to that signal.

### **“smart” spaces**

The current physical manifestation of sensing, computation and processing systems in responsive environments is essentially a machine-systems model. Sensors (small machines), receive inputs and send them to the processor (a machine) which send a signal to the actuator (a moving machine). Because this family of machines is often compared to the processing system of the body, the responsive environment is often described as being a *smart space*—a space that possesses intelligence. Smart spaces are today's responsive environments—a system that relies heavily on humans interfacing with computers. And today, the word “smart” has become synonymous with the word “computer”. Essentially anything that has computational power today is called “smart.” Mark Weiser jokes about the usage of the word “smart” to describe these systems in his text, *Open House*:

“‘Smart House’: Does this mean any more than a house with a computer in it? Does it mean anything like ‘Better House’? Do we really think that everything in the world would be better if it were smarter? Smart Cappuccino? Smart Park? The ‘Smart House’ of 1935 had an electric light in every room. The ‘Smart House’ of 1955 dared to put a TV and a telephone in every room. And the ‘Smart House’ of 2005 will have computers in every room. But what will they do?’”<sup>2</sup>

What Mark Weiser claims, is that today's ideal responsive environment, the “smart” space, put too much focus on the computer, and not enough focus on the human. He emphasizes that the computers should not be the design catalyst for responsive spaces, but rather, human



experience. He encapsulates this concept by saying that “[a] computer I need to talk to, give commands to, or have a relationship with (much less be intimate with), is a computer that is too much the center of attention.”<sup>17</sup> He emphasizes that the awareness in our environments needs to be akin to a relationship with a roommate—interacting with only when necessary. Weiser continues with this thread in asking the following:

“What is the metaphor for the computer of the future? The intelligent agent? The television (multimedia)? The 3-D graphics world (virtual reality)? The StarTrek ubiquitous voice computer? The GUI desktop, honed and refined? The machine that magically grants our wishes? I think the right answer is “none of the above”, because I think all of these concepts share a basic flaw: they make the computer visible.”<sup>17</sup>

This emphasis on the computer is particularly strong in the interfaces that are used today in the responsive environment. Having to tune the thermostat, or talk to an assistant, place an incredible focus on the interface between human and computer, instead of human and space. By making the computer the main experience, we are losing out on the environmental experience.

What Weiser is questioning, is the interaction that we have with our computers in these responsive spaces. He is hinting at an environment where the computer is not the center, but in the periphery. He continues that “[t]he most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it.”<sup>18</sup> This approach to computing, where the computer gets pushed to the periphery, is known as *ambient intelligence*.

### **ambient intelligence**

Ambient intelligence describes a kind of computing that is more humane, and exists on the periphery. It changes the role of the computer from being the center of the experience, and instead makes the human centric. By placing the computer in the periphery, we

have the ability to be receptive to more things than if they were at the center—things in the periphery are attuned by a large portion in the brain that processes peripheral (sensory) information. Thus, Weiser concludes "...the periphery is informing without overburdening."<sup>19</sup> He expands on this:

"Most important, ubiquitous computers will help overcome the problem of information overload. There is more information available at our fingertips during a walk in the woods than in any computer system, yet people find a walk among trees relaxing and computers frustrating. Machines that fit the human environment, instead of forcing humans to enter theirs, will make using a computer as refreshing as taking a walk in the woods" (11.8)

Weiser's vision shapes a new relationship with the minds of responsive spaces to be less about the computer, and more about interactions with the human that are "invisible" and "calm."

But the current structure of this system does not allow for this. Each component exists as separated systems. The connections between the receiving information processing it, and the resulting actuation, are quite different. The system is not internalized and holistic, but externalized and embodied in many computers. Essentially, information is segregated from material. In the human body, the transfer of information is matter based, whereas in the responsive environment, it occurs as deterministic digital signals. Norbert Wiener describes the difference between the biological transfer of information and the machine's transfer as the following:

"The mechanical brain does not secrete thought "as the liver does bile," as the earlier materialists claimed, nor does it put it out in the form of energy, as the muscle puts out its activity. Wiener (1961, *Cybernetics*, p. 132)." <sup>2</sup>

What he is describing is essentially the difference between the localized brain, and the external. Localized decisions, such as are present in nature allow for a more symbiotic relationship between the input, and the output, bringing them together in a single unit. Computing in this

scenario is of the machine, the material, not segregated from it. George Jeronimidis outlines this relationship in his paper, *Biodynamics*.

“Natural systems are quite different. Most sensing, decision-making and reactions are entirely local, and global behavior is the product of local actions. This is true across all scales, from small plants to large mammals. When we run for the bus, we do not have to make any conscious decisions to accelerate our heartbeat, increase breathing rate and volume, or to open our pores to regulate the higher internal temperatures generated. Plants, lacking a central nervous systems and mammalian brain, make growth movements to orientate themselves to the sun or to correct their inclination.”<sup>20</sup>

#### **towards a new interface**

This vision of natural systems is in accordance with the peripheral vision of Weiser and of ambient computing. The current interfaces for responsive environments are still very much exist as separate computers of sensing, computation and actuation—the separation of *mater* and *information*. The responsive environment manifests into “[t]he distinction between matter (mechanics) and information (electronics)...” (27.182) as the integration of electronics into material. But what would happen if both information and material merged into a single entity, as a new kind of medium? What if sensing, computation and actuation molded into the same body?

Simply, the manifestation of this kind of system would have to be the merging of material with brain—essentially, the *information material*.

### ***4.5 Information Materials***

“...this new architecture will be dynamic, responsive, and to some extent maybe even alive. It will evolve and change with its inhabitants and the environment and instead of being made to endure it will celebrate the ephemeral and temporal aspects of life.”<sup>2</sup>

### **information materials**

*Information materials*, as described in Manuel Kretzer's book with the same name, are loosely defined as enabling "resonant, potent architecture."<sup>2</sup> They are materials with dynamic and sensory properties that are inherent to their composition—'intelligence' embedded within the material. He continues by stating that information materials are "describing a larger, more general phenomenon, which completely distinguishes such materials from traditional ones, mainly due to their inherently dynamic nature."<sup>2</sup> Information materials are essentially the merging of surface and intelligence—*of computer and machine*.

There have been tremendous advances in material science over the past decades, that allow for new kinds of material behavior, and the miniaturization of complex intelligence into smaller footprints. Developments in material science, fabrication and electronic miniaturization have had a tremendous effect on the objects and environments that are now possible to construct.<sup>22</sup> No longer can complexity be measured by size: "[t]here is no longer any perceivable correspondence between the complexity of the object and its surface."<sup>23</sup> Materials can now behave in temporal and animate fashion, fluctuating with the flow of time. Because of this, information materials have great potential for new interfaces in architecture using matter.

### **material and surface in architecture**

There has been a strong tradition of materiality in the architectural legacy. Materials have always been important in the fabrication of space, and are the most intimate part of the relationship between human and space, because they are sensory, and interact with our bodies. For this reason, the appropriate use of materials for context has been a large motivation for architects such as Frank Lloyd Wright. Wright described this by stating that "[e]ach different material required a different handling, and each different handling as well as the material itself had new possibilities of use peculiar to the nature of each. Appropriate designs for one material would not be at all appropriate for any other material (Wright 1936, p. 184)."<sup>2</sup>

Louis Kahn has also been an advocate of contextual materiality. In referring to this 'nature of materials,' "...he demands their proper use and contends that every material has its own significance, potential, and limitations."<sup>2</sup> He believes that architecture should express spirituality, which was missing from many of the modernist buildings of his time. Kretzer describes this by saying that "[i]n order to accentuate building from pursuing purely formal or utilitarian aspects toward the creation of meaningful spaces he urge[d] to reveal its construction and materiality through a careful consideration of their interdependence in relation to the respective task and location."<sup>2</sup> Kahn was interested in an approach to architecture that emerged from the material itself, rather than form—towards an architecture of materiality.

"If you think of Brick, you say to Brick, 'What do you want, Brick?' And Brick says to you, 'I like an Arch.' And if you say to Brick, 'Look, arches are expensive, and I can use a concrete lintel over you. What do you think of that, Brick?' Brick says, 'I like an Arch.' And it's important, you see, that you honor the material that you use (Kahn 2003, p. 270)."<sup>2</sup>

Sanford Kwinter, one of today's most prominent architectural theorists, has claimed "material as the new space."<sup>24</sup> This is emerging from a renowned interest around new innovative materials and technologies and their potential for having great influence on architectural space. According to Neri Oxman, "[f]orm's obituary is rapidly being outlined as second generation baby boomers chart out territories for a formal atheism, or, if I am not promoting too lofty a claim, a new religion. It is called, *The New Materiality*."

#### **new materiality**

Materials used to be seen as "static substrates from which to build complex systems, rather than dynamic and responsive elements, which could change their properties on demand and adapt to ever-changing design requirements."<sup>22</sup> But with today's advancements in material science and material technology, this holy grail of material dynamism has become reality.

This new medium not only allows for new material expressions in the built environment, but it serves as a critical step to moving beyond the current interface limitations in responsive space. Hiroshi Ishii, in his text, *Radical Atoms* illustrates the following: "Instead of various information sources competing against each other for a relatively small amount of real estate on the screen, information is moved off the screen into the physical environment, manifesting itself as subtle changes in form, movement, sound, color, smell, temperature, or light."<sup>13</sup> This allows for new interactions to exist between the human body in space, and the body of the space. *Surface will become interface.*

This new kind of interface will not only affect the way that architecture is constructed but it will also have a profound effect on its experience. Kretzer claims that the "concept of dynamic matter, constantly behaving and transforming, goes far beyond functional and technological aspects and actually questions the very core of architecture, *its stasis*."<sup>2</sup> Oxman states that the ability to shape these new forms of expression "will depend on the craft triptych (matter, fabrication, and environment) and its integration into the design practice as an undifferentiated scheme, able to process matter into shape as informed by the environment."<sup>25</sup> What this means, is that the success of surface as interface depends on the synergy between all its parts, from the matter that constructs it, to how it is constructed, to how it constructs space.

This new kind of architecture will not only challenge the current way of building in terms of production, processes, and materiality but propose a fundamental ideological rethink, just as Salvador Dali once affronted Le Corbusier by suggesting that the future of architecture will be "soft and hairy" (1957, p. 29).<sup>2</sup>

Architecture's shift towards a more dynamic surface interface, begins at the threshold where architecture touches environment—the **building envelope**.

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## 4.6 Skin

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### **the envelope as material interface**

The building envelope acts as architecture's skin—in negotiating the states between environment, building and body. Material already facilitates this exchange, but operates passively, merely relying on the static material properties of the assembly to work. But what if the materials in the envelope were dynamic instead of static? First, in order to understand the potential of this new skin, it is important to understand the mechanics of the old skin.

### **old skin vs new skin**

The current manifestation of the responsive envelope is known by a series of names: polyvalent wall, intelligent facade, high-performance envelope, smart skin, double-skin wall. These are all terms that are essentially referring to a thickened envelope that houses many of the highly engineered mechanical and electrical functions of the building, from smart glazing, to photo sensors. Addington claims “this is a return to the idea of the envelope as an environmental mediator.”<sup>9</sup>

This evolution of environmentally responsive envelope systems over the past few decades has been rapid, but “they function as a collection of devices such as louvers and shades, controlled by a central computer that receives data from remote sensors and sends back instructions for activation of mechanical systems.”<sup>20</sup> This describes the machine systems model noted earlier—the segregation of information and actuation. The computer receives, and pushes output into the body. This concept though, isn't modern and dates back to the 19th century. Even though human decision making has been replaced by computational reasoning, it is still deterministic. She casts light on the ways in which natural systems differ in their decision making capabilities, and instead operate in a completely different manner.

Information materials offer a compelling pathway toward realizing the vision of distributed decision-making through non-linear actuation that is more 'fuzzy' and akin to the way that humans process information

globally, rather than as discrete values. This could be seen as a disadvantage where efficiency and precision are concerned, but this is a perspective that stems from an outdated mechanistic point of view, which is inappropriate for the measure of information materials. Kretzer states, that "[t]he materials' transformative processes should instead be seen in a more universal and independent manner, emphasizing their distinction from the rigidity of mechanical paradigms. This would allow focusing on softness and organismic as particular behavioral properties akin to phenomena that occur in nature, which thus might foster a much more intuitive and personal human association than mechanic systems would ever allow for."<sup>2</sup> Don Norman, an influential thinker on design and psychology encapsulates this distinction with the following:

"We are analog devices following biological modes of operation. We are compliant, flexible, tolerant. Yet we people have constructed a world of machines that requires us to be rigid, fixed, intolerant. We have devised a technology that requires considerable care and attention, that demands it be treated on its own terms, not on ours. We live in a technology centered world where the technology is not appropriate for people. No wonder we have such difficulties." <sup>26</sup>

What can be drawn from this idea around natural systems and their analog, localized decision making, is that they integrate inputs in order to probabilistically determine the appropriate reaction, in a way that's more in line with how humans operate, not deterministically.

