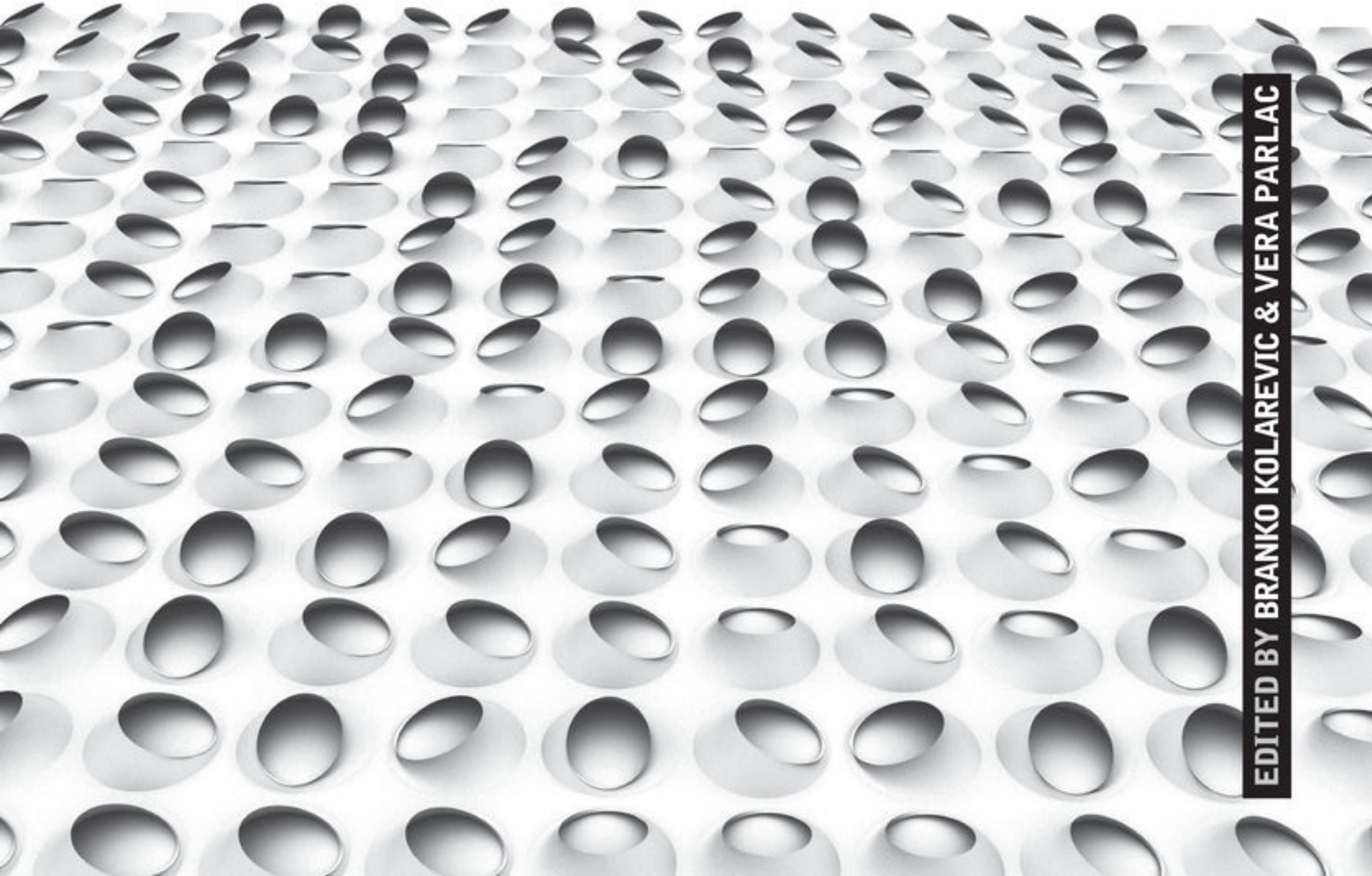
BUILDING DYNAMICS:
EXPLORING ARCHITECTURE OF CHANGE

ROUTLEDGE



EDITED BY BRANKO KOLAREVIC & VERA PARLAC

Building Dynamics: Exploring Architecture of Change

Edited By
Branko Kolarevic & Vera Parlac

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Contents

Acknowledgments

We thank with the deepest gratitude the contributors to this book — their remarkable ideas and innovative, pioneering projects were the main inspiration for this book and the eponymous symposium that preceded it. In April of 2013, we gathered in Banff, in the Canadian Rocky Mountains, to explore over two days what *change* means in architecture and how it is manifested in buildings today. The symposium presentations, enriched by the ensuing discussions and email exchanges, have been further refined and captured in this book. Not all of the authors were able to join us at the symposium, but have kindly agreed to contribute to the book.

The "Building Dynamics: Exploring Architecture of Change" symposium – and the accompanying exhibition of student work and research projects – were organized by the Laboratory for Integrative Design (LID) at the University of Calgary Faculty of Environmental Design (EVDS) and held at the Banff Centre on April 26 and 27, 2013. We are most grateful to the symposium sponsors: Oldcastle BuildingEnvelope, DIRTT, Haworth, and Faculty of Environmental Design at the University of Calgary; without their support, the symposium and this book would not have been possible. Initial formative research was supported by the grants from the University Research Grants Council (URGC) and by funding through the Chair for Integrated Design and Laboratory for Integrative Design (LID) at the University of Calgary.

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Branko Kolarevic and Vera Parlac
Calgary, February 2015

Preface

The book stems from our interest in architecture that can respond dynamically to changes in external and internal environments and different patterns of use. Buildings are increasingly being equipped with sensors, actuators, and controllers, enabling them to collect information from both outside and inside and then process that information and act on it *autonomously* or *interactively* by reconfiguring themselves, changing some of the environmental conditions, or adapting, i.e., responding in some other way. As a consequence, two-way relationships could be established among the spaces, environment, and users: users or changes in the environment could affect the configuration of spaces and vice versa. The result is an architecture that self-adjusts, that continuously changes – an architecture that is adaptive, interactive, reflexive, responsive ...

In a way, buildings are becoming large-scale robots, "transformers" that are (still) fixed to a particular location but could alter their shape or appearance. This book, however, is not just about such technologically-enabled transformations of buildings. It goes beyond the current fascination with mechatronics, i.e. creative combinations of electronics and mechanical systems that process signals collected from the environment through sensors and then generate output signals, turning them through actuating components into forces, motions, and other actions that result in some qualitatively beneficial change.

Our aim with this book is to explore what *change* means in architecture and how it is manifested: buildings weather, programs change, envelopes adapt, interiors are reconfigured, systems replaced. We are interested in the kinds of changes that buildings could and should undergo and the scale and speed at which they would occur. We want to examine which changes are necessary, useful, desirable, possible …

The principal motivation behind the book is that change in architecture is far from being adequately addressed or explored theoretically, experimentally,

or phenomenologically. But that was not the only driver of our interest in what, why, when, and how things change in buildings. *Time* is implicated in any notion of change in architecture; as a design dimension, time is often neglected and is insufficiently explored either in design studio projects in schools or in real-world projects in firms. We need to "make space for time" as David Leatherbarrow argues in his chapter in this book.

The contents of this book emerged out of the eponymous symposium held at the Banff Centre in April of 2013. That event brought together some of the leading individuals from different realms – architects, artists, engineers, technologists, theoreticians – contributors to this book (not all of whom were able to participate in the symposium), with the aim of providing informed views of what is meant by change in architecture. Their chapters offer a diverse and divergent set of ideas as to how change is manifested in architecture today and how engaging it as a design challenge will be relevant tomorrow for architectural design practices. The projects discussed in the pages that follow provide snapshots of emerging ideas, grounded in actual practices already taking place.

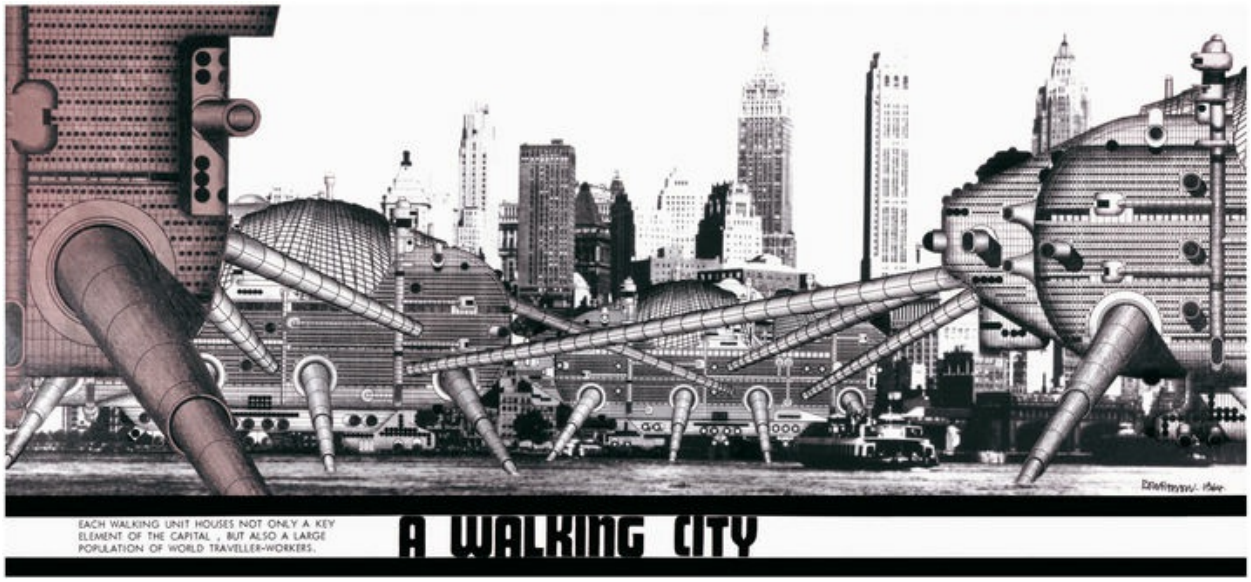
The idea for the symposium was born out of our initial explorations of *dynamic buildings*, which quickly evolved into discussions of *building dynamics* – and *architecture of change* as an overarching theme within which any discussion of the latest and the greatest technological advances should be situated. Our initial scrutiny of the mechatronic technologies and systems that are used to provide dynamic transformation of buildings – the technologies that are increasingly accessible to architects and their consultants – provoked broader questions, such as to what extent *time* actually figures in design thinking and what *change* really means in architecture.

As we engaged the theme in its broader dimensions, we discovered that remarkably little has been written about change – or time – in architecture. We have all witnessed that buildings do change over time; they are added to, they are altered, their spaces repartitioned, doors and windows replaced, walls repainted (often in different colors), etc. Obviously, change in architecture does matter, but, as we have discovered, it means different things to different people. As readers of this book will notice, the meanings of change in

architecture are indeed multiple, intertwined, sometimes contradictory, and, as we concluded, they are irreducible to a simple, coherent, and succinct definition. That definition is at best elusive, yet change underlies quite a few discussions in architecture today, and will do so increasingly in the future.

1
Towards Architecture of Change

BRANKO KOLAREVIC



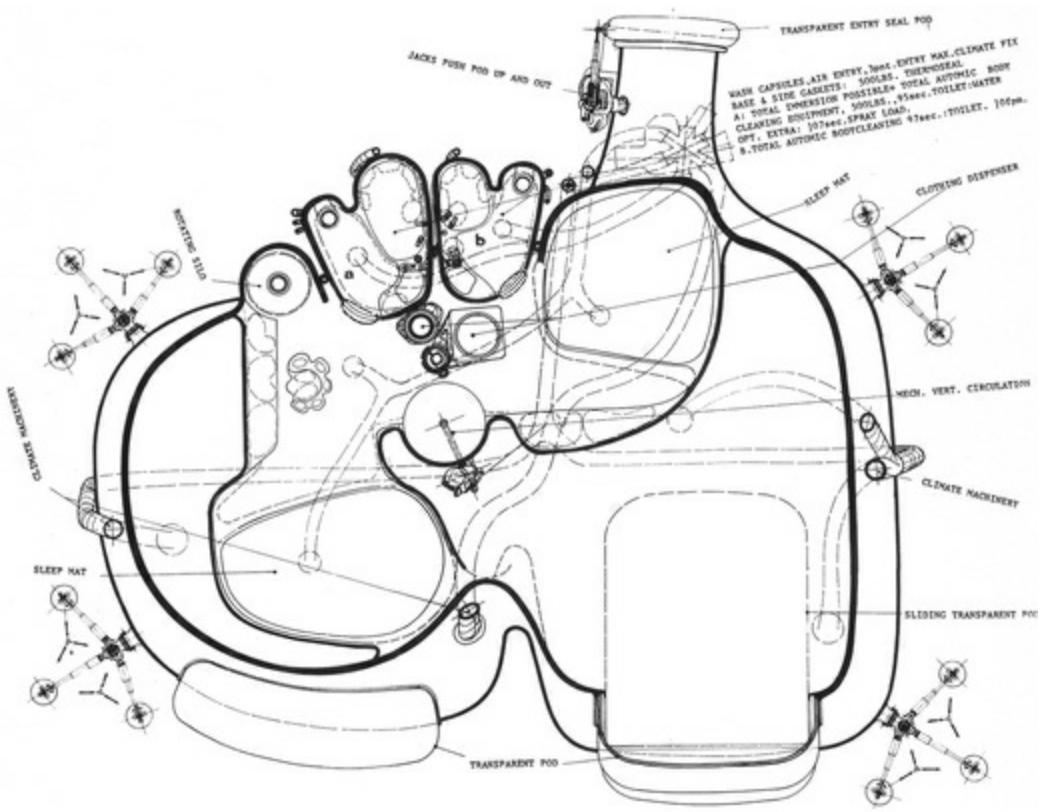
1.1 Ron Herron's *Walking City* (Archigram, 1964).

As the external socio-economic, cultural, and technological context changes, so do conceptions of space, shape, and form in architecture. Over the past decade we have seen an increasing interest in exploring the capacity of built spaces to change, i.e., to respond dynamically – and automatically – to changes in the external and internal environments and to different patterns of use. The principal idea is that two-way relationships could be established among the spaces, the environment, and the users: the users or the changes in the environment would affect the configuration of space and vice versa; the result is an architecture that self-adjusts to the needs of the users. Different terms have been used to describe such architecture: adaptive, dynamic, interactive, responsive, etc. As I will argue in this chapter, the principal idea behind it – facilitating and accommodating change – is not new; what has

changed are the technologies (and materials) to accomplish it.

It all Started in the 1960s

The first concepts of an adaptive, responsive architecture as it is understood today were born in the late 1960s and early 1970s, primarily as a result of developments in cybernetics, artificial intelligence, and information technologies. Such architecture, however, was first envisioned in science fiction. James Graham Ballard, a British novelist, described in a short story from 1962 a "psychotropic house," a machine-like, mood-sensitive house that could respond to and learn from its occupants, becoming "alive" as it was occupied.[1] The imagined responsive house was made from a material Ballard referred to as "plastex," a combination of plaster and latex that allowed the house to change its shape as needed. The house also had many "senso-cells," distributed all over it, which were capable of "echoing every shift of mood and position of its occupants."[2]

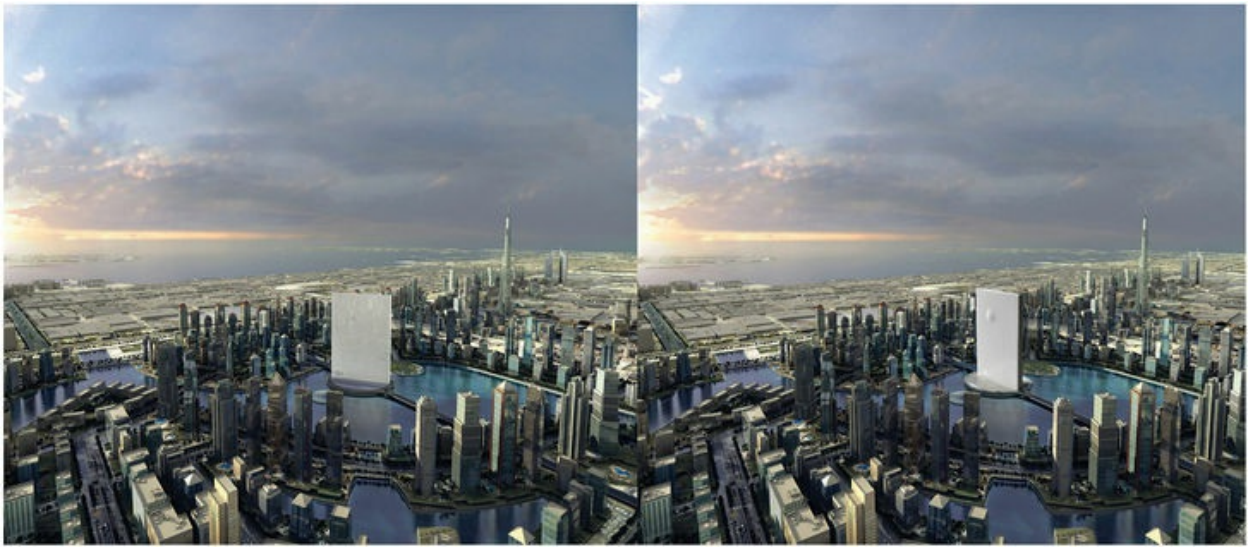


1.2 David Greene's *Living Pod* (Archigram, 1966).

Ron Herron's *Walking City* hypothetical project from 1964 (Figure 1.1) imagined cities as giant mobile, transformable robotic structures that could move to wherever their resources were needed.[3] Intelligent, robotic buildings - self-contained "living pods"-would move within the cities; the pods were envisioned as independent, yet parasitic: they would "plug in" to way stations to replenish resources, moving, connecting, and disconnecting as instructed (Figure 1.2). The cities could interconnect to form larger metropolises or disconnect and disperse as required or desired.

While Ballard and Archigram's Herron and Greene were among the first to envision "alive," changeable buildings and cities capable of interacting among themselves and with their occupants, Gordon Pask, as an early proponent of cybernetics in architecture, is often credited with setting the foundations for interactive environments in the 1960s with his concept of *Conversation Theory,*[4] intended as a comprehensive theory of interaction. Pask's ideas had a tremendous influence on both Cedric Price and Nicholas Negroponte, with

whom he collaborated. Cedric Price adopted concepts from cybernetics to articulate the concept of "anticipatory architecture," demonstrated by his seminal *Fun Palace* and *Generator* projects. Nicholas Negroponte proposed in 1975 that computing power be integrated into buildings so that they could perform better, turning buildings into "architecture machines" that are "^assisted,"augmented/ and eventually ^replicated' by a computer."[5] The aim was to "consider the physical environment as an evolving mechanism."[6] In the last chapter, he made a prediction that "architecture machines" (in the distant future) "won't help us design; instead, we will live in them."[7]



1.3a–d OMA's design for a building in Dubai (2005) that would rotate around its vertical axis, so that main façades would receive no direct sunlight.

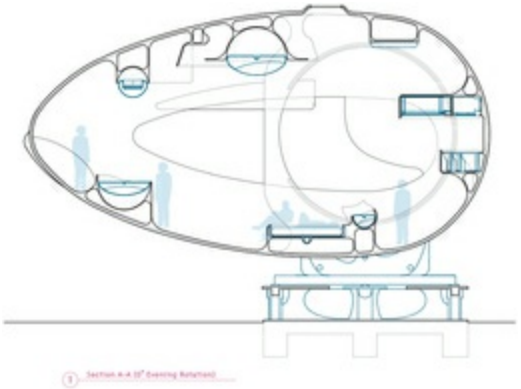
At roughly the same time that Negroponte was working on his "architecture machines," Charles Eastman developed in 1972 the concept of "adaptive-conditional architecture,"[8] which self-adjusts, based on the feedback from the spaces and the users. Eastman proposed that automated systems could control buildings' responses. He used the analogy of a thermostat to describe the essential components: sensors that would register changes in the environment, control mechanisms (or algorithms) that would interpret sensor readings, actuators as devices that would produce changes in the environment, and a device (an interface) that would let users enter their preferences. That is roughly the component make-up of any reactive system developed to date.

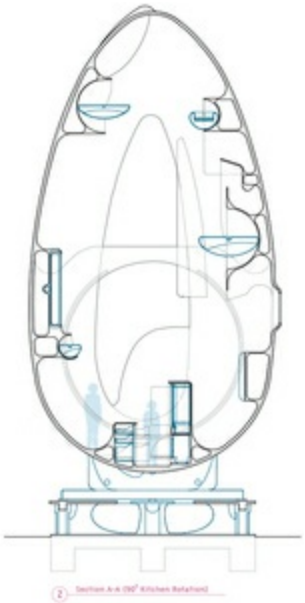
Transformable, Flexible, Adaptive, Responsive Architecture

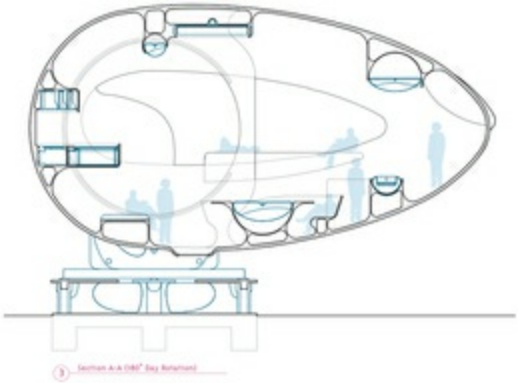
After much initial interest in the late 1960s and early 1970s, not much happened in the next two decades, with the exception of Jean Nouvel's *Institut du Monde Arabe* (Figure 6.2 in Chapter 6 by Kolarevic and Parlac), completed in 1989 in Paris, as the first significant, large-scale building to have an adaptive, responsive façade. With greater attention to buildings' energy demands and increasing capacity to monitor and manage energy use, the building envelope became the locus of technological innovation in the late 1990s. As emphasis shifted away from simply creating energy barriers (to block heat gain or heat loss) towards harvesting energy from the environment and channeling it where it is needed, architects and engineers started to incorporate electronically controlled, mechanically activated shading and ventilation systems into building façades. Double-skin façades with a controlled vented air cavity and operable, integrated shades or blinds started to emerge in the 1990s. Then over the last decade, adaptive, kinetic or

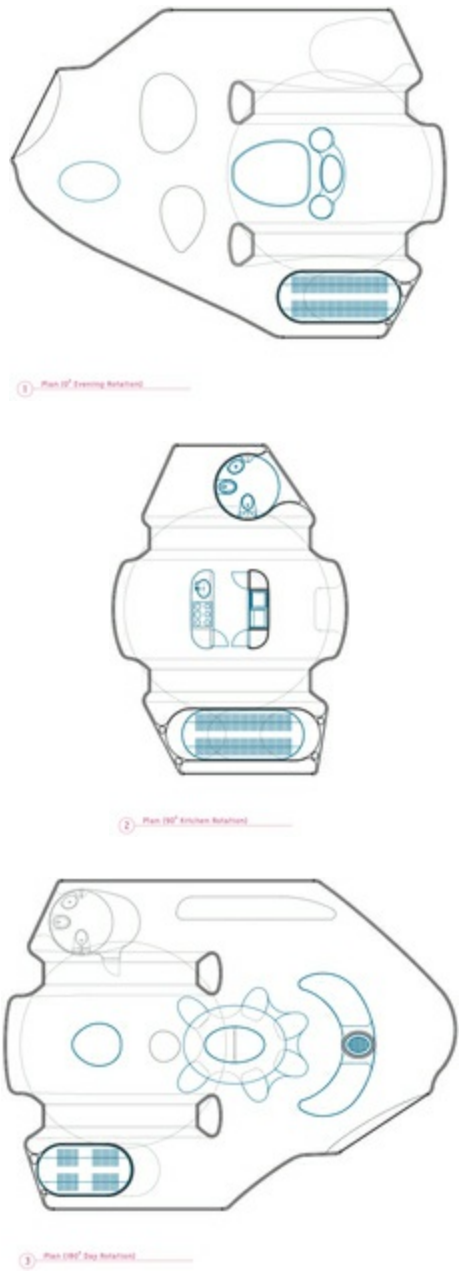
dynamic façades, active and high-performance building envelopes entered architecture's vocabulary – and practice.[9]