### **hygroskin**

One example of the use of information materials to construct new relationships between envelope and environment is a project by Akim Menges called *HygroSkin*.<sup>27</sup> It explores a new way, using responsive materiality, to think about climate-sensitive architecture, by leveraging the innate properties of wood to actuate with the presence of humidity.

Wood, is known to be sensitive to moisture content within the air, and often deforms if too much moisture is present, but returns to its



natural state once the moisture has left. This elasticity is what Menges leveraged to construct a pavilion skin out of thin layers of wood. The skin opens and closes constructed pores whenever increased moisture is present, to allow for the influx of air into the space—modulating the environment—and closes once the air is more dry. This allows for a dynamic relationship between the building envelope and the external and internal environment, where each element is affecting the other. And it also allows for a more natural interaction, where the interface for environmental modulation melts into the periphery, and preserves the quiescence of architecture.

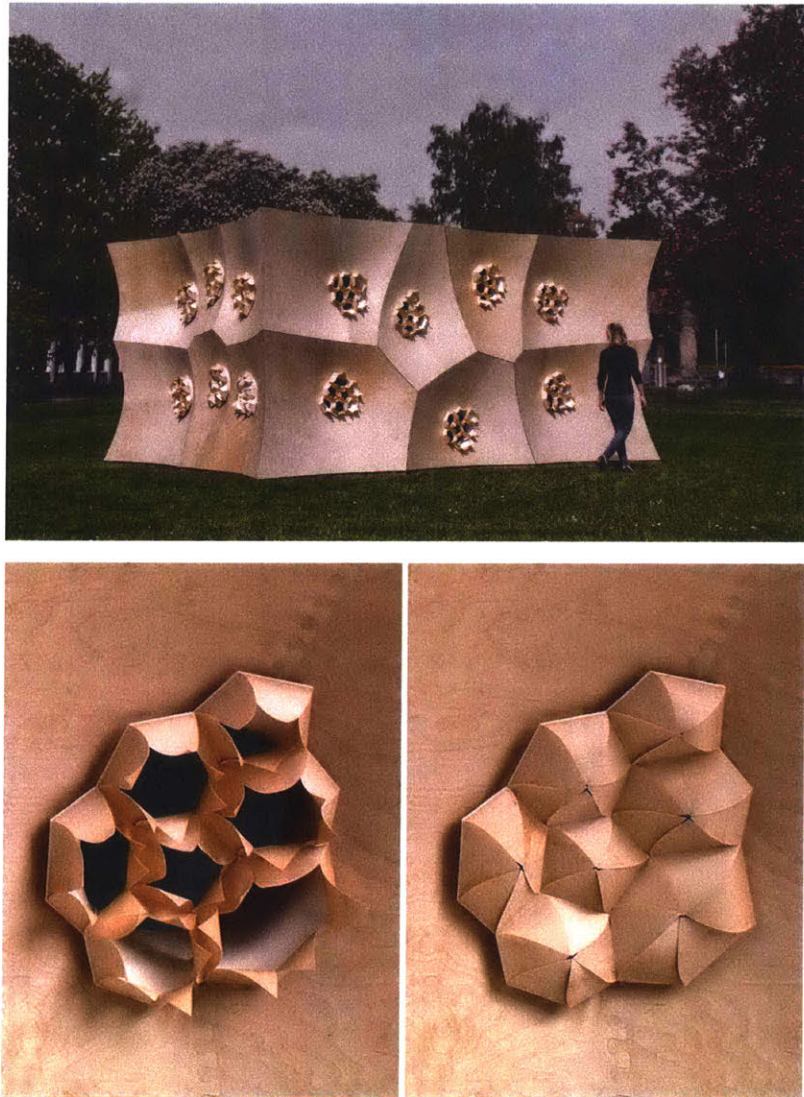


Figure 8. Photographs of HydroSkin

The project was constructed by machine-fabricated modules, with iterative processes to understand the exact correlation between material, fabrication and environmental sensitivity. Instead of digital values, the values that were important in this project were the direction of the grain, the thickness of the wood, and the geometry of the module. This approach towards an environmental mediation via material properties is heading away from the preconceived notion of the static envelope, to one that is more performative naturally.

Despite the evolution of this kind of performative mediation, most responsive scenarios are still quite traditional. Information materials have yet to have an effect on the spatial qualities of the built environment, and are still far from realizing the potential for radical transformation of architectural processes.<sup>2</sup> In addition, these approaches tend to be limited in their material sensitivities, expressing only one type of mediation. As spaces comprise an ever-changing synthesis of environmental components, practical application of information materials requires a significant evolution in the understanding of *material integration*.

"An intelligent wall or a responsive skin is, at its simplest, an environmental manifestation of technology that is already being appropriated (Bullivant 2006). However, in much of the work generated recently which falls under the umbrella of 'responsive environments' there still exists a separation, both in process and authorship, between "what" a building senses and 'how' it does so."<sup>21</sup>

### **towards material integration**

Currently, building envelopes are composed of a series of static layers that are each responsible for a different input. For example, the steel is meant merely as structure, and the insulation is mostly meant for thermal comfort. The two do not interact, nor are they affected by each other. What if structure and thermal conditioning, for example, could be integrated into each other, and dynamically understand and affect just-in-time structural and thermal conditions? Oxman describes this phenomenon as material integration. She states that "[in] fostering

material integration across various scales, architectural elements such as structure and facade are no longer divorced in function and/or behavior, but rather negotiated through the informed distribution of matter."<sup>24</sup> What she is heading towards is an envelope where materials are not separated, but interactive—not just with environment, but with each other: "Difference, describes a condition of non-homogenous organization where the heterogeneous organization of elements or materials acts as one medium to enable performance-based design."<sup>24</sup>

What this concept attempts to illustrate is an approach where many materials act as a single medium to enable this environmental modulation. And as earlier, in order to demonstrate this phenomenon, we turn to natural systems for inspiration: in this case, the *human skin*.

#### **the human skin**

The human skin is a particularly good example of an 'information material' system that acts as a singular medium. Skin acts as both a barrier and a filter, receiving analog information to affect the internal body environment, at the same time that it rejects other kinds of information. Essentially, one could say that the skin is the first interface the human body has with the environment.

The mechanics of the skin are particularly interesting to note as a precedent for possible future envelope assemblies. It is made up of many layers of interacting materials, that send information across the section, with each material having its function. The skin is made up of three major layers, the epidermis (outer layer), the dermis (middle layer) and the subcutis (the deepest layer). The epidermis varies in thickness, depending on the which part of the body it is on, and it consists of many different cell types such as cells that produce melanin (for protection from the sun), cells that fight germs, and cells that can sense pressure. The dermis is made up of a dense network of collagen fibers. It contains a series of nerve fibers (information), blood vessels (metabolism) and the sweat glands (thermal regulation). And finally, the deepest layer is the subcutis. This layer is mostly made up of fat (insulation and shock absorption) and connective tissue. The parallels

between the skin of the body and the skin of the building (envelope) are plentiful.

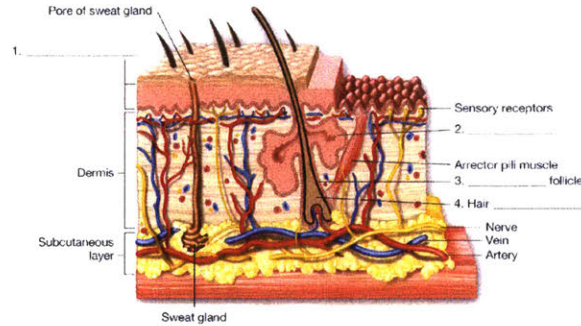


Figure 9. Anatomy of skin <https://anatomybodydiagram.com/anatomical-structure-of-skin/>

But what is more interesting than the individual operations of each layer, is the ways in which they interact with each other. And this communication is called the **somatosensory system**.

### the somatosensory system

The somatosensory system controls the ways in which information is transferred and encoded from the skin to the brain and back. It is the communication interface between these elements and it is receptive to many inputs (stimuli) that affect the body. These inputs are processed through receptors on the skin that send information across the layers to the brain. For example, there are specific receptors for vibrations, others for light touch, and others for thermal changes. Each receptor is part of its own kind of sensory neuron which connect to specific neurons in the somatosensory system within the brain.

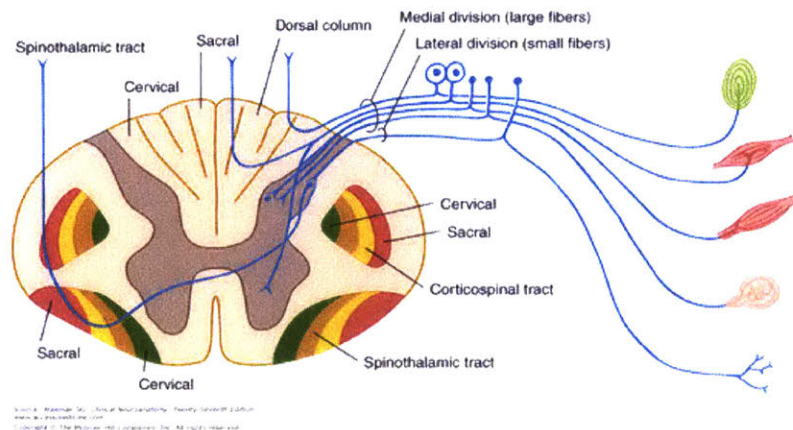


Figure 10. The somatosensory system <https://neurology.mhmedical.com/content.aspx?bookid=673&sectionid=45395979>

Essentially, the skin is a multi-active material assembly, relying on the interaction between its parts in order to understand inputs and appropriate outputs. This relationship between brain and material, offers the perfect precedent for understanding the potential for information material assemblies to construct a new somatosensitive building envelope—*the receptive skin*.

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#### 4.7 Receptive Skins

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##### **the receptive envelope**

**Receptive skin** is a novel approach to material assembly, wherein the materials that form the building envelope are individually 'information materials' (possessing actuation and intelligence) and at the same time, fusing interactions between materials in order to produce a desired environmental modulation. In the modernist tradition, the building envelope promoted a division of functions of the architectural elements: components with pre-assigned forms, materials and structures.<sup>20</sup> But in this new receptive approach, there will instead be an integration of forms, and exchanges of information across the envelope's assembly. The role of the building envelope returns to the primary environmental modulator, but now acting more like skin, rather than machine.

With the return to the envelope as mediator, the classic state of the architectural-environmental relationship—one in which envelope was sealed and had no exchange with its environment—is now disrupted. In the new model, the building envelope plays an interactive role with both human and environment. "Buildings, particularly large-scale building systems, are beginning to be seen from the point of view of establishing a responsive relationship with environmental and physical impacts (Bullivant 2005)."<sup>21</sup>

With a renewed focus on material as generator, the performative envelope can now be understood as a medium that can be approached from many scales. This is a distinct difference from the traditional

approach because “architecture and urban design solutions typically develop in a top down manner, working from abstract representations of a problem, then, progressively detailing a solution. If a system is only understood at an abstract level, then a solution will also address only this; if a problem is understood at a detailed level, then the solution will be comprehensive.”<sup>28</sup> Architects can now start to approach design from the intelligence of the cell instead of the mass produced material.

What receptive skins start to enable, aside from new fabrication approaches, is even more interesting at the moment of the human-building interface. With new materials, the primary contact point of buildings, the surface, now transforms into an input/output device that can become part of the inhabitant’s hybrid identity.

“Walls will dissolve and smoothly connect spaces with their related surroundings. Materials will contain and carry information and energy and become active agents in networked ecologies. Architecture will at last evolve from its primordial purpose of providing shelter and safety toward becoming a new synthetic organism, fusing and coexisting with its inhabitants.”<sup>2</sup>

### **towards a new softness**

An architecture of information materials also starts to have an effect on the expressions of material language in space. Materials can now be softer, like skin, and provide a more nuanced relationship between human and surface, a term Marcelo Cohelo calls, *soft mechanics*: “The term soft mechanics refers to systems based on the use of shape-changing materials and their composites, which generate kinesis and physical transformation via transitions through different memory and elasticity states” (18.64). Physically, building materials can now encompass varying forms and material expressions that support their actuation and processing. Kretzer states that “[t]hese building materials can be conceived as filters acting in oscillations: catching, harvesting, pulling, both expanding human influence and in turn expanding the impact of the world on us.”<sup>2</sup> Essentially what this creates is an interface full of sensitive boundaries.

When somatosensitive skins start to collect environmental information about human and building, they are essentially mimicking biological behavior, or, as Mark Weiser says, "...human made systems or technology, approached the complexity of the born..." (7.5) What this means is that it is now possible for receptive skins to afford new kinds of dynamism in architecture and environment; interactions that are nearing ones that occur in systems that are alive.