The notions of adaptivity and responsiveness are not limited to building envelopes only. There is an emerging interest in dynamic structures that could enable buildings to change their overall shape and internal configuration, either in response to environmental conditions or different programmatic or use arrangements. If not changing its shape, the building, for example, could reorient itself through rotation so that it always presents a smaller surface area to the sun, as was proposed by OMA in 2005 for a large office building in Dubai (Figures 1.3a–d). Greg Lynn describes his *RV (Room Vehicle) Prototype House* as having a small footprint of 60 m^2 but 150 m^2 of usable surface area, which is accomplished by rotating the house around two axes on a robotic base, so that its one wall and ceiling become floor surfaces (Figures 1.4a–c). According to Lynn, the "dwelling challenges the sedentary typologies of a home and introduces a new one based on movement and interaction."[10] The *Sharifi-ha House* (2013) in Tehran, Iran, designed by Nextoffice (Alireza Taghaboni), features entire rooms that rotate in and out of the building's volume to either open or close it, exposing or protecting the interior from the seasonal weather (Figures 1.5a–d).[11]

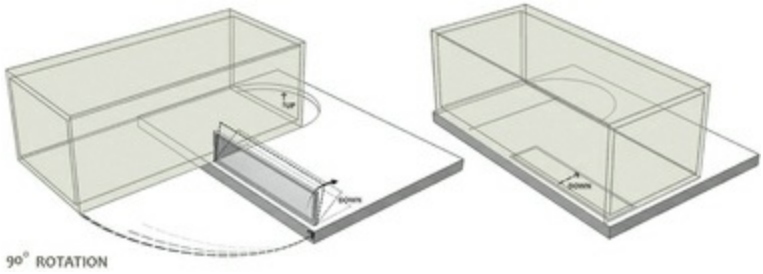








1.4a–c Greg Lynn's *RV (Room Vehicle) Prototype House* rotates to increase the usable space of a house.


90° ROTATION

1.5a-d The *Sharif-ha House* (2013) in Tehran, Iran, designed by Nextoffice, features entire rooms that rotate in and out of the building's volume.

1.6a and b The *Living Room House* (2011) in Gelnhausen near Frankfurt features a bedroom that can pop out of the building like a drawer.

Rotation is one simple way of transforming, reconfiguring, or reorienting building components (or even entire buildings). Translation along a linear path, horizontally or vertically, is another straightforward way to transform buildings on the outside or inside. The *Sliding House* in Suffolk, UK, designed by dRMM and completed in 2009 (Figures 6.20a–d in Chapter 6 by Kolarevic and Parlac), features an enclosure that can move along recessed tracks to cover or uncover different buildings along its 28m-long linear path: the house, garage or the annex. The *Living Room House* in Gelnhausen near Frankfurt in Germany (2011), designed by Formalhaut, features a bedroom that can come out from the main volume like a drawer and cantilever over the street below (Figures 1.6a and b). OMA's well-known *Maison Bordeaux* (1998) in France features an open hydraulic elevator platform (Figure 1.7) that enables its wheelchair-bound owner to move vertically between different levels of the house. The elevator platform is actually the owner's office – a room that changes its location within the house throughout the day.

Others are exploring adaptivity and responsiveness in architecture at the other end of the scale – that of materials – and are relying on changing the properties of materials to create an adaptive response in building surfaces and systems.[12] Then, there are issues related to building "intelligence," i.e. controlling the various adaptive responses in buildings and managing potential conflicts that may arise in operation.

1.7 The *Maison Bordeaux* (1998) in France, designed by OMA, features a room on an open hydraulic elevator platform that changes its location within the house.

In *Flexible: Architecture that Responds to Change*,[13] Robert Kronenburg argues that for a building to be "flexible," it must be capable of: (1) adaptation, as a way to better respond to various functions, uses, and requirements; (2) transformation, defined as alterations of the shape, volume, form, or appearance; (3) movability; and (4) interaction, which applies to both the inside and the outside of a building. Such capacities in buildings will be provided by "intelligent" building systems, which will be driven by many factors, from environmental ones, such as the control of energy use, to changing the appearance of the building through varying images and patterns. The systems could be either automatic or "intuitive," suggesting the capacity of the system to infer from the context an appropriate set of responses without overly explicit inputs.

These different strands of inquiry were brought together at the "Adaptive Architecture" conference held in 2011 at the Building Centre in London.[14] At

this seminal event, convened by Michael Stacey, presentations were grouped into four thematic categories: *Dynamic Façades*, *Transformable Structures*, *Bio-Inspired Materials,* and *Intelligence*, which could be considered as a taxonomy of current research efforts in this area. The thematic area of adaptive architecture is vast, spanning inquiries that range from highly technical and pragmatic explorations of dynamic, responsive building envelopes to speculative, conceptual explorations of "emotional" responses by built spaces to their occupants' moods.

From Psychotropic to Emotive Houses

> It was a beautiful room all right, with opaque plastex walls and white fluo-glass ceiling, but something terrible had happened there. As it responded to me, the ceiling lifting slightly and the walls growing less opaque, reflecting my perspective-seeking eye, I noticed that curious mottled knots were forming, indicating where the room had been strained and healed faultily. Deep hidden rifts began to distort the sphere, ballooning out of one of the alcoves like a bubble of overextended gum.
>
> (J.G. Ballard)[15]

While Ballard's "psychotropic house", mentioned earlier in this chapter, belongs to science fiction, the *E-motive House* by Kas Oosterhuis (2002) edges closer to contemporary technological and material reality. Oosterhuis describes a responsive, interactive house that can develop its own emotions, "a house with a character of its own, sometimes unyielding, sometimes flexible, at one time sexy, at another unpredictable, stiff and unfeeling."[16] The goal is to create an "emotional relationship between the house, its occupiers and the elements." The *E-motive House* can be a "reactor" as well as an "actor," where the "acting will be made possible by a cooperative swarm of actuators like pneumatic beams, contracting muscles and hydraulic cylinders."[17] The house is also capable of reacting: "The movement of the users and the changes in the weather are registered by a diversity of sensors, and are translated by the brain of the house into an action." In this way, the inhabitants and the actuators of the house will develop a common language so that they can

communicate with each other.[18]

In 2003, Oosterhuis and his Hyperbody research group designed and constructed the *Muscle*, a working prototype of a programmable building that can reconfigure itself "mentally and physically."[19] The *Muscle* is a pressurized soft volume, wrapped in a mesh of tensile Festo "muscles," which can change their own length and, thus, the overall shape of the prototype. The public connects to the prototype by sensors and quickly learns how the *Muscle* reacts to their actions; the *Muscle*, however, is programmed to have a will of its own, making the outcomes of interactions unpredictable. The ultimate goal of the project is to "develop an individual character for the *Muscle*." The *Muscle* has demonstrated that the *E-motive House* is not so techno-utopian – and that Ballard's "psychotropic" house could perhaps become a reality of our inhabitation in the future.

Open Building

In the quest to establish a context for change and variety in architecture, an international network for *Open Building*[20] was established early in this decade. In *Open Building*, the focus is on disentangling building systems and subsystems from each other so that they can be better organized to facilitate not only their efficient assembly, but also their disassembly and reassembly in different configurations. *Open Building* separates the major systems into the building site, the structural envelope, the division of space inside the building, plumbing, wiring, heating/cooling, and the cabinets, furniture, and "other stuff that people put inside the building." One of the main distinctions that *Open Building* makes is between "support" and "infill," where "support" refers to the structural envelope, and "infill" to all the other systems that are housed within the envelope. Without referencing the *Open Building* movement, Tristan d'Estree Sterk also separates the components of buildings into two main classes of parts: (1) the serviced spaces (responsive, internal partition systems, and (2) the external shells (responsive building envelopes or

structures).[21] Thus, building design operates on two levels: first, the overall structural envelope is designed, and then the infill. Critical to successful implementation are interfaces between different systems, which should be designed to allow different choices of systems and their replacement, as in different fit-out systems applied in each unit, depending on the choices made by the users.

1.8 Gerrit Rietveld's *Schröder House* (1924) features an adaptive large space on the upper floor.

While *Open Building* as a design and building method aims to address the changing social and technical context in which we live and work, it focuses on building systems as a technological enabler for effective changes in use (i.e., adaptive re-use). It recognizes that there are distinct levels of intervention in the built environment; that users may make design decisions, as well; that design is a process that involves many different disciplines and professionals; and that the built environment is in constant transformation (i.e., subject to

continuous change) and is the product of a never-ending, ongoing design process in which it is transformed part by part.

Ed van Hinte and the other authors of *Smart Architecture*[22] also articulate a need for architecture to develop ways of designing buildings that can change, but do so with a dimension of time explicitly in mind. According to them, buildings could be divided into seven system-based layers, each with its own lifespan that ranges from centuries, down to a couple of years. The layers are (in ascending order, depending on life span): location, structure, access, façade, services, dividing elements, and furniture. They warn that the dynamics of these layers – and their different life spans – have to be taken into consideration when designing "integrated" buildings. (A building with tightly integrated building systems may not have a capacity for change if the systems are impossible to separate and disassemble.)

Lo-Tech, Hi-Tech, or Both?

The notion of adaptive, changeable buildings and spaces is anything but new. It has been present for centuries in building traditions of many different cultures around the world. For example, in a traditional Japanese house any room could be a living room or a bedroom (or a dining room). What makes this adaptability in use possible are two key features: first, all furniture is lightweight and could be removed into large storage closets; second, the size of a *space* could be easily changed using sliding partitions (*fusuma*) that separate adjacent rooms. Such spatial porosity is also present in traditional Korean houses.

The Modernist *Open Plan* is based in large part on these East Asian precedents, as were the associated notions of adaptability and flexibility. Gerrit Rietveld's seminal *Schröder House*, built in 1924, features on the upper floor an adaptive large space that can be left open or subdivided using sliding and revolving partitions into four separate rooms, i.e. three bedrooms and a living room (Figure 1.8). Similarly, Steven Holl's apartment complex in

Fukuoka, Japan, completed in 1991, relied on hinged wall partitions to create adaptive apartment units in which spaces could change daily or on a larger time scale as family size changes (Figures 1.9a and b).

1.9a and b Steven Holl's *Hinged Space Housing* (1991) in Fukuoka, Japan.