"...this new architecture will be dynamic, responsive, and to some extent maybe even alive. It will evolve and change with its inhabitants and the environment and instead of being made to endure it will celebrate the ephemeral and temporal aspects of life."<sup>2</sup>

### **biomimetic behavior**

With respect to the mechanical systems of the envelope, Fox and Kemp predicted "the end of mechanics" and claim that we are heading towards a "paradigm shift from the mechanical to the biological in terms of adaptation in architecture."<sup>2</sup>

John Frazer, a pioneer in applying technologies to architecture, also agrees with this approach of heading towards a biomimetic architecture. He argues that "architecture has become an essential part of the natural ecosystem and should therefore draw direct analogies from natural processes."<sup>2</sup> He continues by emphasizing that this approach should go beyond just formal similarities, and start to engage in symbiosis with the human through focusing on nature's "organic operating principles."<sup>2</sup>

The potential for information material assemblies to produce interactions that start to mimic natural behavior is grand. Having building interfaces that mimic biological systems can produce new words for describing this behavior, and replace the words that often describe current responsive interfaces, such as 'smart.'

"The terms 'smart', 'functional', 'multifunctional' and 'intelligent' are often used interchangeably. This is reasonable, if confusing, for the first three terms but the last almost certainly suggests a degree of consciousness that does not exist in any non-biological system. There is arguably no such thing as a 'smart material' per se - there are only materials that exhibit interesting intrinsic characteristics which can be exploited within systems, or structures that, in turn, can exhibit 'smart' behavior (Institute of Materials, Minerals and Mining 2003, pp. 5, 11)" (4.56).

This transition could perhaps shift the conversation from possessing intelligence, to understanding what the different kinds of behaviors that can be designed are. Weiser illustrates this point by saying that "[r]esearch about the organization and evolution of the born should be particularly concerned with questions such as: how do they cope with errors, with change, with control, with goals, and so forth. For instance, beehives were found not to follow a controlling head."<sup>14</sup> This new kind of behavior allows for architects to now design not just for aesthetic and material properties, but start to design with behavior in mind, and draw from the already existing systems found in nature. And even more so, it will help designers start to think about ways in which the built environment can physically morph in order to account for changes in the environment—similar to how natural systems effortlessly do—a term that is known as *thigmomorphogenesis*.

Thigmomorphogenesis, according to Jeronimidis, "is the changes in shape, structure and material properties that are produced in response to transient changes in environmental conditions."<sup>20</sup> These changes vary depending on organism, stimuli, and context, and as he illustrates, "such as heliotropism in sunflowers. These are all growth movements, slow adaptations to changes in specific conditions"<sup>20</sup> Where this becomes most interesting is when adaptive systems are considered in respect to their affinity for the living, in terms of behavior, intelligence and material constitution.<sup>2</sup>



In order to head towards a somatosensitive architecture, the condemnation of biomimetics needs to be addressed. Rachel Armstrong calls this condemning of biomimetics as “an aesthetic formalism or metaphor for sustainable, but essentially unworkable, aspirations within an urban context...”<sup>2</sup> She is reiterating that the current perception that biomimicry is merely a formal, aesthetic expression and that opposition to the approach stems from a lack of understanding of the potential to draw further dimensions from the operation of the natural.

Armstrong calls for the fabrication of information materials and assemblies that are “dynamically connected and responsive to their surrounding.” She concludes that because incorporating of biological systems into built requires energy and intense support and maintenance, she suggests “the invention of a new kind of synthetic biology, native to its surrounding and inherently sustainable, following a bottom up approach (Armstrong 2011, p. 72).”<sup>2</sup>

In order for the receptive skins of envelopes to evolve into this nature-inspired condition, there need to be incremental shifts that have to occur in the field of architecture. Kretzer illustrates these evolutions below:

“The first level is based on copying forms or structures that appear in nature, which depending on their usage and context might be more efficient or aesthetic than others. The second level refers to the mimicking of natural processes, of how something is made and produced, and the last part is related to the imitation of natural systems, reasoning that any kind of biomimicry has to be evaluated within a larger context for its long-term purpose and effect (Benyus 2008, p. 40).”<sup>2</sup>

What receptive skins are enabling is a new paradigm for interface—one that is not digital, nor mechanical, but analog and biological. The remaining pages of this thesis propose a design example that takes all of

the components of this theory and places them in a physical prototype as a possibility to illustrate a piece of the concept. The prototype is an autonomous respiring assembly that is embedded in situ within the built environment to modulate and respond to the components of ventilation.

This shift from passive to receptive skins, elevates the medium of the responsive environments from a machine-systems model to a ***material-systems model***.

# **Part III**

## *Design Example*

## *Chapter 5: The Respiring Skin*

In order to test the framework of the receptive skin, this thesis proposes a built design exercise, where the details of the investigation will be outlined in the following pages. The project emerges as an attempt to understand the envelope as an integrated active material assembly, that is built for a specific site, with a specific purpose in mind, in order to drive its design. These sections will be divided into parts of the investigation, in order to encompass the totality of scales that need to be addressed in order to answer some of the unresolved questions that arise about the experience of this new kind of building interface and relationship.

This project aims to demonstrate the integration of responsiveness with building skins that are receptive to human and environmental inputs. The research navigates through scale and medium, in order to thoroughly examine this new design space. Each of these sections will describe in detail the design process to address the question, the prototypes built to test the options, and the rationalization for the final decision and the final manifestation of the completed panel.

Through the development of this working prototype, this chapter represents how dynamic material integration could present itself as an opportunity for exploration of the performative building skin, through non-mechanic or digital means, but pure material. Beyond the 'proof of concept,' the prototype is treated as a pilot experiment for the demonstration of 'receptive skins' as a new design methodology which unites material intelligence and material performance with sensory capabilities, as a new way to approach the question of responsive environments.

## 5.1 *The New Material Model*

### **material-systems model**

In order to build a *receptive skin*, it is important to understand the transition from a machine-system to a material-system. In the old manifestation of the responsive environment, sensing, computation and actuation were segregated machine systems—different components were responsible for different parts of the system. But what a material-systems model affords, is the integration of these components into a single material—body, brain and muscle as a single material. The responsive system can now become a “*receptive*” *skin*.

Similarly to the shearing layers of a building, the *receptive skin* is also composed of components with varying layers of time. Below is the breakdown of these components:

**the assembly:** The assembly is the conglomeration of all the materials that define the final skin. This is the unique combination and layering of all the materials that enables the fusion of information. This layer is the one that changes the least because it is the logic of the system.

**the composites:** The composites are individual layers of materials that are made up of several parts. Each layer is designed for a specific function in mind to add to the entire system (similar to the human skin). These materials can be changed after some wear and tear has occurred, but that typically takes a while to occur.

**the global behavior:** The layer of global transformation is the large actuation of the system—the one that achieves the main environmental modulation. This layer changes often, but not rapidly.

**the local behavior:** This is the most rapidly fluctuating layer of the material shearing layers. It is composed of the components that are the most sensitive to fluctuations, and change at the micro-scale. If many local behaviors are transformed, then it can contribute to the transformation of the global behavior.

Receptive skins can now allow for local transformations to occur at the level of the material, instead of having the shearing layers of buildings end at material.

### **the components of receptive skins**

In order to properly use this design exercise to test out the design framework, it is important to establish fundamentals with respect to the foundations of the idea of *receptive skins*. Below are the principles for designing around:

*reversible transformation:* It is extremely important for receptive skins to have reversible transformation because this allows the responsiveness to occur many times, as opposed to occurring only once. With reversible transformation, the actuator finds itself back to its natural state once the trigger has been relieved, and can repeat this action indefinitely.

*inter-material interaction:* The foundation of inter-material interaction stems from the integration between components into a single medium. This allows disparate components within the skin to communicate information across, from one side to the other.

*integration of actuation, computation and sensing:* The premise of receptive skins is to achieve the holy grail of the fusion between actuation, computation and sensing. This allows the systems to be integrated and to communicate in a localized and probabilistic manner, much differently than current digital media.

It is also imperative to understand what the individual components of receptive skins are. Below are the parts of the system, and serve as the structure of the rest of the chapter.

**environmental mediation:** Environmental mediation is the global objective of the responsive environment—it is the part of the environment that the material-system is meant to modulate and affect. This can range across the components that Fitch described in

his previous diagram—the factors of the environment. For example, the goal of the *receptive skin* can be to affect the sonic environment through the action of dampening sound. It can also, for example, mediate the luminous environment through the action of shading.

**the site:** The site is an important component in the design of *receptive skins* because it determines location, environmental factors affected, scale, and form. The site can be a home, an office, a whole building, etc. It is important to define site in order to understand the residual design constraints.

**the system:** The system is the typology of actuation behavior that can result in the desired environmental modulation. For example, shading of the luminous environment can be achieved by modulating transparency and opacity, modulating solid and void or even modulating color. The specific system used, determines the design of the components that make up the resulting material.

**the form:** Form is the global body of the skin—from structure, to fabrication constraints, to global actuation.

**the material:** The material is main material logic that determines the composite, as well as the confluence of all the materials that form the entirety of the experience.

**actuating and sensing components:** Actuating and sensing components are the materials that define the local actuation and sensing. As a collection, they affect the global behavior

**activities and behavior:** The activities of the components define the global behaviors of the skin. This is the confluence of all activities enabled by the material assemblies.

**the interaction:** This layer defines the gradient of possibilities that exist when certain conditions exist in environment and how the material responds.

## 5.2 *The Mediated Environment*

### **environmental mediation**

There is a type of input that is extremely important to this investigation: the status of the environment. In regards to the environment, there are certain components, that make up the totality of experience, and many of those were addressed earlier in Fitch's digram of environmental-building interface. To recap those components they are the thermal, atmospheric, aqueous, luminous and sonic environments. These are essentially the building blocks that make up environmental fluctuations and the pieces that can be understood.

But aside from just the components that could be sensed, are the actuations that can be induced. For example, the act of preventing light is shading, the act of relieving air conditions is ventilation, and the act of softening the sonic environment is called dampening. Each one of these actions affect pieces of the sensed components. In order to design this holistic interaction, there must be a desired environmental mediation that is decided first.

From the earlier exploration of the history of the building envelope, the most instrumental type of environmental modulation that contributed to the current manifestation of the envelope was the action of *ventilation*. Today, the desired state of the building envelope is to "Build Tight" and "Ventilate Right" but ventilation is no longer mediated by the building envelope—but instead dependent on systems such as the HVAC system. Ventilation used to be a behavior that was the responsibility of the building envelope, and with the *receptive skin*, there is the potential to bring it back.

Ventilation is a mediation that is the confluence of many environmental systems—from thermal, to aqueous, to atmospheric, to luminous. It is dependent on the parameters of these systems to determine whether ventilation is necessary or not, so it provides the perfect design constraints in order to pursue this physical prototype. But before diving into the materials, it is important to investigate the *site*.



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## 5.3 The Site

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### envelope intervention

The aim of this design example is to illustrate a novel approach to bring back the responsibility of ventilation to the envelope—a respiring skin. In the ideal state, the skin would manifest itself as an entire surface of a room, or the entire exterior of a building. But in order to explore the conditions of the specific design example, a case study example shall be implemented on the scale of a modular wall panel. The panel provides the opportunity for the intervention to be tested in a series of contexts and conditions, with agility and iteration, all while still possessing the same characteristics of an entire wall surface.

In the City Science Group, we have designed a platform for spatial intervention called the EscPod, and this is where the receptive panel will be tested in situ.

### escpod

The *EscPod* is a reconfigurable spatial laboratory, designed for enabling in-situ research about spaces and human-building interface. This platform is a room that is made up of kinetic and reconfigurable components, which allow the space to be in constant flux. Inside the space there is a vertically actuating bed (that moves from an active to inactive state), a configurable table that changes in height depending on the condition, and an electrochromic glass that changes opacity depending on privacy preferences. But perhaps the most relevant dynamic component of the space is the interchangeable panel system.

Three of the four walls in the *EscPod* are retrofitted with a panel grid, where each panel is individually addressable via a central server. These panels are an infrastructure that is provided for study on wall interfaces. This panel system will be the site for this design investigation on the production of a receptive panel. It allows not only for the physical space to build in, but for the ability to understand the interface in situ.

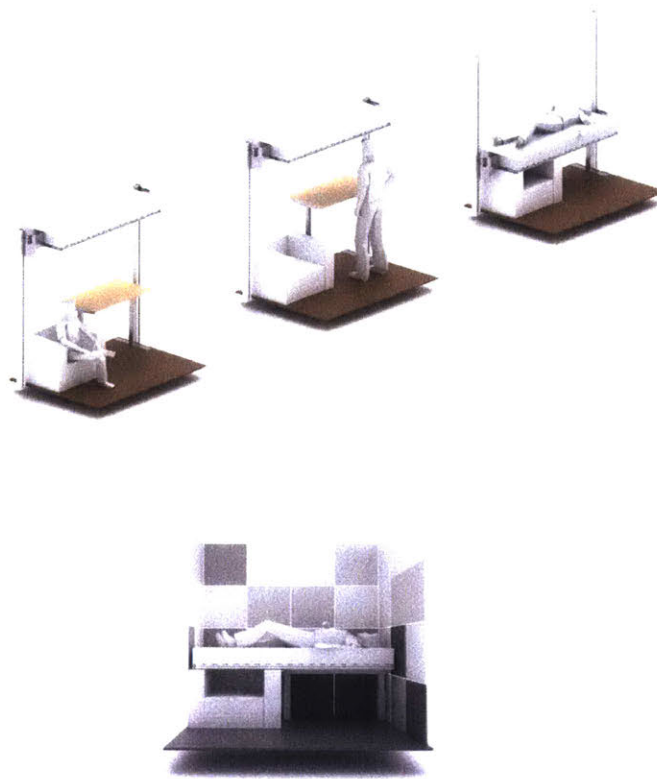


Figure 11. Renderings of the EscPod

### the panel infrastructure

The panel is attached by fasteners into the structure of the *EscPod* and varies in size between 19" x 19" or 19" x 21". The construction of this panel infrastructure stems from a pursuit similar to this thesis, where the wall and the envelope can form a direct relationship with understanding and responding to the body. The panels were originally designed with the idea of surface and skin, and how that continuity can be brought onto the walls of the building.

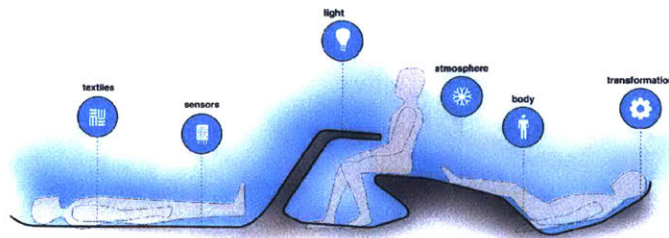


Figure 12. Surface and skin potential

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## 5.4 The Medium

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### **the breathing skin**

The physical prototype built for exploration, taps onto the delicate interface of *ventilation*. The process of ventilation talks about establishing equilibrium between various elements of the environment: *temperature, light and air*. Ventilation is imperative for the livability of a space because it cleans out the used air and allows for the filtering of fresh air. But, ventilation is also necessary when certain environmental factors hit peak threshold for comfort. For example, when the sun shines into a space, and the ambient temperature of that space is already warm (think in spring time or summer), then the sun heats up the ambient temperature to a point that is uncomfortable. At this moment, the instinct of the inhabitant is to open a window or trigger the air conditioning. These actions though, require the human to hit the point of being uncomfortable before they take action. But, can the envelope of the building know when a certain fusion of thresholds have been met, and trigger a physical deformation of the envelope skin to open itself and 'breathe' in fresh air?

Since the thesis is attempting to investigate an integrated sensing and actuating material system, combining the medium of the action with the medium of the sensing could produce a more holistic approach to the problem. Is it possible to utilize the medium of sound to dampen sound, or air to ventilate air? This integration of medium and integration of materiality would allow for there to be an integration of language as well. Can the medium of the sensed also be the medium of the actuated?

### **the respiring skin**

The first investigation that was explored in the design space of a breathing skin, was the understanding of material technique that could encompass this behavior. As seen earlier with *Hygroskin*, there are many material techniques possible to illicit a specific kind of behavior out of a material interface. The first step was to explore the possibilities of techniques and decide on one that was holistic to the medium of the

investigation: air. And examination of the use of air in architecture was the natural conclusion.

The material of air in architecture is often leveraged as a volume. HVAC systems push air through and suck air out of the volume of space, in order to facilitate air conditioning. But air is also often used as a building material. In many of the structures of the 70s, pneumatics were experimented on as possible new manifestations of architectural structure—how the volume of air can cause enough pressure to construct a space. This technique of using the same air that fills a volume as the same air that builds a space, is the kind of material integration that this thesis strives to achieve. So it became apparent that pneumatics and inflatables arose as the inspiration for respiration—a technique to facilitate an autonomous envelope ventilation system.

Since the manifestation of this design prototype is a panel, it was imperative to understand in what ways pneumatics can be used to facilitate ventilation via pure materiality. Having explored the world of soft robotics with a previous collaborative project, “Spatial Flux,” the use of pneumatics as actuator felt very much in line with the physical constraints of this panel and the philosophical foundations of the thesis. So the next step was to explore *air as actuator*.

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## 5.5 *The Material*

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### **respiring assemblies**

There are many possibilities for the expression of inflatable architectures. They are essentially volumes of material expressing the deformation of a material by air. But the ways in which this action can be facilitated through material is quite varied. Below are examples of ones that were tested for this thesis:

#### *balloon and valve technique*

This technique essentially relies on pre-formed latex balloons, and a network of valves to push air through the volume and inflate.

### *multi-material fabric assembly*

The fabrication of multi-material assemblies are dependent on the confluence of many layers of material to produce form and deform on inflation. The layers consist of fabric, TPU, and wax paper. Form is determined by the design of a non-stick layer, where the rest of the materials are heat-pressed around. This assembly allows for rapid form generation, since the layers are just laser cut and assembled, but it does not allow for the materials themselves to be intervened on.



### *bio-plastic assembly*

Bio-plastics are materials that are composed of organic or biological material. In this case, the bio-plastic was made from a combination of gelatin and glycerin, and molded into place. Although the curing time of this method was quick, and it allowed for a lot of flexibility in generating unique composite materials. The largest problems with the use of bio-plastic is its lack of flexibility with regards to inflation, and that its food based nature makes it emit bad odor, and be susceptible to molding after a few days.



### *silicone composite assembly*

This material fabrication technique was the most successful for the context of the project and for the versatility needed to achieve the vision. The silicone proved to be the stretchiest of the assemblies, and provided appropriate durability and the elasticity of material, and also provided the ability to produce a custom composite, and could be programmed through pure material techniques.



Many of these techniques were adapted from work that has been done previously on soft robotics and on a previous project in collaboration with Carson Smuts called, "Spatial Flux". These assemblies have been proven to work, and allowed for enough of a solid foundation to build new ideas and techniques off of, especially in the realms of the *composite, the form and the behavior*. At its basic form, the final assembly of the pneumatic consists of a top layer that is made of soft silicone, a spine that is molded into the soft top layer as air chambers, and a bottom layer that is made of a stiffer silicone. Below is the discussion of the fabrication.

### **fabrication**

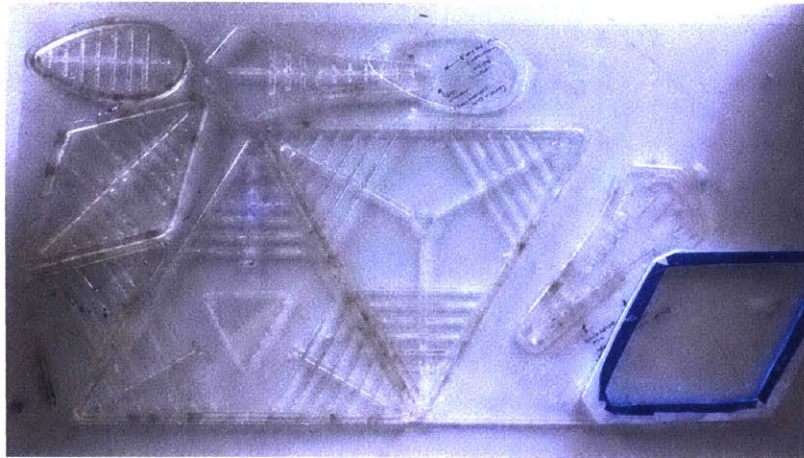
As expressed earlier, many of the techniques for fabricating these soft pneumatics have emerged from a wealth of knowledge accumulated from both the recent experiments in soft robotics, and through the iterative process in designing "Spatial Flux." The fabrication is relatively simple at the macro level, but there are many nuanced variables that affect great change onto the behavior and form of the final mold. These techniques fall under the umbrella of programmable materiality,



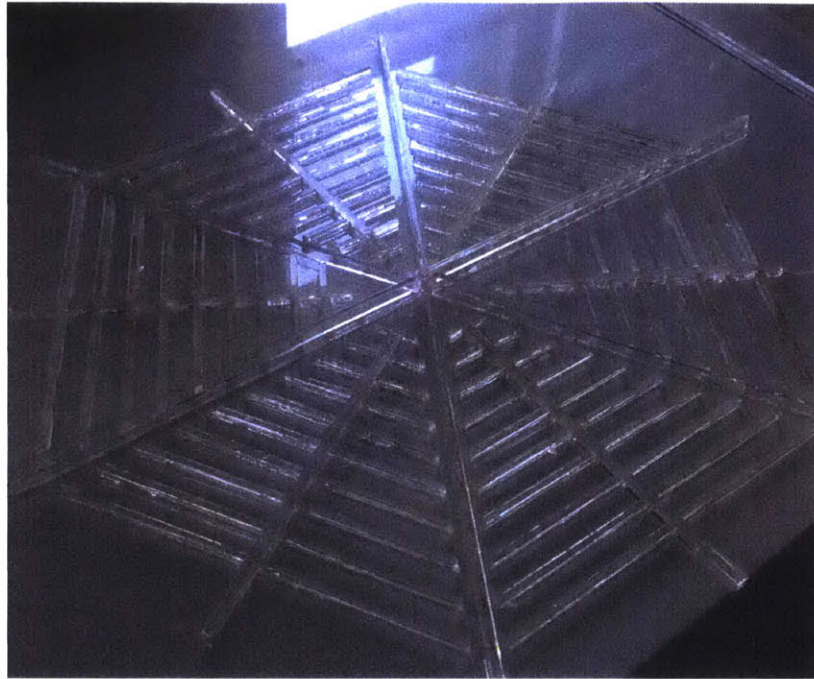
wherein the fabrication of a material allows for programmable behavior in the final resulting object. The three parts worth noting in the fabrication technique of this pneumatic are the *construction of the mold, the design of the spine, and the pour sequence.*

#### *the mold*

The mold can be built in many ways, from CNC milling (carving) to 3D printing (depositing) to laser cutting (stacking). The technique that was chosen to be the quickest and most flexible for this experimentation was to laser cut layers of plexi glass, and assemble the sheets into the final 3D mold. This proved to be the most efficient way of working with the prototyping process because it allowed for faster feedback and reconstruction of iterations (3D printing and CNC milling took too long and used a lot more material). The way this mold was constructed was that there was a continuous bottom layer which served as the bottom of the mold, laser cuts of the exterior geometry and laser cuts of the interior spine.



There were separate molds for the construction of the bottom, stiffer layer, and the top flexible layer. These two components had to be poured separately because the spine need to "float" on top of the bottom layer. The pour of the bottom layer should be a bit larger than the boundary of the top, in order for the process of lamination to fully fill the edges properly. In the current iteration, the mold for the top layer is 3/16" tall, the bottom later is 1/8" tall and the spine is 1/8" tall.



*the spine iteration*

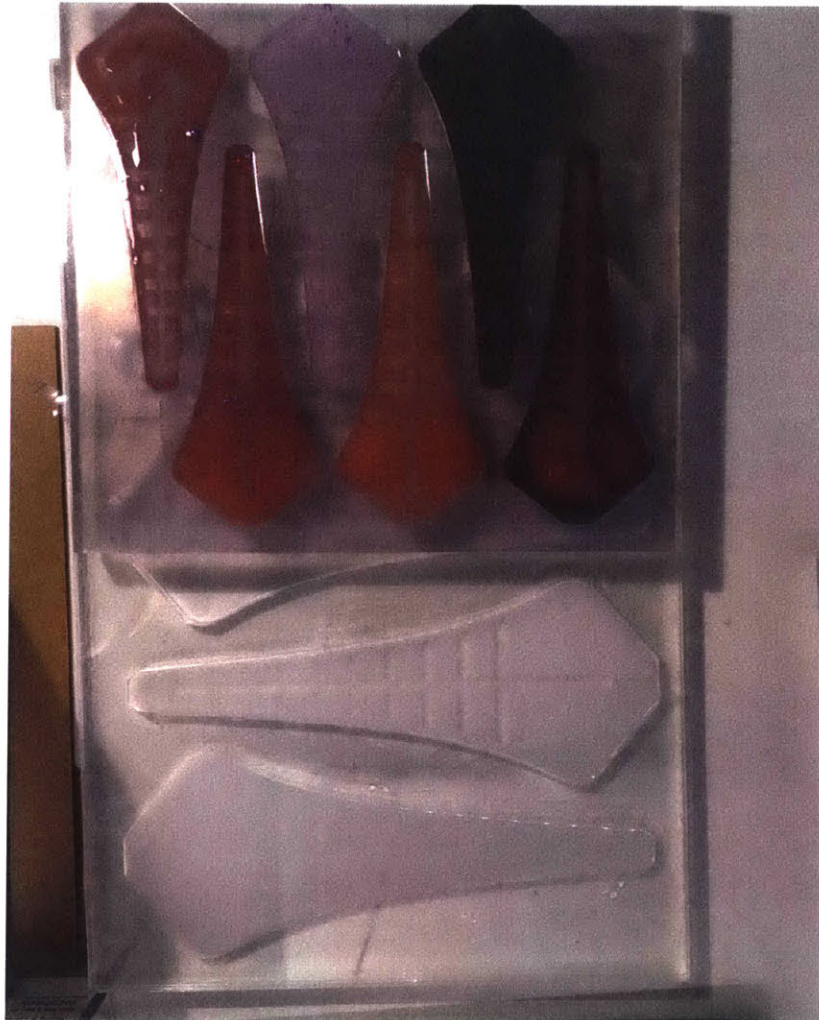
The spine iteration was an instrumental part of making the final prototype work properly. Because the outer boundary of the module doesn't have a direct effect on the behavior of the pneumatic, it was imperative to have removable spines in the mold so that the construction of a new spine didn't mean the construction of an entirely new mold.