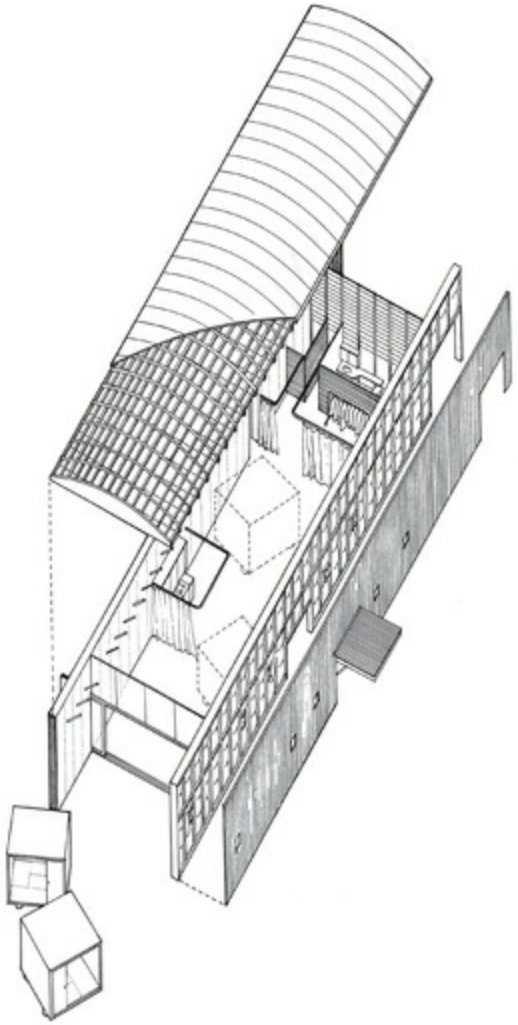
As more and more designers and firms begin to experiment with innovative technologies to create kinetic, adaptive spaces and systems, it is worth remembering that wheels and hinges – if used imaginatively – could create very potent transformable environments that need not rely on any fancy mechatronic set-ups. The *Naked House* in Kawagoe, Japan, designed by Shigeru Ban and completed in 2000, features four movable rooms on wheels inside a large, shed-like space (Figures 1.10a and b). The 6 sqm rooms are open

on two sides and can be located anywhere within the large interior space or even moved outside; they could be also joined to form larger spaces if needed.

We should not lose sight of simple, low-tech solutions in our current quest for adaptive systems infused with the latest sensing, control, and activation technologies. Oftentimes, simply adding wheels and tracks (and/or hinges) to elements that are then moved by people is all that is necessary for some adaptive designs to be effective spatially and programmatically. It is also worth remembering that any cutting-edge technological system of today becomes an obsolete technology rather quickly. One way of addressing this challenge of obsolescence is to rely on technologies that are already "obsolete," but which could be deployed in an innovative way. The dimension of time is rather critical for the designers of adaptive, responsive, interactive building systems of tomorrow – not only conceptually, but also operationally, at the most pragmatic, tectonic level.

Reactive, Interactive, Participatory Architecture

Another critical issue in the design of any highly automated adaptive, responsive system is the user override. If an installed, automated system requires frequent manual overrides by annoyed users, its "life" will likely be short; a simple, people-activated "high-performance" and low-tech solution would probably more than suffice in such cases. Social and cultural factors need to be taken into account in set-ups that rely on automated systems to attain certain technical performance goals. We shouldn't be blinded by technologies of the day and should not lose sight of the qualitative, i.e. non-quantifiable performative aspects of the project and whether they could be better served by no-tech or low-tech solutions. There is also the ever-present danger of creating "gimmicky" architecture that very quickly becomes boring.



1.10a and b Shigeru Ban's *Naked House* (2000) in Kawagoe, Japan, features movable rooms on casters.

The primary goal of constructing a truly responsive, adaptive architecture is to imbue buildings with the capacity to interact with the environment and their users in an engaging way. Architecture that echoes the work of Nicholas Negroponte could be understood as an adaptive, responsive machine – a sensory, actuated, performative assemblage of spatial and technical systems that creates an environment that stimulates and is, in turn, stimulated by users' interactions and their behavior. Arguably, for any such system to be continually engaging, it has to be designed as inherently indeterminate in order to produce unpredictable outcomes. The user should have an effect on the system's behavior or its outcome and, more importantly, on how that behavior or outcome is computed. That requires that both inputs and outputs of the systems be constructed on the fly. It is this capacity to construct inputs and outputs that distinguishes interactive from merely reactive systems.

The distinction between interactive and reactive is what enables adaptive, responsive architecture to be seen as an enabler of new relations between people and spaces. When Philip Beesley and his colleagues describe a responsive environment in *Responsive Architectures: Subtle Technologies* as a "networked structure that senses action within a field of attention and responds dynamically with programmed and designed logic,"[23] they are referring to what is essentially a reactive system. In contrast, Michael Fox and Miles Kemp argue in *Interactive Architecture* that the interaction is circular – systems "interact" instead of just "react."[24] The distinction between interaction and reaction (i.e., a system's response) is not clear-cut, because a dynamic action of a component, for example, could be seen not simply as a reaction but also as a part of the overall scenarios of interactivity. Tristan D'Estree Sterk distinguishes direct manipulation (deliberate control), automation (reflexive control), and hybridized models as forms of interaction between the users and the technologies behind responsive systems.[25] For Sterk, "The hybridized model can also be used to produce responses that have adjustable response criteria, achieving this by using occupant interactions to build contextual models of the ways in which users occupy and manipulate space."[26]

As Usman Haque puts it, the goal is

> a model of interaction where an individual can directly adjust the way that a machine responds to him or her so that they can converge on a mutually agreeable nature of feedback: an architecture that learns from the inhabitant just as the inhabitant learns from the architecture.[27]

Thus, one of the principal challenges is how to construct (Paskian) systems that would provide enough variety to keep users engaged, while avoiding randomness, which could lead to disengagement if the output cannot be understood. The key challenge is to design an architecture that avoids boredom and retains a high degree of novelty. As observed by Haque, "Unlike the efficiency-oriented pattern-optimization approach taken by many responsive environmental systems, an architecture built on Pask's system would continually encourage novelty and provoke conversational relationships with human participants."[28]

When it comes to designing adaptive, responsive environments, the

"software" side does not seem to present as many challenges as the "hardware" side, the building itself, in which the majority of systems is inherently inflexible. That is perhaps where the biggest challenges and opportunities exist, as buildings would have to be conceptually completely rethought in order to enable them to adapt (i.e., to reconfigure themselves). Then there is the "middleware" that sits among the software and hardware and the users as devices that facilitate the feedback loops between the components of the system. There are other, more operational-based challenges that have to do with resolution of potential conflicts within systems. For example, Sterk discusses the coordination of responses at coincident, i.e. shared boundaries between spaces, as in a movable partition wall between two spaces, which can have actuators accessible through two independent control processes.[29]

Another issue is that while change is desirable, for most purposes, it would have to occur in predictable and easily anticipated ways. If that is not possible, then there ought to be a way (in certain circumstances) for users to preview changes before they are executed, or to choose among alternatives for one (perhaps suboptimal) that fits the current circumstances, needs, and/ or desires. Users may need to be informed of the impact that selected changes would have on the environment or the shape and configuration of the space. The overall issue of control is critical, as was already mentioned. In *Smart Architecture*, Ed van Hinte warns that "sometimes a simple and hence ostensibly 'dumb' building is smarter than a technology-dominated living-and-working machine over which the user has lost control."[30]

There are also some fundamental questions that have yet to be adequately addressed. For example, while Beesley and his colleagues predict, "the next generation of architecture will be able to sense, change and transform itself,"[31] they fail to say clearly towards what ends. Even though they ask what very well may be the key question – how do responsive systems affect us? – they do not attempt to answer it explicitly. Similarly, Fox and Kemp, in their *Interactive Architecture* book,[32] avoid explaining fully – and admit as much – why interactive systems are necessary, meaningful, or useful, and simply state, "the motivation to make these systems is found in the desire to create

spaces and objects that can meet changing needs with respect to evolving individual, social, and environmental demands." Fox and Kemp position interactive architecture "as a transitional phenomenon with respect to a movement from a mechanical paradigm to a biological paradigm," which, as they explain, "requires not just pragmatic and performance-based technological understandings, but awareness of aesthetic, conceptual and philosophical issues relating to humans and the global environment."[33]

Architecture of Change = Architecture of Time

> Accepting the dynamics of buildings and cities … can turn architectural change into an ecologically efficient process as well as a new urban experience.
>
> (Ed van Hinte, *et al.*, *Smart Architecture*)[34]

If we were to accept change as a fundamental contextual condition – and time as an essential design dimension – architecture could then begin to truly mediate between the built environment and the people who occupy it. As Ed van Hinte and his colleagues note, "Instead of being merely the producer of a unique three-dimensional product, architects should see themselves as programmers of a process of spatial change."[35] The principal task for architects is to create "a field of change and modification" that would generate possibilities instead of fixed conditions. The inhabitable space would then become an indeterminate design environment, subject to continuous processes of change, occurring in different realms and at various time scales:

> It is the form that is no longer stable, that is ready to accept change. Its temporary state is determined by the circumstances of the moment on the basis of an activated process and in-built intelligence and potential for change. Not product architecture then, but a process-based architecture whose form is defined by its users' dynamic behaviour and changing demands and by the changing external and internal conditions; an architecture that itself has the characteristics of an ecological system, that emulates nature instead of protecting it and therefore engages in a enduring fusion of nature and culture.[36]

As Ed van Hinte and his colleagues point out, "that would be a truly ground-

breaking ecological architecture."[37] But to get there, we need to first answer some fundamental questions pertaining to change as a conceptual and time as a phenomenological dimension in architecture. We need to go beyond the current fascination with mechatronics and explore what change means in architecture and how it is manifested: buildings weather, programs change, envelopes adapt, interiors are reconfigured, systems replaced. We need to explore the kinds of changes that buildings should undergo and the scale and speed at which they occur. We need to examine which changes are necessary, useful, desirable, possible …

In short, much remains to be done: I would argue that change – and time as a design dimension in architecture – are far from being adequately addressed or explored theoretically, experimentally, or phenomenologically. As we probe and embed adaptability, interactivity, and responsiveness into the buildings and spaces, we must not unconditionally and blindly chase the latest technological advancements. As I have argued in this chapter, an effective adaptive, responsive – and responsibly designed – building could be based on simple, low-tech, low-energy solutions. It could be actuated by people who live or work in it, who could push, pull, turn, flip, move things … and it could be intelligently augmented with sensors and an Arduino board here and there, as needed.

Acknowledgments

Parts of this chapter have previously been published by the author.

Notes

1 Ballard, James Graham, "The Thousand Dreams of Stellavista," in *Vermilion Sands* (London: Vintage, 2001, originally published in 1962, then 1971).

2 Ibid.

3 Ron Herron was a member of Archigram, an avantgarde architectural group formed in the early 1960s in London. Other members of the group were Peter Cook, Warren Chalk, Dennis Crompton, Michael Webb, and David Greene. The group devised a series of hypothetical projects, drawing inspiration from the technological, social, and cultural context of the 1960s.

4 Pask, Gordon, "Architectural Relevance of Cybernetics," *Architectural Design*, September 1969, pp. 494–496.

5 Negroponte, Nicholas, *Soft Architecture Machines* (Cambridge, MA: MIT Press, 1975).

6 Ibid.

7 Ibid.

8 Eastman, Charles, "Adaptive-Conditional Architecture," in N. Cross (ed.), *Design Participation: Proceedings of the Design Research Society Conference* (London: Academy Editions, 1972), pp. 51–57.

9 For a discussion of adaptive building envelopes, see Chapter 6 by Branko Kolarevic and Vera Parlac in this book.

10 For more information about *RV Prototype House*, see http://glform.com/buildings/rv-room-vehicle-houseprototype/.

11 The turning mechanism used in the house is a commonly used one for rotating theatrical set-ups and turning car exhibits in showrooms.

12 For a discussion of adaptive materials, see Chapter 12 by Vera Parlac in this book.

13 Kronenburg, Robert, *Flexible: Architecture that Responds to Change* (London: Laurence King Publishing, 2007).

14 See www.buildingcentre.co.uk/adaptivearchitecture/adaptive.html.

15 Ballard, op. cit.

16 See www.hyperbody.nl for more information.

17 Ibid.

18 Ibid.

19 Ibid.

20 See www.open-building.org for more information.

21 Sterk, Tristan d'Estree, "Responsive Architecture: User-Centered Interactions within the Hybridized Model of Control," in *GameSetandMatch II: On Computer Games, Advanced Geometries and Digital Technologies* (Rotterdam, the Netherlands: Episode Publishers, 2006), pp. 494–501.