One more fabrication process that utilized the spine was the construction of a composite for the use of liquid and solid material to produce reaction within the chambers after inflation. This will be discussed further on in this chapter, but for the insertion of material other than air into the chamber a separate spine mold needed to be constructed. This mold had the material poured into, and frozen so that it was solid for pouring.



*the pour sequence*

The final important component to consider for fabrication of this system was the sequence of pouring and assembly. Since the top and bottom pieces are casted with different kinds of silicone, curing time was an issue. The stiffer bottom piece took many more hours to cure than the fast curing EcoFlex 00-30 (at 5 hours). This meant that it was possible to cast them at the same time, and then “glue” with a layer of silicone the top piece to the bottom piece while it was still curing (but not fully wet). This allowed the two pieces to fuse together into one module.



### **the form**

At the same time that experiments in understanding the composite and fabrication were occurring, there needed to be experimentation on form, especially at the scale of the pneumatic unit, and at the scale of the panel. The design of the unit needed to be designed with the understanding of the final assembly as well, in order to design for inflation, connection, and total behavior.

### *the spine*

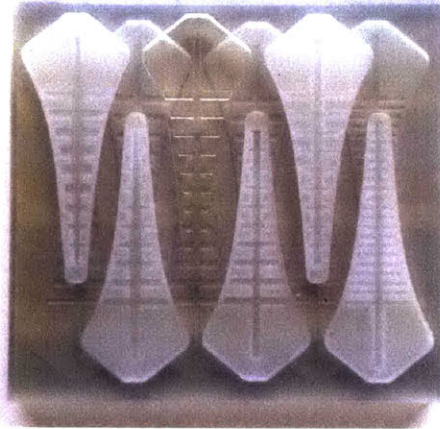
The first mode of experimentation in regards to formal generation, was the designing of the spine. Many of the lessons correlating geometry with curvature came from the iterative process we engaged in during the construction of "Spatial Flux," but they were built upon and tweaked for this new iteration of the silicone pneumatic. The spine is essentially the pattern of the molded air chambers, and the shape of these chambers directly affects the curvature of the pneumatic actuation. Below are some of the lessons learned from iterating on spine geometries:

*spacing between chambers:* This characteristic was perhaps the most influential in defining the curvature of the pneumatic. The closer the chambers were to one another, the more the tighter the curve, and the further apart they were, the wider the curve. This was especially important in understanding curvature in relation to the final inflated form, and the gradient in between.

*width of chambers:* The width of the chambers also had an effect of curvature. The chambers acted like hinges, so the larger the hinge, the larger the curvature of that hinge. Also, the larger the chambers were, the larger the resulting bubble was. If the width was small, the piece curled, but without the bulge.

*width between spine and edge:* This was a component that wasn't originally realized to be a parameter, but through more experimentation proved itself to be. The more material there is between the edge of the chamber and the edge of the piece, more likely it is to flex flat.

*width of the central chamber.* This parameter was perhaps the final one to be tweaked correctly. Originally, there wasn't much experimentation on the variance of the central spine, but then it was realized that if the spine itself was wide, that it itself would also inflate instead of just acting like a vehicle for the chambers. So in the final iterations it shrunk.

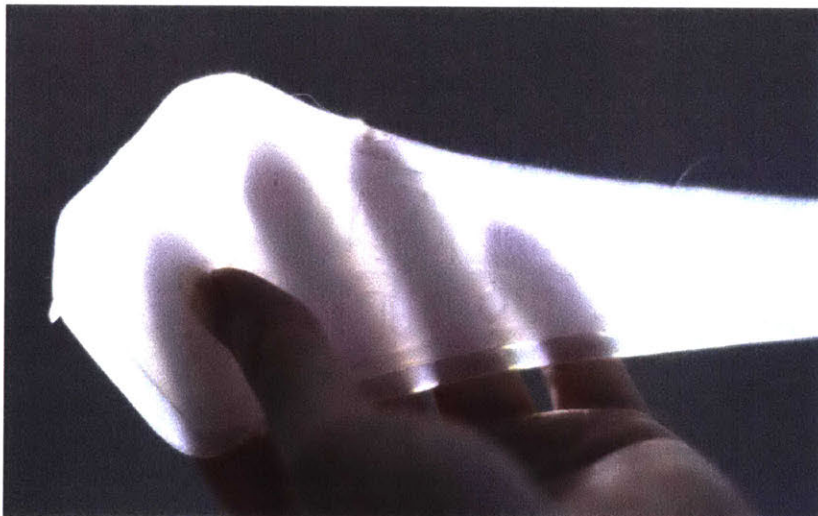
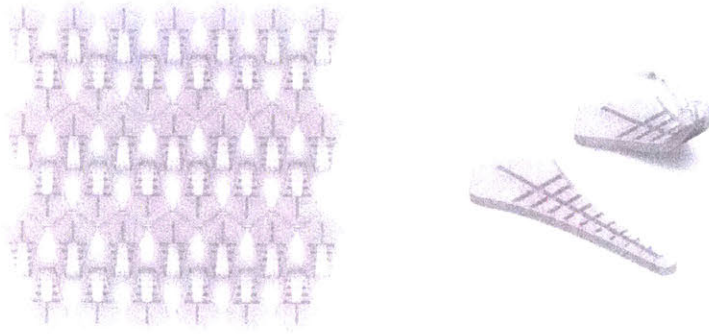


*geometric form (unit)*

There were five iterations of unit forms that were attempted for this prototype before the final one was decided. Below is the summary of this experimentation

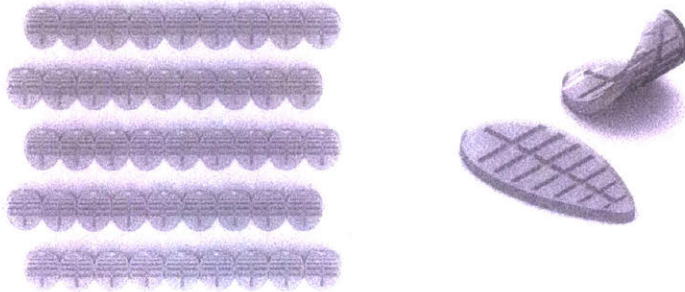
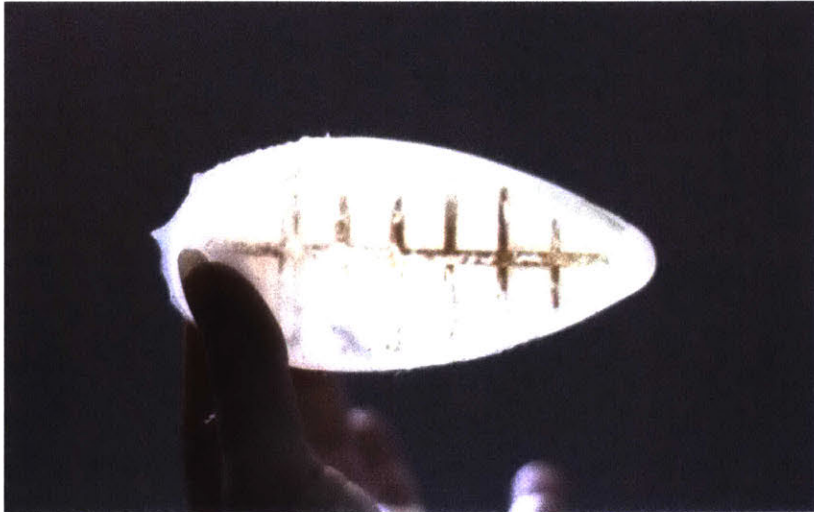
*the arm (unit):* This form was borrowed as a starting point from the "Spatial Flux" project in order to understand the potential that further geometric tweaks would have. The arm was wide at the top and exponentially became slender, in order to keep the insertion point stiffer, and the inflation chambers actuated. This arm was designed to be fastened at the base, and would curl up to reveal the void.

*the arm (assembly):* The ways in which the unit of the arm propagated into the larger assembly was similar to petals of a flower. This assembly was designed to have staggered, overlapping layers of the module in order to allow for staggered voids to open. Ultimately this assembly and unit were not chosen because there was not enough uniformity in the form, and the slenderness of the base did not allow for control.



*the petal (unit)*: The design of the petal was a direct evolution from the arm prototype, as an attempt to have a more consistent formal expression, and one that was more familiar to textures found in nature. The petal's connection point was also at the top, near the air insertion point, with the intention that the fixed point would be above the inflation module.

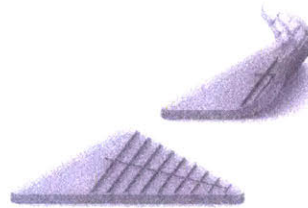
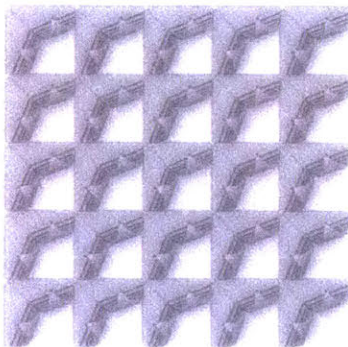
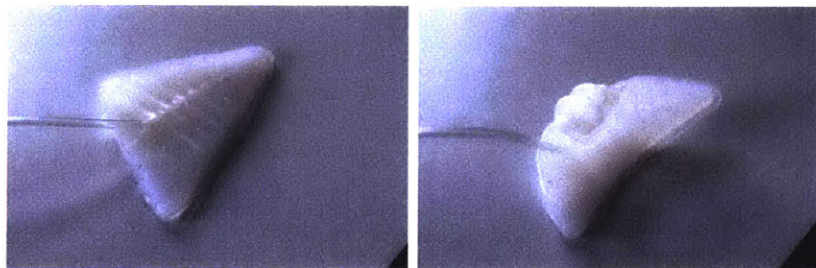
*the petal (assembly)*: The assembly derived its structure from the from the patterns found in bird feathers and butterflies. Macro images of these skins show a staggered assembly of overlapping modules that vary in a gradient of color over the flesh. Although this assembly proved to be visually engaging, it didn't functionally allow for large enough openings to allow for productive ventilation after the actuation.





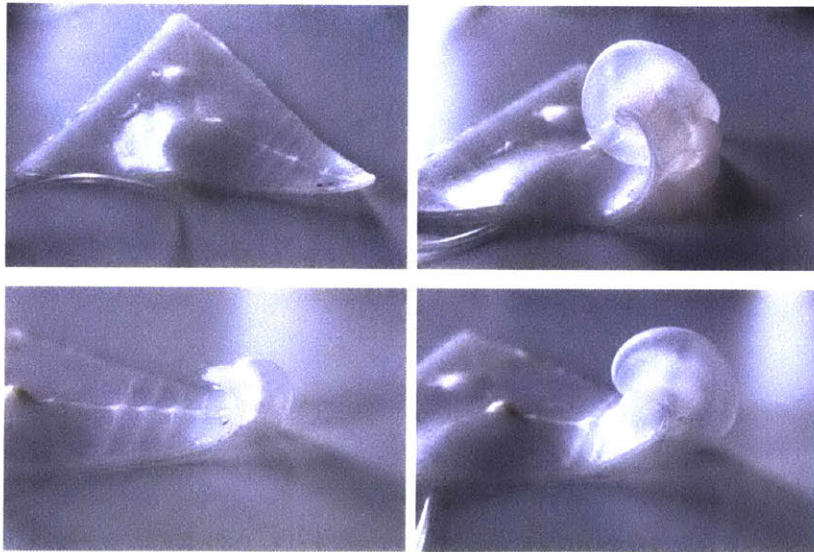
*the triangle (unit)*: This unit was an evolution of the petal, as an attempt to test out a new kind of opening—one that would curl at an angle as opposed to straight up. The intention of this unit was to allow for units that didn't need to overlap, but could "peek" open when actuated, and then close in a flush manner. The module was designed as a right angle, with the location of the spine parallel to the bottom. This would cause the piece to inflate at an angle rather than straight up.

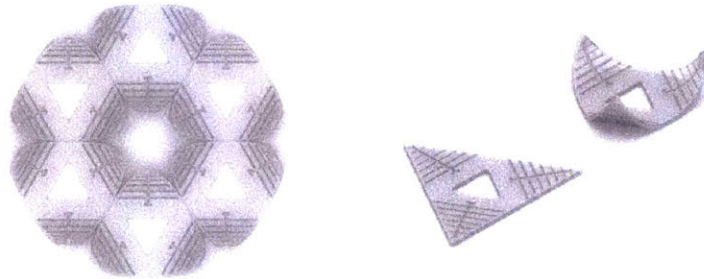
*the triangle (assembly)*: The resulting assembly from the triangle was difficult to resolve because it required a different understanding of pinned location vs. inflated part. The resulting assembly didn't prove to allow for enough openings to satisfy the intention of ventilation so it wasn't adopted.



*the triple triangle (unit):* The previous unit of the singular triangle didn't work as a unit, so there was an attempt to rethink the fixation point, in order to generate a new triangular unit—and that was where the resulting module emerged from. This new module was designed around a fixed point in the center, with a three-pronged pneumatic appendage around it. There were two tests: one to understand how the units could have one source of air, and another looking at the possibility of them having three input points. The triangle was designed differently than the previous unit and curled straight.

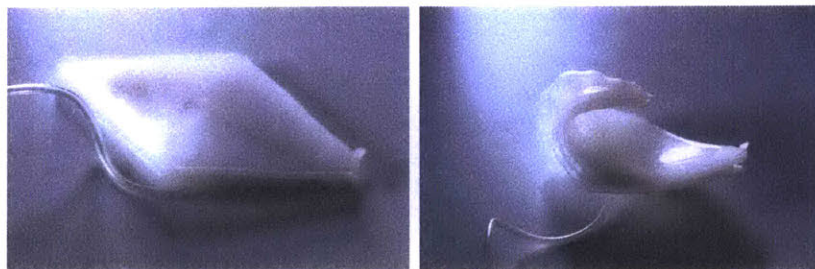
*the triple triangle (assembly):* The assembly of this new unit proved to be a bit difficult to design because the resulting module ended up quite large. The unit couldn't shrink because it has the constraints of the spine and any smaller would make it non-functioning. Because the panel in the EscPod had preset measurements, it was one of the immovable design constraints to stay within this boundary. The modules ended up taking too much space, with not enough openings for ventilation. Therefore, as much as this unit behaved beautifully, it was one of the least successful assemblies.



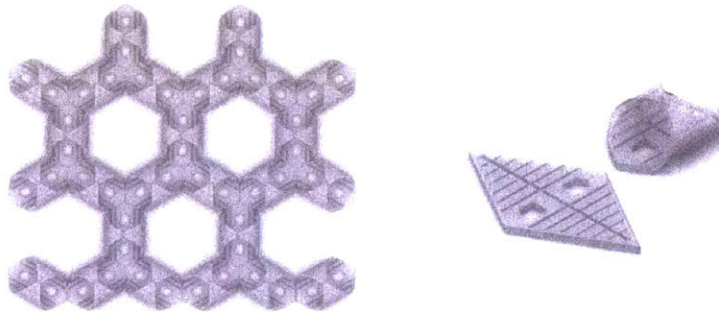
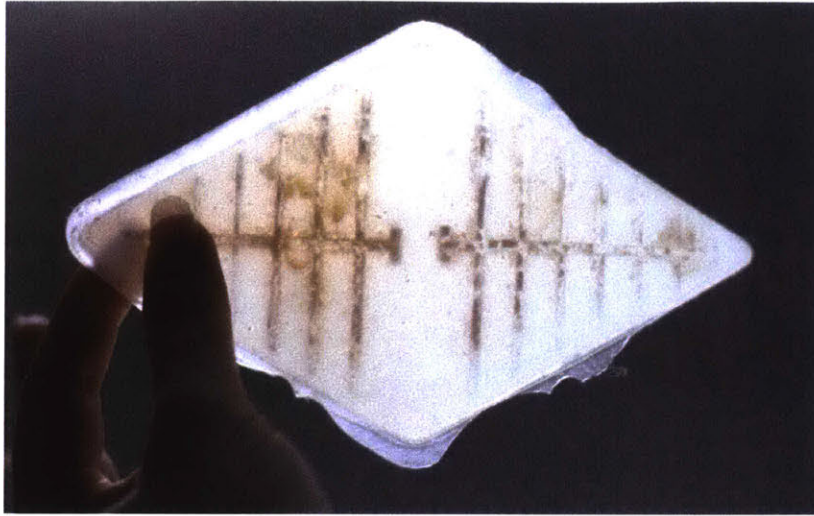


*the diamond (unit)*: This iteration of geometry was the near-final one—a diamond shaped unit. This unit was modified for the final prototype, but was the seed from which the final iteration evolved. The way this unit was designed, was essentially operating as two triangle modules synthesized into one diamond shaped assembly. The fixation points were also at the center, and the unit inflated from flat to curled on both sides. This module was the most successful confluence of size, shape and assembly.

*the diamond (assembly)*: The original assembly of this unit looked towards having the diamonds arranged radially, in order for large apertures to open when the inflation was active. This assembly had smaller diamond shaped units that inflated on both sides to trigger these openings. The designer, not the assembly, made this decision.







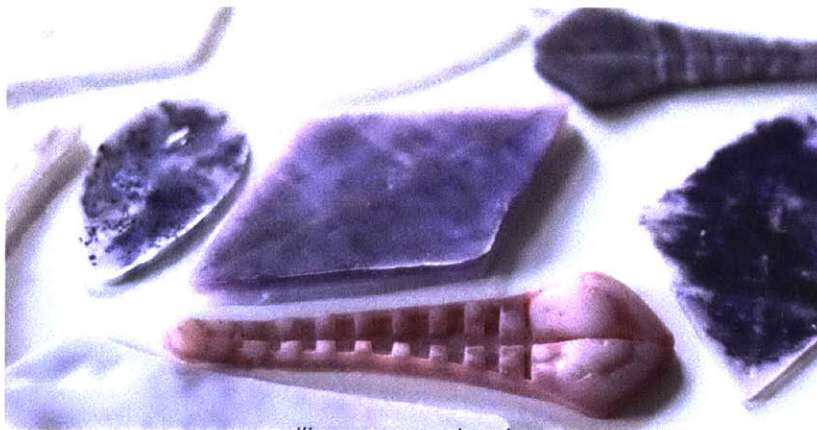
*the final half diamond (unit):* The half-diamond unit derived itself from the full diamond iteration. It is a larger scaled version of its former self, and instead of being fixated at a point, it molds itself into the surrounding structural silicone and seamlessly inflates just the part that needs to be inflated.

*the final half diamond (assembly):* The final prototype assembly that resulted was an adaptation of the original diamond assembly. Essentially, it is a single aperture that is scaled up from the original model, with the half-diamond unit still arranged radially. This assembly

was chosen because in the end, it was the one that worked best as a panel, and that most resembled a novel kind of window.

### **the composite**

Because receptive skins are to have pure material techniques for engaging with actuation and sensing, it was important to design the right composite to encompass all the necessary behaviors in the material. The creation of a composite was similar to cooking—there was a base material (the silicone) and a series of other 'ingredients' to be mixed within it in order to create the final composite. The most important elements of this experimentation were, the silicone superstructure, the ingredients, the combinations of those, and their ratios.



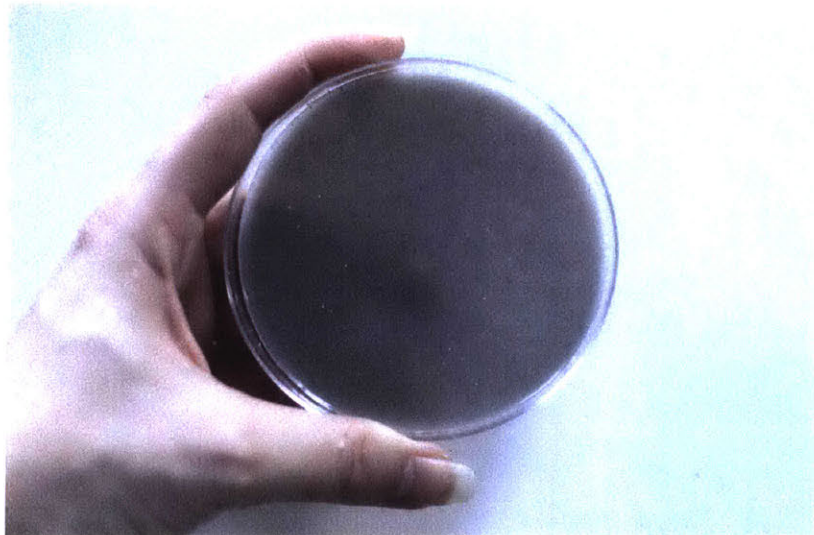
*silicone superstructure*

In order to produce a soft-pneumatic prototype, it was imperative to understand the relationship between the rigid elements (structure), and the soft elements (actuator) and what their ratios and relationships were. The soft silicone (Ecoflex 00-30) was combined with a more rigid and dense silicone (DragonSkin 10) in order to allow for a more controlled bend upon inflation. The two parts were fused together in order to allow for integrity of material assembly, and their operation was contingent on the ratios between the amount of soft material and the amount of hard.

### *inert ingredients*

In order to understand the manifestation of materiality, it was important to not only assume that the panel would manifest itself as just silicone, but could also in theory be combined with other textures and materials to produce a different aesthetic and tactile effect. For this reason there was intense experimentation on possible inert material combinations to produce a different kind of material. Below are some of the examples of materials used and their effects:

**silicone + concrete:** Concrete is also a poured and mixed material so in terms of fabrication techniques, was interesting to combine with silicone, another mixed material. Two techniques that were used were homogeneous mixing, heterogeneous mixing. In the homogeneous pour, the concrete material was mixed directly into the silicone and mixed thoroughly in order to create a more consistent texture. What resulted was a flexible, gray and textured composite that felt more like rough, dark silicone. The heterogeneous technique involved pouring the silicone first, and then pouring drops of concrete dispersed around the pour after mixing it separately. Because of the weight difference, the concrete immediately sunk to the bottom of the dish, and attached itself there. When the mold had cured, it was quite difficult to take out the concrete because of its inflexibility, it would crack as it flexed.





**silicone + dyes:** In order to understand the reaction between the silicone and different kinds of dyes, various dyes were mixed with the silicone. In one condition, a water based dye was dropped into already poured silicone. This produced voids in the material upon curing, because the silicone and the dye didn't mix, but when the dye was mixed in with the silicone more evenly, it produced a translucent color. Powder pigments mixed more seamlessly with the base, and could either be more concentrated or more evenly distributed. They produced an opaque color that was either eventually distributed across the material or in a cluster.



**stiff silicone + soft silicone:** In order to understand what the effect of two kinds of silicone would be onto one another, Ecoflex 00-30 and DragonSkin 10 were poured into one another in uneven distributions. The resulting effect produced a silicone that had deformations from shrinking, and a resulting uneven surface.



*reactive ingredients*

As well as experimentation with materiality and tactility, the poured nature of silicone also allows for testing of materials with reactive qualities. These reactive ingredients allow the silicone to take on different behavioral qualities, just through the “flesh” of the material itself, which also allows it to detect certain conditions. This composite direction was influenced by the skins of the octopus and the chameleon—skins that react to stimuli external to the body.

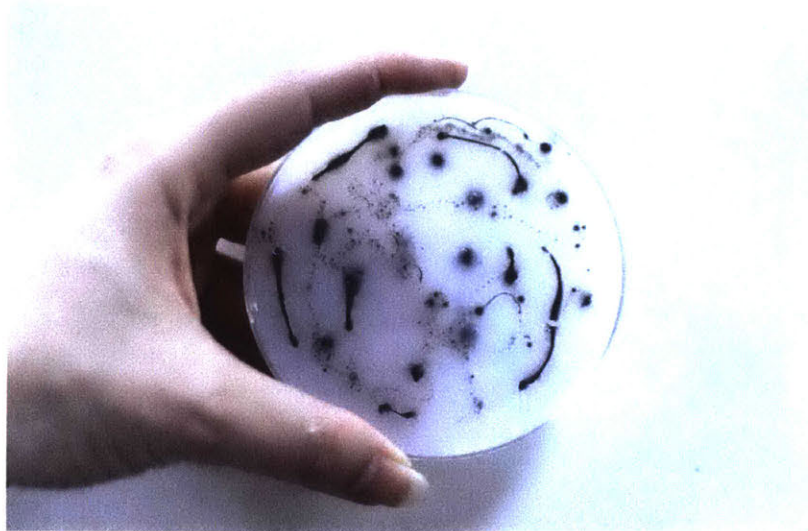
**silicone + liquid crystal:** Liquid crystal is a substance that acts like a liquid but possesses reactive properties to thermal conditions, and thus constantly reorients its molecules around this sensitivity. This reorientation produces a swath of color gradients that change depending on temperature. Liquid crystal was mixed with the pour in the anticipation that the silicone would take on these properties, but that proved to be false. Since the liquid crystal acts like a liquid, it needs to be suspended in a condition where it has room to adjust, and the curing of the silicone made too stiff environment for it to orient its molecules so it didn't shift color.

**iron filings:** Iron filings were mixed into silicone with the anticipation that it could take on magnetic properties. Since iron filings are highly susceptible to being attracted to magnets, the addition of this ingredient in a silicone composite would give it inert actuating properties, that are only triggered by a magnetic presence. In mixing the iron filings with the silicone, the material took a bit more time to cure, but when it finally did, and a magnet was held up against it, it deformed at that point and moved towards the magnet. The magnetic strength of this composite however, was quite weak, so the adjustment of ratios would perhaps allow for a much stronger magnetic response.