22 van Hinte, Ed, Neelen, Marc, Vink, Jacques, and Vollaard, Piet, *Smart Architecture* (Amsterdam: 010 Publishers, 2003).

23 Beesley, Philip, Hirosue, S., Ruxton, J., Trankle, M., and Turner, C., *Responsive Architectures: Subtle Technologies* (Toronto, ON: Riverside Architectural Press, 2006).

24 Fox, Michael and Kemp, Miles, *Interactive Architecture* (New York: Princeton Architectural Press, 2009).

25 Sterk, op. cit.

26 Ibid.

27 Haque, Usman, "The Architectural Relevance of Gordon Pask," in Lucy Bullivant (ed.), *4dsocial: Interactive Design Environments, Architectural Design*, no. 77 (London: Wiley Academy, 2007).

28 Ibid.

29 Sterk, op. cit.

30 van Hinte, *et al.*, op. cit.

31 Beesley, *et al.*, op. cit.

32 Fox and Kemp, op. cit.

33 Ibid.

34 van Hinte, *et al.*, op. cit.

35 Ibid.

36 Ibid.

37 Ibid.

2
Making Space for Time

DAVID LEATHERBARROW

2.1 *Guthrie Theater* (2006) in Minneapolis, designed by Jean Nouvel.

The basic thesis of this chapter is this: through temporality one gains access to the primary order of architectural topography and thus to the reality and meaning of landscapes, streets, buildings, rooms, and their details. Time, I will try to show, is not a contingent attribute of the places intended in design and realized through construction but a key to their essential structure and significance.

For some, I suspect my thesis will seem like "thoughts out of season." Given

our steady attention to a building's readiness for immediate experience – I mean the direct perception of the materials, spaces, and dimensions that are *presently* apparent (Figure 2.1) – the work's former and future conditions will seem largely insignificant. We tend to believe that the work is complete when its construction, layout, and look have been brought to the state that was specified in design. From that moment onward we expect the work to stay as it first was, suffering but enduring the effects of inhabitation and environmental influence. Permanence is a building's first premise and greatest virtue.

Uncontroversial as these truisms may seem, they are contradicted by the fact that the building's "move-in" and "photo-ready"' condition never last very long, hardly more than a season, certainly not through the years and decades of its use, well after the builders have left the site. Inhabitation inaugurates alteration. Succession is the inevitable result; new appearances succeed old, each different, even if the modifications are barely perceptible. Retrospective views of resemblance do not overcome, they reaffirm these differences. A key task of design is making space for *this* kind of time, the time of continual change.

There is no good reason to privilege a work's first over its later appearances, nor to judge any present condition as necessarily superior to those that preceded and will follow it. Our tendency to concentrate on the qualities of the work that display the designer's intentions is, I think, a disciplinary prejudice that neglects the building's post-professional life. I realize this observation runs against the grain of most building restoration campaigns, no matter whether they are undertaken by preservationists, historians, or the designers themselves. But the truth of the matter is that many buildings *improve* over time. Sometimes this occurs through intentional modifications that compensate for inadequate foresight. Changes can also result from the operation of manual or digital devices, which aim to improve a work's usefulness – they alter its appearance as well. Today buildings and elements that incorporate these devices are said to be "intelligent." An intelligent façade, for example, is one that incorporates instruments that moderate climate, accepting or rejecting free energy from the external

environment, reducing the amount of artificial energy required to achieve comfortable internal conditions. Materials, too, can be endowed with intelligence, more or less.

2.2 *Wells Cathedral* (Cathedral Church of St. Andrew) in Wells, Somerset, UK.

2.3 *Fisher Fine Arts Library* (1890) in Philadelphia, designed by Frank Furness.

But design is not required for changes to occur; alterations can also result from a work's 'natural' tendency to settle into its location, absorbing into its physical body qualifications that often render it more congenial to ambient conditions, even if they alter intended finishes. Georg Simmel, speaking of material change in his paper on ruins, said that eventually "nature reclaims what was taken from it."[1] The spectrum of surface alterations, of course, ranges very widely, from bleaching, absorption, saturation, and staining, to polishing and abrasion. One of the best-known instances of abrasion is the dishing of treads that occurs over years of use, a re-profiling to which thousands of anonymous individuals contribute unknowingly (Figure 2.2). Yet, the result, the path most prefer, is prominently visible – even legible. Another eloquent example is the festive – at least seasonal – whitewashing of vernacular buildings.[2] Obviously, this practice is subtended by extra-architectural ideas and traditions; Easter renewal, for example. The sun also plays a role in *remaking* architectural appearances: a building's sun and shade sides show different degrees of both chromatic intensity and variation. Consider the stone on the north and west sides of Frank Furness's *Fine Arts Library* in Philadelphia (Figure 2.3), or the alternately prominent and recessed parts of a single façade, such as the wooden panels on Kahn's *Salk Institute* (Figure 2.4). The power of light and shadow to animate an architectural surface is similarly obvious. Recently, Kengo Kuma developed a theory of "particles" that elaborates this basic fact of building under the sun (Figure

2.5).[3] Alterations that result from the sedimentation of air-borne particles are also familiar. Surface marks sometimes enrich, sometimes stain. In the case of Marcel Breuer's *De Bijenkorf* department store (Figure 2.6) a radically different façade has resulted from these alterations. I doubt he imagined this but I have a hunch he liked it. Changes that are unforeseen interest me the most because they often enrich works in ways that exceed what design intended. Even if we postpone judgments about the merit of modifications that were never envisaged I think we must admit that unforeseen changes are inevitable in works that last and therefore should be taken into consideration in any account of their concrete reality, as well as in their initial designs.

2.4 *Salk Institute for Biological Studies* (1966) in La Jolla, designed by Louis I. Kahn.

Temporality in Architecture

Nevertheless, when given just a little thought, the temporality that is peculiar to architecture seems contradictory. In architecture, time *maintains* what it

has brought into being while it simultaneously *schedules the work's transformation* – ultimately its disintegration. How can the two – sameness and difference – occur concurrently? By virtue of its physicality, suitability, and familiarity every work keeps its past present; now, like then, the walls of this room are still plaster, timber, and glass; its apertures and furnishings allow one to use it as others have and will; *in time* it will still be *this room*. During any of these uses the distinction between what the setting once was and now is has no real force. The only aspects of the setting that show themselves to be "of the past" are the few that have lost their tacit relevance. Practical involvements abrogate the familiar, but essentially conceptual, distinction between now and then. The chief impediment to grasping the reality of change is our uncritical dedication to objective or clock time, as opposed to the time of an event. On this point, William Faulkner offered a blunt observation: "Time is dead as long as it is being clicked off by little wheels, only when the clock stops does time come to life."[4]

2.5 *Nakagawa-machi Bato Hiroshoghi Museum of Art* (2000) in Nasu Tochigi, Japan, designed by Kengo Kuma.

Thanks to the qualities I have just mentioned (physicality, suitability, and familiarity), every built setting not only recalls its past, it pre-figures its future; in the case of a lecture room, for example, the moment when the next lecturer or conference will begin, or more prosaically when the floor will be cleaned, lighting repaired, and the overall appearance renewed. In other words, the room's "present state" continually outreaches itself toward its recent past and near future, impinging on each of them simultaneously. Here is the key point: temporality is not only nor always moment-by-moment succession. The chronology of regular intervals, clock time, is not lived time, as Faulkner said. The past lingers into the present, just as the future extends it; every now is also a former future and every future is at the same time a present yet to come.[5] Every "present moment" in the living reality of an architectural work reasserts the presence of a history which it also supplants, while it anticipates what is yet to come, although incompletely. My general point is that past and future define essential dimensions of the work's "present" reality, albeit as conditions that are "no longer" and "not yet" present in the way they once were and will be. Accordingly, we need to reconsider what we conventionally mean by the completion of the construction process. Building materials are *pre-qualified* in the quarry – that's how they recommend themselves for use – then are *qualified* through the labors of construction, and lastly are *re-qualified* through use and patterns of environmental influence. This means the labor of finishing never comes to an end.[6] Can we think of works as essentially unfinished? More importantly, can we design them that way?

2.6 *De Bijenkorf* department store (1956) in Rotterdam, designed by Marcel Breuer.

Finally, the temporal order that seems to be contradictory – now plus then – unfolds at several levels. Every built work – and by that I mean every room, building, garden, and urban setting – has a stratified temporal horizon, from which it obtains definition and in which it renews itself. I will explain the levels or kinds of time below.

But, first, I shall propose a more compact version of my opening thesis: *architectural permanence realizes itself in time*. I say "in time," not *through time*, not diachronically, as the philosophers say, or pathologically, as Aldo Rossi once said; but synchronically, or, in Rossi's terms, a propelling sort of permanence that allows adaptations and alterations.[7] To exemplify propelling permanence he mentions the *Palazzo Ragione* in Padova. An even more eloquent case, I think, is the cathedral in Ferrara (Figure 2.7); particularly the additions and alternations to the flanking walls of the nave, coupling in a fascinating way the side chapels within the church. The principle of propelling permanence has two corollaries: continuance without change is impossible in architecture, and individual buildings like places are co-defined by the "no longer" and "not yet" of their history. Although condensed, these observations should indicate the limitations of the conventional view of architectural permanence, poignantly stated by the great Austrian theorist, August Schmarsow, whose writings show sensitivity to social and historical change.

He observed:

2.7 *Ferrara Cathedral* (*Basilica Cattedrale di San Giorgio*) in Ferrara, Italy.

> Architecture prepares a place for all that is lasting and established in the beliefs of a people and of an age; often, in a period of forceful change, when everything else threatens to sway, will the solemn language of its stones speak of support.[8]

Even though it contradicts all that I have said, Schmarsow seems right: well-designed buildings defy transience, because they abide, they assure. What land is to sea, architecture is to worldly change, its polar opposite and fix. Moreover, this conceit encourages designers to pursue essences in their work – to dream of infinitely durable form – just as it allows a satisfying sense of cultural authority. But obvious notions are not necessarily true. I have argued, and now want to explain more concretely, that architectural reality appears in time: works last because they change.

2.8 *Banca Popolare di Verona* (1973) in Verona, Italy, designed by Carlo Scarpa.

Kinds of Time

We can take the next step in understanding how architecture makes space for time by distinguishing the *kinds of time* that are embodied in the buildings. I believe there are three distinct chronologies that co-exist non-synchronically yet indivisibly in all built works.

First, there is what I call *the time of the world*, combining the calendar of

environmental change with the schedules of daily life. The former include seasonal, diurnal, and atmospheric changes, the latter include the rhythms, patterns, and cycles of inhabitation. Anticipations and outcomes of these combined histories can be seen in the work's defenses, allowances, and accommodations; which is to say, the material, mechanical, and spatial preparations that anticipate the play of ambient forces and recall it: harder timber for treads than for risers, screens that filter environmental passage and blinds that block it, rainwater conductors and collectors, thermal breaks and expansion joints, and so on. One of the more creative treatments of water handling within a work's façade is Carlo Scarpa's bank in Verona (Figure 2.8). His sill-receptacle, surface-channel, and spout recall marks made on nearby façades, just as they anticipate similar processes in his building's similar forms, and they express his design's synchronization with its location by making these actions legible. Here change is not only managed but shown.