**conductive paint:** With the intention to remove all electronic elements from the responsive material, conductive paint as a possible transition phase from wires to material was imminent. Silicone was poured into the dish, and then magnetic paint (Bare Conductive) was then placed in strategic strings across the material. After curing, the composite took on conductive qualities, and was able to run current through it. The paint mixed quite well with the silicone.





**photochromic pigments:** Because the panel would be situated as the envelope of the building, it was important to test the potential for photochromic pigments, especially since the reception of the sun was a major element in this mediation. Photochromic pigments have unique responses to UV light (as comes from direct sunlight) and they can be programmed to have specific conversions, colors, and reactions. Typically, photochromic pigments transition from clear (or white) to a color when they come in contact with the sun. And this reaction was in line with the ability for the panel to indicate and modulate sunlight. Photochromic pigments of different colors and at different ratios were mixed into the silicone pour in order to understand the desired reaction. The pigments that were darkest in final form, allowed the transition to filter out sunlight and effect that would allow the flesh to have functional reactive properties (blocking out immense sunlight). If too much pigment was mixed though, the resulting cure would be too opaque, and not allow for sunlight to penetrate through.

**hydrochromic pigments:** Similarly to the photochromic pigment, the hydrochromic pigment transitions from clear to color when it comes in contact with water (or the opposite). The possible functional behavior that can stem from this reaction is the potential for the presence of

color to be an interface for indicating whether or not it is raining outside. This would serve as a silent visual interface—as a spatial notification. The hydrochromic pigment reacted similarly to the photochromic, in that it would change color immediately when in contact with water. For this reason, unlike the photochromic which would be homogeneous and evenly distributed, since the hydrochromic would be more of a notification, it made sense for its manifestation to be localized to a non obstructive pattern on the material.

**phosphorescent pigments:** Phosphorescent pigments are essentially materials that absorb sunlight, and emit it when it is dark —glow in the dark pigment. This can allow the absorption of sunlight for later use.





**thermochromic pigments:** The final reactive material that was used in these experiments, and the one that found itself as the predominant reactive medium for the flesh was the thermochromic pigment. Thermochromic pigments act similarly to photochromic and hydrochromic—as color transitioning reactions—but they react to temperature. The pigments used in this experiment either transitioned from color to clear as the higher threshold was reached, or from one color to another color. The uniqueness of thermochromic pigments as well, is that they can be tweaked to react to different temperature thresholds. For example, the ones used for this experiment phase changed at 68 °C, 72 °F, 85 °C and 90 °C. The variation in transition point allowed the pigments not only to react differently to ambient temperatures, but it also allowed for the opportunity to start to pair different phase points together in order to indicate the range of temperature that is currently present. For example, a 72 °F pigment that is mixed with an 85 °F pigment can allow the human to know that their space is above 72 °F when the color of that pigment is clear, but still below 85 °F when that secondary color is still present. This combining of behaviors prove to be a successful visual interface for encoding thermal information within the flesh of the panel in order to demonstrate the triggers for ventilation.



## 5.6 The Behavior

### the conditions

In order to be able to design behavior, two things needed to be considered—the typology of reaction, and the components necessary to build that reaction. So essentially, there needed to be a fusion of knowledge from the iterative experiments, with a synthesis of the components that are needed to evoke that. These behavioral conditions are divided into *mediating materials*, *visual cues of environmental information*, *shape-changing actuation*.

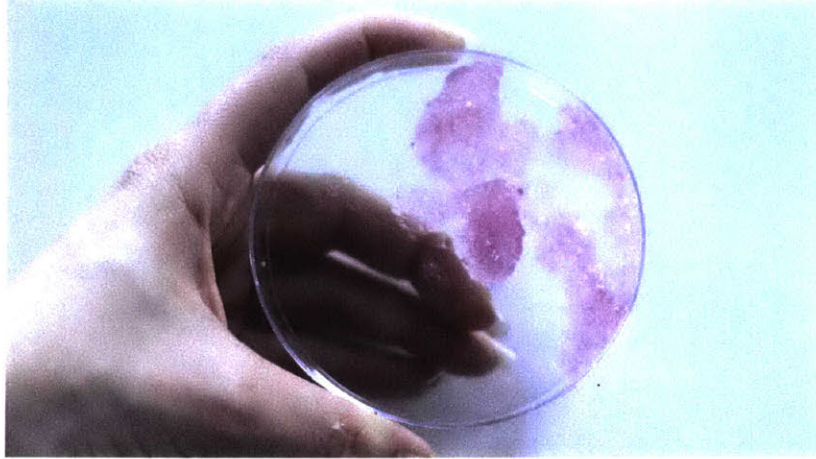
### mediating materials

The experiments conducted with these materials are done with the intention for these materials to be used in isolation within a secondary chamber of the pneumatic, but still contributing to the holistic effect of the medium. They are materials that produce a sensory effect rather than just a visual one.



*aqueous*

**hydrogel:** Hydrogel is a material that is hyper absorbent and can absorb much more water than its body weight. It is the predominant material used in diapers. In the case of environmental modulation, hydrogel has the ability to absorb water from the aqueous environment to relieve humidity, or it can behave in the opposite manner, and absorb water in order to release it slowly into the air. Also, because hydrogel has the ability to increase so greatly in size, it can be used as an actuator during the rain.



*luminous*

**bioluminescent dinoflagellates:** Bioluminescent algae are a living material that reacts to circadian rhythms of day and night to produce a glow at night when the material is shaken or hit. The bacteria have bioluminescent capabilities and can be passively inserted into the pneumatic in their own chamber, to enable a tactile light reaction via the striking of the panel at night. This luminous reaction does not require any electricity to occur—only the inner workings of the algae's natural state.

*thermal*

**sodium acetate supersaturated solution:** The final experiment with mediating materials to infuse into the panel was the heating capabilities of a super-saturated solution of sodium acetate. Found in reusable heating pads, this solution consists of a supersaturated liquid of sodium acetate, that gets triggered into a solid when the liquid is disturbed. The reaction emits heat for a few minutes while it transitions from liquid to solid, and it reversible if headed up to a high temperature (as is possible with direct sunlight). This material was thought to be used as a localized heating source to emit heat when the user needs it.



### **visual cues**

Just as with digital interfaces, visual cues are necessary to understand conditions. This feedback doesn't need to be attention seeking, but on the contrary, can be manifested as a calm interface, and exist in the periphery for reference when needed. The city dweller doesn't notice the sounds of the traffic outside, but processes the loudness or softness ambiently. Through the experiments with the material composite, it was realized that the variety of pigments allowed the flesh of the wall to receive information about their environmental condition through the visual feedback by the pigments. Below are some examples.

### *aqueous*

By mixing in hydrochromic pigments into the silicone substrate, the material can start to indicate to the dweller when it is raining outside through the presence of color, or lack of color in a pattern on the panel. This feedback can allow them to understand the external aqueous conditions.

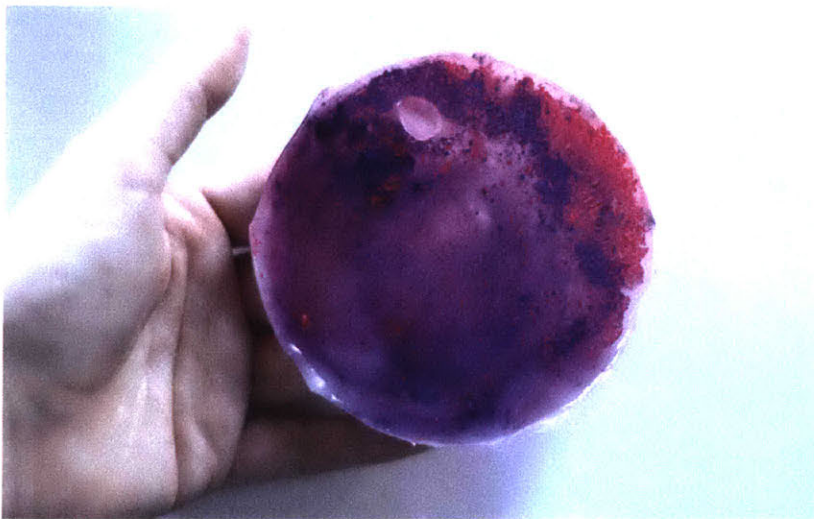
### *luminous*

If phosphorescent pigments were added to the material substrate, then they could grab sunlight, and emit it when it is night for functional use as a light source. This behavior is less of a visual cue about a specific condition, and more of a trace of one.



*thermal*

The thermal condition is the one that ended up filtering itself into the final manifestation of the prototype. This is because the thermal condition is important in the host of elements responsible to trigger ventilation. And the most interesting part of the thermochromic pigment as medium is the ability to be able to mix in pigments that have different phase transition temperatures, in order to understand the zone in which the current temperature is in. Not only can this medium allow for the visualization of temperature, but it can also give feedback about the moment in which the pneumatic is about to trigger, if the highest temperature threshold of the pigment is in line with the trigger temperature of the pneumatic. Essentially what this means is that the entire panel can go clear right before the pneumatic actuation occurs, and the iris is opened.

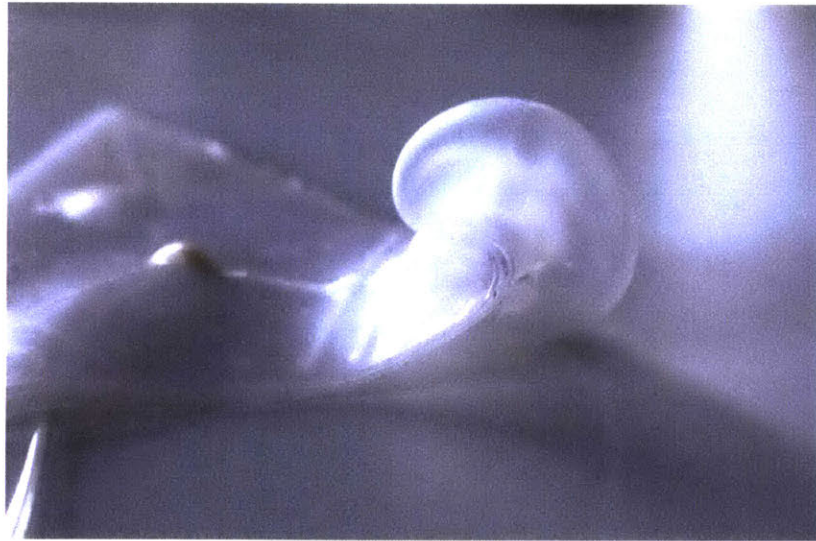


**shape changing actuation**

The second element that is important for the design of the panel's behavior is the design of the air actuation. Typically the source for pneumatic actuation resides in a mechanical actuation. For the purpose of this thesis though, it was important to understand this baseline way to actuate, in order to attempt to find novel ways of actuating with air that are pure material in their foundation. Below are the experiments that had been completed for this thesis.

*mechanical source*

Mechanical actuation of pneumatics requires a few specific elements: pumps, valves, processor, tubes and sometimes a pressure sensor. The combination of all these elements allows for the digital communication of information that leads to triggering the pump, and allowing the valve to direct the air appropriately. Because soft pneumatics are enclosed spaces, it is not only important to have a valve that is bringing the air into the pump, but it is also important to have one that shift air out when the pneumatic is full, in order not to let it pop. The process for designing this system is essentially coding a digital program to communicate to all the components throughout the circuit. This, though works well, possesses the same fundamental flaw that current responsive environments have—lack of integrated elements where the processing is separate from the material and the actuation. So thus, it was imperative to find another solution that was pure material based.



*chemical reaction*

Chemical reactions are interesting ways of bypassing the need for pumps, and head towards self-contained, autonomous pneumatics. There are two ways that chemical reactions can produce air—acid based reactions that produce oxygen, and state changing reactions that go from liquid to gas. For the purpose of this experiment, both were tested

*acid based reaction:* Acid based reactions are ones that release oxygen when two chemicals are combined. In this experiment, a combination of citric acid and sodium bicarbonate was tested. The reaction produced an inflation that allowed for the pneumatic to inflate properly, and with enough pressure, but unfortunately, this reaction was not reversible, so the material stayed within the spine, and the module eventually deflated (from micro air release).

*state change reaction:* After experimenting with the capabilities of acid-based reactions, the conclusion led me to seek out a bidirectional chemical inflation, and phase change was the next step. State change reactions occur when materials reach a certain temperature and pressure ratio, and a new state is approached — from solid to liquid to gas. Solid phases occur at a lower temperature and gaseous ones at a higher (also known as boiling point). To leverage this potential for phase change from liquid to produce gas to inflate the internal chambers, the project turned to low-boiling point liquids. Low-boiling point liquids are liquids that have a much lower boiling point than water (212 °F). In order for them to functionally actuate for ventilation, the state change temperature needs to be low enough that it can operate within high ambient temperatures. In seeking out non-toxic materials, ethyl-alcohol and methylene chloride presented themselves as possible options.

The boiling point of ethyl alcohol is at 171 °F, and methylene chloride is 103.3 °F. These temperatures are a bit too high for lower warm ambient temperatures to have an affect. But, because boiling point is a ratio of temperature and pressure, essentially, a decrease in pressure at the spine (through a partial vacuum) can be implemented to allow for the liquids to boil at a lower room temperature. This was simulated for ethyl alcohol in a syringe and it indeed worked. But, the problem with the utilization of these liquids as actuators is that ethyl alcohol will have to near full vacuum in order to work because it's boiling temperature is already high, and methylene chloride corrodes silicone. So another method was sought out.



*biological reaction*

After experimenting with the possibilities for chemical mediums to trigger gaseous release for inflation, my research took me to the reactions of yeast respiration. As yeast is "awoken" with warm water, and fed sugar, it respire carbon dioxide as a byproduct. As seen in many children science experiments, this respiration has the ability to inflate a balloon over an extended period of time, depending on the ratio between amount of yeast, amount of sugar, and temperature. More yeast produces a faster reaction, as well as higher temperatures and more sugar produces a longer reaction. In testing the injection of yeast, water and sugar in the pneumatic assembly, enough carbon dioxide was built up to enable inflation. This success allowed the project to ask more questions about how to better this reaction, and produce a closed system without the need to keep feeding the yeast.

Since the feeding of the yeast on sugar is the catalyst for the production of gas, the yeast needs to constantly be fed sugar in order for the reaction to occur. If the yeast has sugar, and the temperature is warm enough, then inflation will occur. But, if there is no sugar present, then the yeast will starve, and no gas will be produced. The only solutions



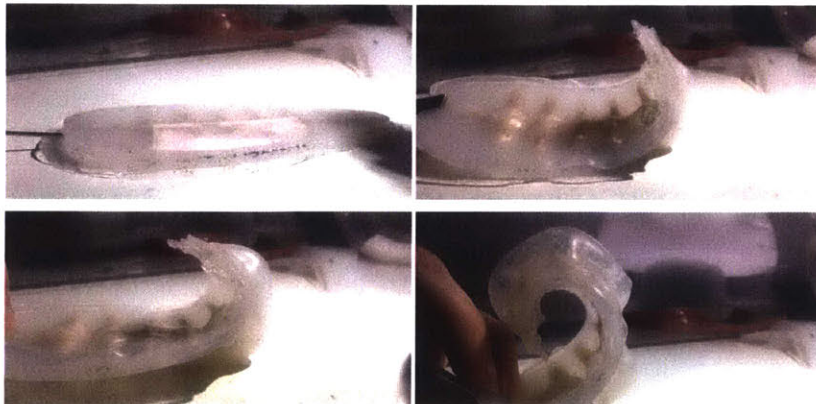
that are present to solve this problem are the creation of a pouch that will constantly be filled with sugar in order to feed the yeast (like the constant watering of a plant, except in this case, it's the feeding of a wall), or to find a solution where the byproducts of the yeast can feed another system that produces sugar. I decided to go with the latter.

After a bit of research, I came to the discovery that algae is an organism that feeds off of sunlight and air in order to produce sugar. And luckily, yeast and algae coexist in nature (with fungi) in symbioses called "lichens." These cultures are some of the most symbiotic in nature, and the organisms coexist off of the other organism's byproduct. This creation of this culture within the pneumatic is the solution for a closed-loop biological actuator that is sensitive to environmental conditions.

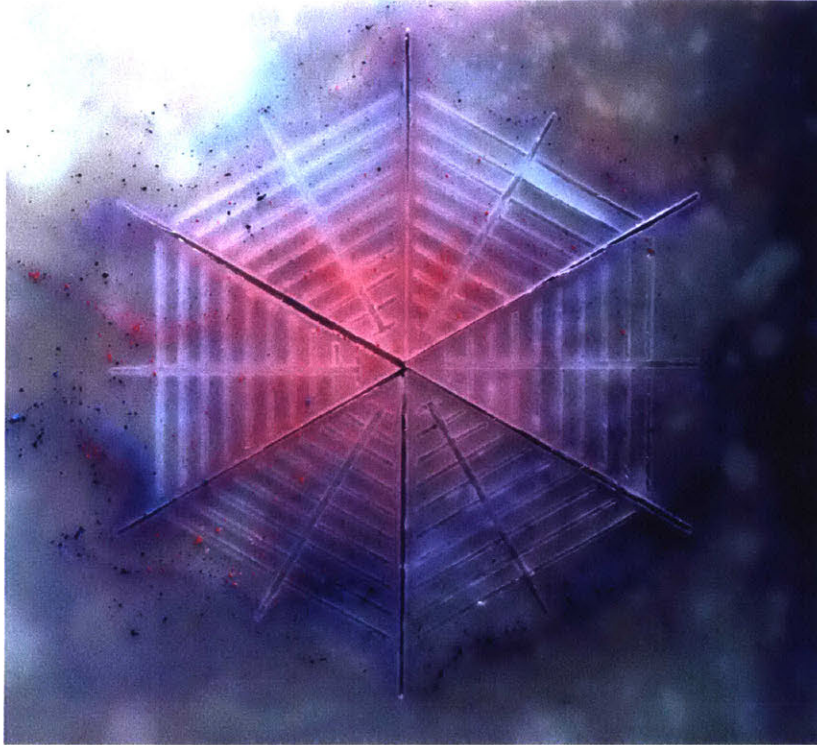
This system is both sensitive and reactive to the right environmental conditions that culminate to form the factors needed to trigger ventilation: heat and sunlight.

*heat:* In order for the yeast to be awoken and trigger the gaseous reaction, the temperature needs to hit a high ambient temperature. This is the same kind of temperature that is necessary in order to provoke discomfort and prompt the action of inducing ventilation.

*sunlight:* Sunlight triggers the photosynthetic reaction in the algae to produce sugar, which inadvertently feeds the yeast.



## 5.7 The Interaction



### **the final respiring panel**

The final manifestation of the final is a composite inflatable that consists of thermochromic, photochromic, and photoluminescent pigments, and is biologically actuated to open during specific environmental conditions via an algae-yeast culture. The culture reacts to heat and sunlight, and produces the by-products necessary to cause the respiration of the yeast, and inflate to open and facilitate ventilation. When all the factors are met, the pigments all go clear, as a visual indication that the panel is about to open.

The panel is both sensate and dynamic, simultaneously understanding and responding to the environment in order to mediate it—all through pure material mediums.

### environmental sensing and modulation

The final full interaction of the panel with respect to environmental sensing, computing, and actuating is as follows: If there is sun present, it will execute photosynthesis in the algae, which will produce sugar for the yeast. Once the air temperature reaches a certain temperature, it will heat up the yeast to trigger it, which will get it to start feeding on the sugar and respire. This respiration will trigger the pneumatic to inflate and lift, triggering ventilation. Below is the diagram and the simulation:

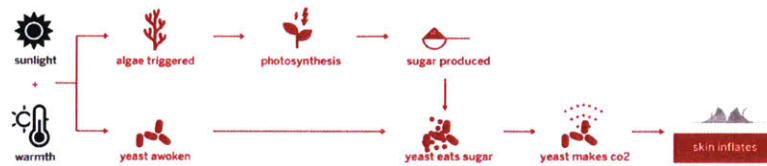


Figure 12. Diagram of material processes

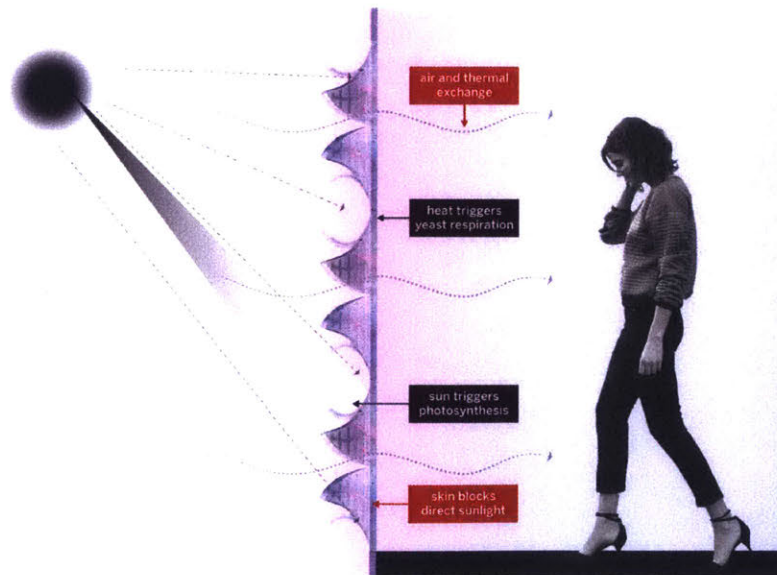


Figure 13. Diagram of triggers and responses



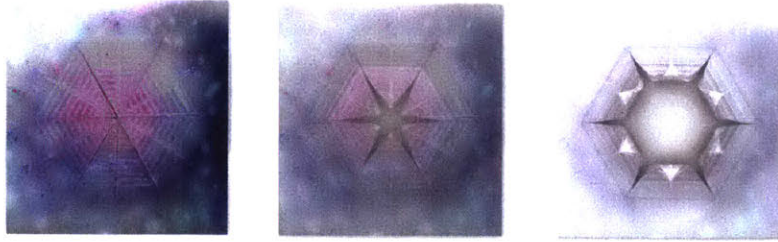


Figure 14. The states of the panel

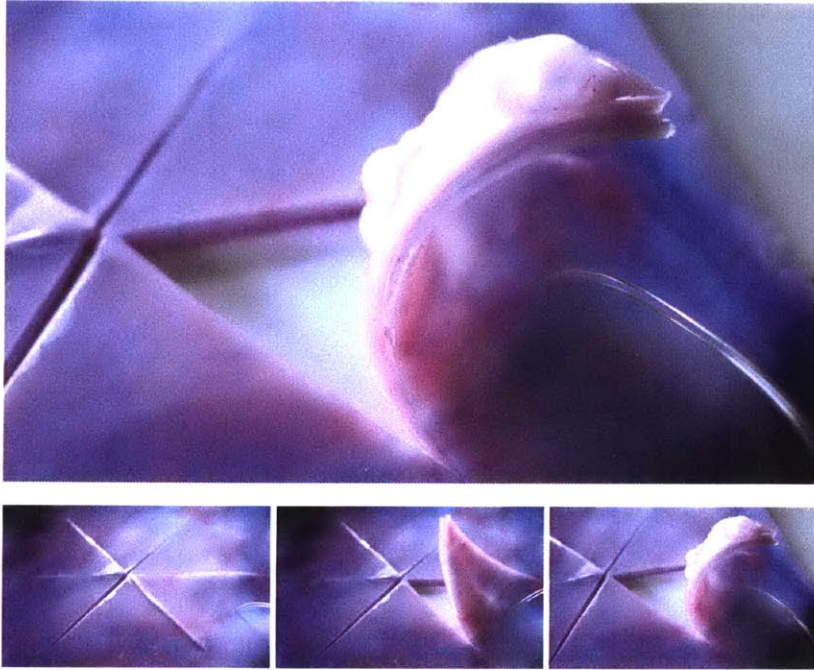


Figure 15. Renderings of the panel in the EscPod

### matrix of fusion possibilities

Because this respiring panel is a fusion of a series of sensing and actuating material elements, it is possible for the user to create their own panel based on the conditions of their preference. The mixing of ratios and tweaking of components creates a similar, but entirely different ratio of triggers such as temperature of curvature of actuation. Below is a table showing the entire spectrum of possible parametric interactions

daytime	high temperature	sunny	----->	open yeast activated algae activated
daytime	high temperature	cloudy	----->	closed yeast activated algae dormant
daytime	low temperature	sunny	----->	closed yeast activated algae active
nighttime	high temperature	dark	----->	closed yeast activated algae dormant
daytime	low temperature	cloudy	----->	closed yeast dormant algae dormant
nighttime	low temperature	dark	----->	closed yeast dormant algae dormant



### 5.8 Concluding Remarks

The result of the built prototype showed how an integrated sensing, computation, and actuation could be designed from a pure material system, and exemplify a parametric behavior from environmental conditions. This allowed for the visualization of an envelope system that could bring it back to being the main environmental modulator, and shift architecture from manufactured to mediated environments. The prototype demonstrated responsiveness to a multitude of environmental conditions to behave in accordance with its material mapping.

This suggests that we may be able to shift our assumptions that buildings should be static entities, and instead start to view them as living, breathing organisms—towards a **somatosensitive** architecture.

## ————— *5.9 Future Directions* —————

The future manifestations of this project have the potential to pull together a library of desired interactions and sensors, fused with possible materials for use in architecture, and present them as a toolkit for parametric materiality. This approach allows for a new kind of design process with architecture: one that starts with the interaction between human, environment, and space. This design prototype focused mostly on the expression of environmental modulation, but there is an entire slew of possibility in the space of human interaction with this skin as well, and the hope is for the future direction to approach that. In allowing this framework to exist as a tool, starting from a kit of material behaviors, rather than a kit of mass-produced materials, allows for an architecture that is not only dynamic, but born. To start from materiality is to start from the relationship between skin and skin.

"Home and skin turn into a single sensation."

-Juhani Pallasmaa<sup>3</sup>

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