The time of the world is also inscribed on buildings through the ancient and inevitable effects of the sun. A well-known example of sun-screening is the early experiment with the *brise-soleil* undertaken by Oscar Niemeyer, Lucio Costa, and others in Rio de Janeiro at the *Ministry of Education* (Figure 2.9). Here, too, we see the impress of memories and anticipations: adjustable panels wait for and respond to light that is too bright, producing shadows that record the path and progress of their solar source. But listed under this heading should also be changeable elements within the building, all the moveable furniture, deployable equipment, and adjustable lighting that attune the work to variable dwelling requirements. An early modern design that elaborated this temporality very creatively is Pierre Chareau's *Maison de Verre*. An equally good case is Eileen Gray's *E 1027*. World time is also apparent in the modifications to a building's surfaces that attest to its sufferings and show its enhancements. Consider, for example, Sverre Fehn's *Villa Busk* (Figure 2.10). Outside, the wooden window surrounds have lost nearly all of their color, inside these same timber elements have rich chromatic intensity, especially in shadow – which Mr. Busk seems to have preferred when making recordings. All of these figures provide a visible record of the project's past and a proposal for its future, as if the work were at once a clock, calendar, and chronicle.

2.9 *Brise-soleil* at the *Ministry of Education* building (1942) in Rio de Janeiro, designed by Lucio Costa, Oscar Niemeyer, and Le Corbusier.

2.10 *Villa Busk* (1990) in Bamble, Norway, designed by Sverre Fehn.

The second sort of time that exists in built works is *the time of the project*.[9] The first and most difficult distinction that must be made is between project making and production. For production to occur, one must assume that much, if not most, of the design development has been completed. Like all progressive endeavors, productive work is oriented towards the future. It is unique insofar as it converts an orientation towards what is ahead into a taking hold of it, abbreviating a process of approach in order to accomplish arrival. The prefix *pro* means before or in advance, in front or in favor of. Architectural projects, we say, advance *pro*-posals. Etymologically the word project means "to throw forward"; a *projectum* is something thrust ahead, a projectile. Production *completes* the project's advance, achieves its goal, insulating design's procedures against future interferences. Single-mindedly dedicated to its ends, approximately locomotive, production marginalizes all possibilities but one in order to arrive at the work's concluding stage. This process draws the yet-to-come of the project back into the now, placing the future in the grasp of the present, as if project-making were planning, which it is not. And once projects discard their preliminaries the form they achieve bears little or no trace of its formation. A significant aim – also risk – of today's new instruments of "design development" is to close the gaps between the several phases of project development and implementation, overcoming the problems of "associativity" between software packages, linking together in one seamless flow the work of documenting the context, diagramming a possible solution, developing the design, refining its articulation, integrating systems, specifying materials and products, and both scheduling and controlling their assembly. A highly advertised recent addition to the list of new instruments is "building information modeling" software. Whether or not the promises for a speedier and more controlled process are kept, the change in thinking allowed by this and similar programs is significant. When the outcome is assured at the beginning, unforeseen possibilities have a reduced role in project development, particularly those that cannot be described in the data sets that have been developed. The risk that attends to this aim is the reduction of the work to what the designer imagines it will be.

2.11 An early drawing for the *Dominican Sisters Mother House* (1966) in Philadelphia, designed by Louis I. Kahn.

Projection – which I take to be the real core of project making – is different. Similar to probability in scientific discourse, projection in architecture remains within the limits of the likely. The basic idea here is that architecture – designed and built – never offers more than *the conditions under which* something is likely to occur: more than a possibility, less than a promise. Although project making is indeed forward-looking, it is never more than a pre-figuration of a final product, a foreshadowing of an outcome. Far from being a deficiency, its partiality allows the participation of other agencies of formation. The advances of projective thinking are always coupled with delays, even retreats, another apparent weakness compared to self-assured production. Yet before the proposal can anticipate anything final, let alone achieve it, it must define its relationship to what exists, partly tearing itself away from the present, because at least some of its provisions no longer suit current needs, and partly remaining there, for that is where changes must be made and where their effect will be seen. A complete break is refused and adhesions are required. The difficulty for an uncritically progressive notion of design development is that these dimensions always overlap and intersect.

It could be said that good design development has a kind of blind logic that unfolds *during*, rather than being set out *before*, the project, detouring after

advancing, then turning back, renewing beginnings by rethinking premises, and moving forward once again (Figure 2.11). Paul Klee once described drawing as letting a line go for a walk, moving freely without a goal, a walk for a walk's sake.[10] If allowed a goal, the ramble he had in mind illustrates the path of a project very well, forward-looking but open to the attractions of unforeseen encounters, as well as their distractions. The games people play would lack structure and never develop momentum if players did not know with reasonable certainty the outcomes of certain moves. At the same time, they would fail to excite if foresight could be extended indefinitely. Projects play with circumstances and are played by them. In his last text, Le Corbusier said this alone was key: to play the game.[11] For my part, I would say the processes of project making are less a matter of foresight and calculation than of cunning, requiring wide-eyed alertness to possibilities as they emerge. Alison and Peter Smithson had a good term for this type of intelligence: wit + eye. Through project making, then, existing conditions in "the present" are both surpassed and preserved. This double movement will never result from the kind of experimentation that closes the work in on itself, nor from methods untainted by extra-disciplinary involvements. Project development requires movement away from its own methods toward conditions that are not of its own making, an eccentric procedure dedicated to the unseen potentials of the world it seeks to remake.

2.12–13 *Annenberg Public Policy Center* (2012) in Philadelphia, designed by Fumihiko Maki.

More purposeful and much quicker is the third kind of time that plays a decisive role in architecture, *the time of experience*. This sort of movement is paced by one's passage through a built work, including the moments of residing. It involves all the accelerations, delays, and lingerings that occur between and within a building's several settings. I will try to explain this by describing a recent building in Philadelphia by Fumihiko Maki, the *Annenberg Public Policy Center* (Figures 2.12 and 2.13).[12]

Behind the building's unbroken glass envelope are adjustable wooden panels. At the same time that their changing positions indicate patterns of use within the building, they also expose and conceal different depths of interior space. Various aspects of offices can be seen, as well as deeper passageways, central shared spaces, and still farther, parts of buildings beyond it. Because some aspects of these settings are seen and others are hidden, full understanding of any one of them is only intimated, which is to say delayed. Parts are shown but their counterparts are concealed. This is because overlapping results in occlusion, occlusion that has been increased because the layers of the façade have been multiplied and its parts allowed to shift. And what the façade inaugurates, the plan and section elaborate, for passage into and through the building encounters openings and concealings that initiate and prolong spatial discovery. Content is made apparent and kept out of

reach, awareness excited, appreciation postponed. Occlusion is not the only technique of spatial adumbration; corner entries, diagonal movements, and divided pathways serve the same function.

The free-standing column at the entry corner (see Figure 2.12), for example, splits the view and the approach along two lines, one that accelerates past the gridded façade toward the crossroads in the distance and another that is slowed by the shadows that shelter passage into the reception hall. Two paths also diverge from the reception desk, one toward the guest lounge on the façade's opposite corner and a second down the passage toward the *agora*. A run of columns in this latter passage also splits movement, but farther along these paths rejoin where the threshold to the so-called *agora* concentrates a cluster of opportunities that implies a structure of involvements that will be enjoyed well beyond this setting. The opportunities become apparent at the moment of arrival: the involvements appear once movement forward takes its first interior step. Additional steps are greeted by yet other ensembles of suggestions, which are followed by still others as one progresses through the building's public spaces.

Surface layering in this building starts the clock of spatial passage while the clustering of heterogeneous volumes rewinds it. Permeable edges serve the same purpose, extending one's orientation outward and endlessly. While much of the building argues for movement, change, and temporal unfolding, its repetitions, simple massing, and stable orientation assert sameness and fixity, as if its fluctuations were nothing more than different ways of revealing its constancy. Layers of space, discreet settings, and architectural elements can be recessive and withdrawing, what is partially present can also keep itself remote. Spatial order of this showing/concealing kind is contingent on temporal structures: the settings "behind" any one we now see were experienced some time "before," while those "beyond" this one are yet to be experienced. At any given moment, places and times have linkages to distended conditions that are present as *hidden*, which is to say recalled and anticipated, seen partially and implied. The key point is that the work's recessive aspects allow it to *give more than it shows*, to yield content that exceeds what is seen at any moment as well as what might be expected or

remembered.

My general point about the time of experience or of movement is that every work has a structure of sequences that stage the incremental and retrospective sense of its spaces, giving the whole ensemble its characteristic rhythms, which are apprehended by the body as much as the mind. Goethe had this in mind when describing Palladio's architecture:

> It might very well be thought that … architecture works for the eye alone, but it ought primarily … to work for the sense of movement in the human body. When, in dancing, we move according to certain rules, we feel a pleasant sensation, and we ought to be able to arouse similar sensations in a person whom we lead blindfold through a well-built house.[13]

Two key distinctions are made here: one between ocular and bodily apprehension, and the other between the simultaneous and successive sense of settings.

Three kinds of time, then, can be found in well-designed buildings: the time of the world, of the project, and of experience. The permanence that is proper to architecture realizes itself through each of them, even as they resist perfect synchronization and perfect preconception. But as I have said, that apparent failing of design may also be the key to the building's potential richness.

Notes

1 Simmel, Georg, "The Ruin," in *Essays on Sociology, Philosophy and Aesthetics* (New York: Harper & Row, 1965, originally published in 1911), pp. 259–266.

2 I allude to this in *Uncommon Ground* (Cambridge, MA: MIT Press, 2000) and cite Aris Konstantinidis' beautiful account of Easter whitewashing in Greece; see Konstantinidis, Aris, *Elements for Self-Knowledge* (Athens: Agra, 1981), p. 305.

3 Kuma, Kengo, "Breaking Down into Particles," in *Anti-Object: The Dissolution and Disintegration of Architecture* (London: Architectural Association, 2008), pp. 98–120.

4 Faulkner, William, *The Sound and Fury* (New York: Random House, 1946, originally published in 1929), p. 104.

5 These terms paraphrase Merleau-Ponty, Maurice, "Temporality," in *Phenomenology of Perception* (New York, Humanities, 1961, originally published in 1945), pp. 410–433.

6 I have developed this set of observations about "qualification" in a text called "Necessary Qualifications: Design Before, During, and After Construction," in A. Dutoit, J. Odgers, and A. Sharr (eds.), *Quality Out of Control: Standards for Measuring Architecture* (London: Routledge, 2010), pp. 105–118.

7 He introduces these terms and makes this distinction in Rossi, Aldo, *Architecture of the City* (Cambridge, MA: MIT Press, 1982).

8 Schmarsow, August, "The Essence of Architectural Creation," published in 1893, cited in Mallgrave, Harry, *Empathy, Form, Place* (Santa Monica, CA: Getty Center for the History of Art and the Humanities, 1994), p. 295.

9 I have developed a number of the points outlined here more fully in: "The Time of the Project," *Nordic Architecture: a journal of architecture*, no. 3 (2012): pp. 67–72.

10 Klee, Paul, *Pedagogical Sketchbook* (New York: Praeger, 1953, originally published in 1925), p. 16.

11 Žaknić, Ivan (ed.), *The Final Testament of Père Corbu* (New Haven, CT: Yale University Press, 1997), p. 88.

12 The summary account that follows abbreviates an earlier text: "Passages in the Landscape of Time," *Shinkenchiku*, 85 (2010): 85–87.

13 Goethe, W., "Palladio Architecture," in Gage, John (ed.), *Goethe on Art* (Berkeley, CA: University of California Press, 1980), pp. 196–197.

3
Flexible Architecture: Continuous and Developing

ROBERT KRONENBURG

3.1 A doorway in Barcelonetta, Barcelona, Spain. Intuitive flexible use of space combined with “place” making.

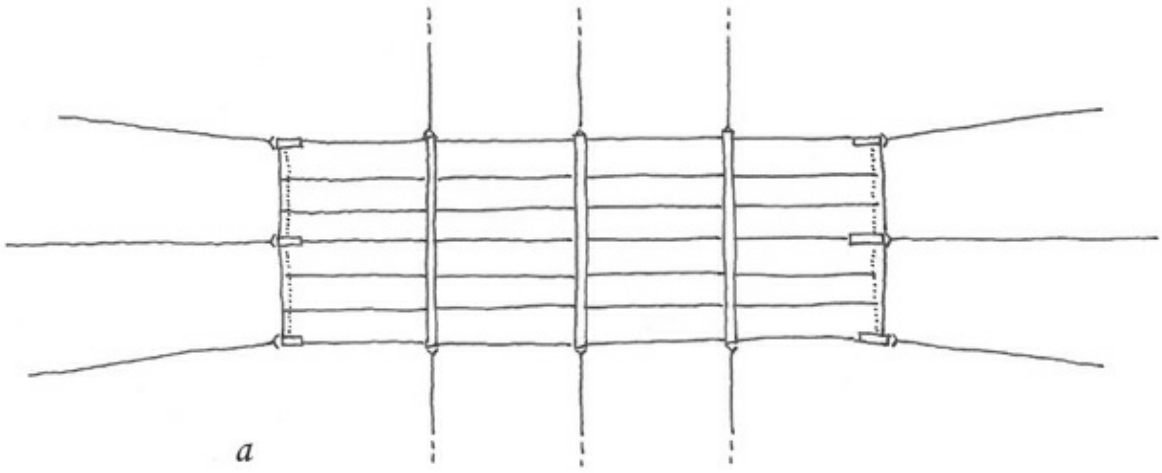
Human beings are flexible creatures. We move about at will, inhabiting space in a fluid and dynamic way as our needs and desires require us to. We manipulate objects that we have shaped in simple or sophisticated ways, again to suit our needs and desires. We can operate in a wide range of environments, and go beyond the natural limitations of our physiology by using the tools we make to adopt and adapt space so that it accommodates our requirements best. It can be convincingly argued that the general advancement of civilization is directly related to this natural desire of humanity to enhance our environment, achieved via a continuous search for

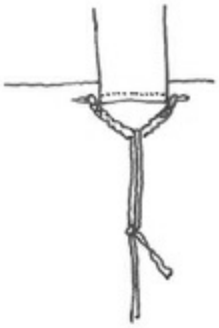
utility and flexibility. Humanity is able to do this because of our intellectual ability to imagine ways in which the world we inhabit can be made to work with greater convenience, efficiency, and beauty – and then to be able to act to physically improve it by the application of skills, craft, and technology. Although in the present day, we are used to sophisticated design appearing from the work of professionals, throughout humankind's existence, elegant solutions to the physical problems of living have resulted directly from the knowledge, skill, and experience of ordinary people. The desire to create a responsive environment goes beyond practical convenience – it is something that occurs in the human psyche at a deep intuitive level.

It can be argued that to be truly successful, architecture must be flexible. There is evidence for a sound philosophical and psychological foundation as to how this characteristic can make architecture better. People use their buildings in their own individual way (Figure 3.1), even if its physical form is so restrictive that it only means they move the furniture around and decorate the walls. Even this limited personalization can alter it from *space to place* – making it somewhere that has special meaning for the individual or group.[1] Furthermore, *time-in-use* generates the special essence of place that is necessary for maturity in human-made architecture, urban space and landscape. This maturity enables special place connotations to be manifested in sufficient strength to be passed down through generations of individuals, for decades, centuries, and even millennia. Though there are many static, fixed buildings that have been preserved as symbolic preserved examples of a bygone heritage (valuable though these can be), there are many more that have been demolished as they proved too difficult to adapt to the changes that were thrust upon them. However, there are also some special building places that are less well preserved (and less valued by the heritage lobby) but nevertheless well used and re-used over time – structures that have been successfully re-purposed and revitalized as each generation has passed through their doors.

Architecture for the Changing World

The world is going through dramatic technical, social, and economic change. In December 1995, there were 16 million Internet users, amounting to 0.4 percent of the world's total population of 5.8 billion. By December 2012, there were nearly 2.5 billion – 35 percent of a much increased world total population of 7.1 billion.[2] In 2013 alone, the number of motor vehicles produced in China was over 22 million, an increase in production over the previous year of 14.8 percent, and a quarter of the world total, which adds 241,000 cars to the roads every day.[3] Some 70 percent of all global growth comes from emerging markets, with 40 percent coming from India and China alone. Consequently, middle-class spending is forecast to double in 15 years with over 80 percent of the increased demand coming from Asia.[4] The dramatic changes brought on by the world-wide web, faster transportation, and global markets have resulted in a revolution in lifestyle for increasing numbers of the world's population. These cultural shifts are happening faster and are more visible than ever before, and take place against the background of an urban infrastructure that often is struggling to keep pace in terms of the numbers and quality of buildings available.





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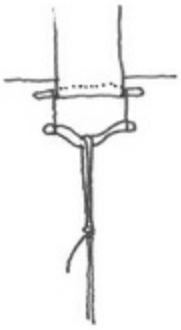

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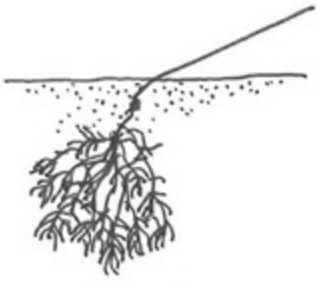

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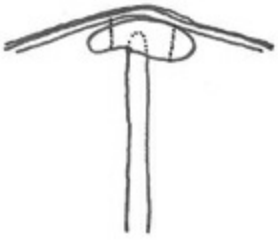

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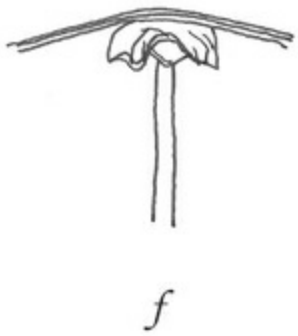


3.2 Bedouin tent: roof plan (a); fastener details (b, c); anchor with rope fastened to buried bush (d); roof pole spreaders (e, f); after an illustration by Torvald Faegre.

Some aspects of the human-made world are therefore not as responsive to change as humanity itself. Most of the buildings that are built are not designed with flexibility as a priority – demolition is frequently the only way to fulfil the changing operational requirements. The new replacement is then often built with detailed improvements in specification and layout done primarily to follow building codes and regulations rather than to meet the challenge of creating something that will respond well to future changing needs over the many decades it will be in use. There is, however, a different way to build. Flexible architecture results from the design of buildings that are only complete once people inhabit and use them. It is designed with immediate interaction with its users in mind, which results in efficient responses to future changing situations. Though by no means universal, flexible architecture nevertheless has a long-established history with a well-embedded human cultural context. It is a type of architectural design that continues to develop, focused on the question: if human beings are so flexible, and the world around us in constant flux, shouldn't our buildings, the largest and most complex objects that we make, be as flexible as we are? There are excellent examples from history that answer this with a resounding yes!

Traditional architecture is inherently flexible. It consists of buildings made by people close to the problem, who intrinsically understand the materials they work with, and utilize construction technologies developed over generations to be suitable to their purpose. Perhaps the earliest form of independent shelter is the tent, first created using simple animal skins

suspended over branches, but developed over millennia into countless different building patterns tuned to local conditions and user requirements.[5] For example, the Bedouin Tekna tent of south-west Morocco (Figure 3.2) is lightweight, easy to assemble, and capable of coping with different ground and environmental conditions, as it must cope with the nomadic herding lifestyle of its owners as they move in a regular cycle around seasonal grazing grounds. It is made from local materials crafted into elegant and beautiful forms and is easily repaired and serviced as needed. The Central Asian *yurta* or *ger* is a form of traditional building that utilizes prefabricated components and sophisticated structural systems. Structurally independent cladding is fitted to a lightweight frame using a geodetic collapsible wall panel with circular compression and tension rings that support the roof.[6]

3.3 *Sears Modern Home No. 11*, reproduced from the 1908 Sears Roebuck Catalog.

Both the tent's suspended tensile structure and the *yurta*'s lightweight dome are early construction patterns that have been developed into much larger, complex permanent building types that are now familiar throughout the developed world. The prefabricated, modular assembly strategy used in their manufacture and assembly has similarly flexible architectural descendants. Sears Modern Homes (Figure 3.3) were one of several companies selling prefabricated buildings in component form via a catalogue during the first half of the twentieth century.[7] Prospective owners could order their house in stages as they could afford its various components, the kit parts being delivered to the nearest railway station for onward transportation to the site. The method of timber construction was simple and adaptable, allowing changes to be made both during and after assembly. The manufacturer was closely tuned into what the customer would purchase – simple, elegant, comfortable, economic homes. Contemporary manufactured housing is a direct descendant of homes like the Sears product, providers being closely aware of what their customer base requires, making pattern-built homes that nevertheless have great degrees of flexibility built into the designs due to the modular way in which the buildings are manufactured. This is a type of semiformal architecture, in which a design professional is involved, although the owners' requirements, affordability, and efficiency are prioritized over appearance and site context. In this design methodology, flexible characteristics, particularly in layout and construction, are adopted without inhibition as long as they are useful and achievable.[8]

Larger flexible engineered structures also have a long history. Manufacturing innovations during the Industrial Revolution in the late eighteenth and nineteenth centuries led to new materials like plate glass and cast and wrought iron. The possibilities of significantly increased manufacturing tolerances meant that a high degree of dimensional coordination could be used in creating prefabricated buildings that could be made in one location and shipped for speedy assembly far away. All types of buildings from small dwellings to enormous lighthouses were manufactured in Great Britain and subsequently erected as far away as Australia, Ceylon, and Bermuda. However, the most significant use of this technology was

domestic, created by Joseph Paxton for the erection of the Great Exhibition building in London in 1851.[9] Manufactured in just six months, the vast 71,500 m^2 building itself was as much an attraction for its visitors as the exhibits it contained. The giant glazed structure, dubbed the *Crystal Palace,* was a *tour de force* of prefabricated, mass-produced components, which had been erected at dramatic speed due to modular construction methods. These also enabled unprecedented flexibility in layout and the capability for future relocation and change. Even during the construction phase, its builders, Fox, Henderson and Co., forecast a remarkable re-assembling of the components as a skyscraper, although in fact its relocation was in a similar, larger, and more usable form on a new site at Sydenham a year later. The Great Exhibition building spawned many copies and developments of the technology used, such as, and most visible today, the 1889 Eiffel Tower in Paris, a legacy from that city's own Great Exhibition.

Paxton's concept of a building that could be used in many ways, and be open to future adaptation to as yet unknown purposes, is a crucial concept in flexible building design, not only for its practical benefits but also as a tool to engage better with the building's users. A contemporary building that uses some of the Great Exhibition building's philosophies for this purpose is the Sendai *Mediatheque*, Japan, designed by Toyo Ito in 2001 (Figure 3.4). Created with the intention of being an interactive resource for Sendai's city residents, the building's initial function is that of a library/community center that can change and adapt as new media and functional opportunities arise. Its form is a simple glass cube with transparent walls through which internal activities can be seen by passers-by in the street, and likewise building users can see the outside environment. Internally, a series of flat floor plates are suspended by steel lattice "trees" that are also physical and visible links between each level. Each floor has a specific function such as library, performance area or café, but also can be multi-purpose spaces and ambiguous "adoptable" spaces. Walls and furniture are movable. The informal character of the building enhances an interactive community of uses in which people can wander around, and if they wish, interact with the activities taking place and with each other.

3.4 *Mediatheque* (2001) in Sendai, Japan, designed by Toyo Ito.

The same reasons that make traditional and semi-formally designed architecture flexible – because it makes it more useful and efficient – apply to sophisticated contemporary buildings like the Sendai *Mediatheque*. They are designed to respond to users' needs in providing shelter and comfort in a particular environment whether they are large or small, handmade or machine-manufactured. And yet, although it appears to be a natural human response to build flexibly, it is clear that most buildings are not made this way because of a blinkered focus on short-term goals. It certainly cannot be because human ingenuity is lacking. Every aspect of human activity provides examples of our irrepressible inventiveness and need for responsiveness in work, rest, and play (Figure 3.5). Freedom and flexibility are integral aspects of human existence. It is a way of life for some who take their need for choice

of lifestyle and dependence on their own efforts to extremes, e.g., in sport or exploration, but for all of us there is a part of our life that works best when we are allowed that flexibility and is unnecessarily restricted when it is proscribed. The ability to do things the way we want to do them is a deeply ingrained human need, and, many would argue, a right.

3.5 A restaurant for two people: a “pop-up” soba noodle hut in Osaka, Japan.

One important example where the natural ability of human beings to respond flexibly to changing situations can be effectively used is in disaster relief. Providing relief in areas of the world affected by natural disasters or human conflict is an enormously complex undertaking. Problems arise not only in providing appropriate relief in the location where it is needed as fast as possible, but also in ensuring it arrives in a usable form and aids the people who need it rather than others who might divert it for their own use or profit. In the past, a considerable amount of disaster relief has been criticised as donor-led – the type of relief provided being determined by those who are donating it, with relatively little interaction with the people on the ground who are actually suffering and who therefore are in the best situation to describe what they need. Thanks to careful research, effective communication, and better feedback to the non-government organizations that organize most relief, over the last decade this situation is now much improved.[10] ShelterBox is one of the charities that specifically engages with those whom it is trying to

help by providing effective relief that they can make use of easily and speedily. The ShelterBox is a container that contains everything a family needs to quickly establish a temporary place to live after a disaster has removed their usual home. It includes a specially developed tent, heating, cooking and building equipment, and other carefully considered items including a learning and play pack for children. The box is easily portable, allowing them to establish a new base close to their damaged house and thereby protect their possessions, re-establish their livelihood, and be on site to begin rebuilding. This swiftly provided aid supplements more formalized health and provisions support, treats the victims of disaster with respect, and acknowledges their capacity to help themselves by giving them the tools to do it.[11]

The life-saving capacity of flexible building design has many precedents throughout history, ranging from the simple provision of shelter to more complex, mid-to long-term architectural projects that enable the re-establishment of severely damaged communities. The best of these allow flexibility and adaptability to be prioritized, acknowledging that situations change and cannot always be fully predicted. For example, the simple wooden sheds that were set up by authorities after the 1906 San Francisco earthquake (Figure 3.6) proved their usefulness as they could be easily relocated from the open park areas where they were originally established, to the sites of residents' fire-damaged homes, providing a base from which to tackle reconstruction. Similarly the "blue tarp" programme instituted by the Army Corp of Engineers in response to the Hurricane Katrina disaster in New Orleans in 2005 meant that many thousands of people could quickly cover their damaged homes and this could give them time to remove or protect their belongings and set about quick temporary repairs. Shelter after disaster is one example of flexible design's continuing value and relevance throughout history, however, it can be seen in every aspect of human activity, from entertainment to education, expedition to health, commerce to manufacturing.

Adapt, Transform, Move, and Interact

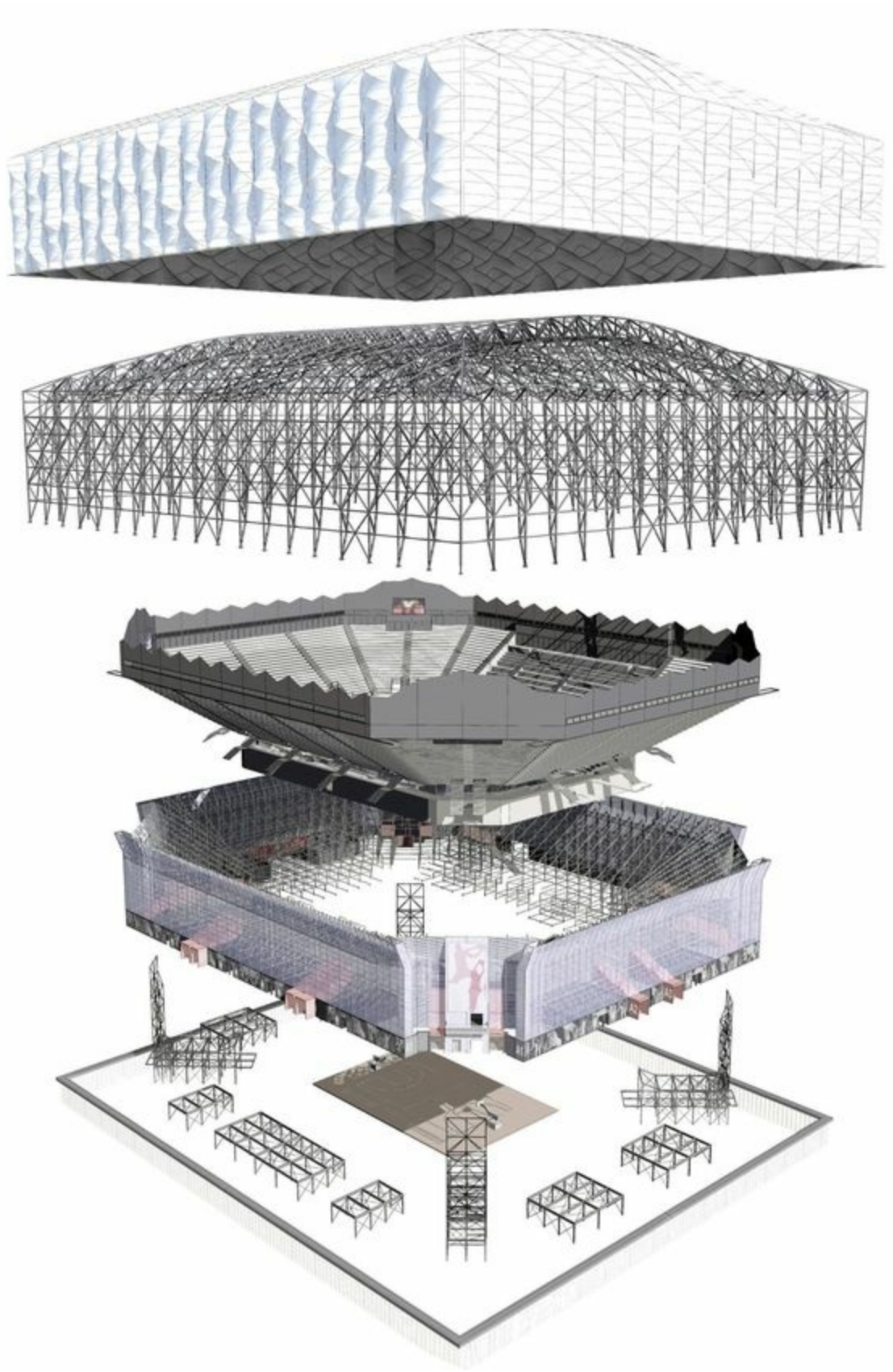
The full application range of flexible architecture can best be explored by considering the typology of characteristics that have shaped its manifestation. It is important to note that it is not possible to pigeonhole flexible architecture into specific categories, as good design often transgresses boundaries and makes use of multiple strategies within a single project, however, it is useful when trying to understand the manifestation of this type of complex architecture to organize it into themes. This helps in comparing how well specific strategies have worked and in seeking cross-overs for different problems or developing situations. There are four principal themes into which the characteristics of flexible architecture can be organized: Adapt, Transform, Move, and Interact.[12]

Adapt includes buildings that are designed to adjust to different functions, users, and climates (seasonal or associated with climate change). The designers of this form of architecture understand that the future of a specific building cannot be fully appreciated at the time of its inception, that what they create must be able to respond to future changes in occupation needs, user requirements, and external factors. In the past this type of architecture might have been categorized as "long life – loose fit," however, good contemporary adaptable architecture is not created around the philosophy of one size fits all, but with truly flexible intentions that allow specific solutions to be available within the primary building fabric without recourse to major expensive renovation. This is sometimes identified as design using Open Building principles, in which a series of intervention levels creates a framework for flexibility.[13] Each level defines an area of building activity from the urban city level down to the fit-out of individual rooms. When designing each level, this is done in relation to the next with the aim that no work is done that will have the impact of reducing the capacity for change in the adjacent levels. Levels can be given an operational life span, e.g. the building's primary structure 100 years, the secondary systems of walls and floors 20 years, the tertiary system of surfaces and environmental systems 10

years, etc. This enables change to take place in a planned way. An example of planned change building is in the houses for old people, designed by Dutch architect Frans van der Werf. As people age, they are typically required to move between residences as their physical capacity declines – from a conventional house, to assisted living, to a nursing home – moves which can be traumatic and debilitating. Communities designed by van der Werf, such as Rijnwaarden te Tolkamer, in the Netherlands, 2003–2005, are designed to adapt to change in the physical capacity of the resident, enabling them to stay in the same home for many years longer than would be the case in conventional housing. The apartment layouts can be designed around the needs and desires of the individual when they first move in, but as their needs change, they can then be easily altered to accommodate mobility and other health issues with the minimum of intervention.

3.6 Wooden sheds used for shelter after the 1906 San Francisco earthquake and fire. Many were subsequently transported to victims' damaged homes and used as a base for rebuilding work.

Transform includes buildings that change shape, space, form or appearance by the physical alteration



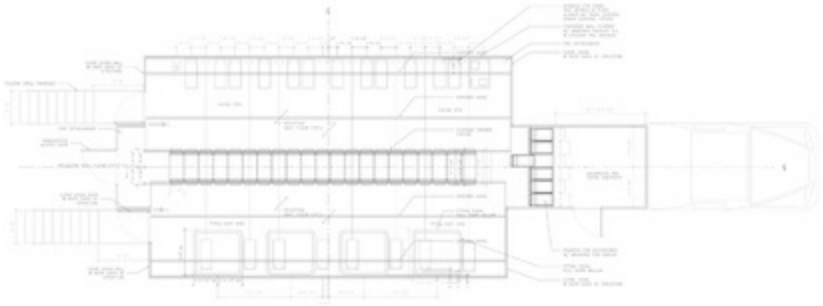
3.7 *Olympic Basketball Arena* (2012) in London, UK, designed by Wilkinson Eyre.

of their structure, skin or internal surfaces. This type of architecture takes the normal operational features of a building: its furniture, windows, doors, shutters, and blinds, and extrapolates the flexibility to include whole segments of the structure. Elements that would normally only be changeable via demolition and alteration can be changed relatively easily to accommodate changing requirements and conditions. An opening window is a welcome engagement with the external environment enabling ventilation but also the sounds of the outside environment to enter a room. Moving an entire wall aside does something more, converting the room into an inside/outside space that engages with the external environment in a different and more immediate way. However, buildings can also transform in more fundamental ways. Wilkinson Eyre Architects' London 2012 *Olympic Basketball Arena* (Figure 3.7) was designed to be temporary but also to be transformable, as it had to serve two different sports during the Olympic Games. The 115 by 90 m stadium was made from a componentized modular steel frame, and contained temporary raked seating for 12,000 spectators. Part-way through the games the layout was changed over a 22-hour period from the basketball competition to the handball competition with a new floor laid and 2,000 seats removed. The building was transformable in other ways. Its 35 m-high façade was clad in a PVC skin that formed a screen for a projected nightly light show. Two-thirds of the building components were standard reusable elements that could be used again in a different structure once the Games were over.

Move includes buildings that relocate from place to place – this is architecture that rolls, floats or flies. Despite the intrinsic problems associated with designing a building – traditionally a large and heavyweight object – so that it can move from place to place, mobile architecture is not only common but has been used continuously throughout history. Contemporary moveable buildings are made because they solve a problem better than a static one, or because there is no other way at all for the problem to be solved. Expeditionary and military needs often lead to mobile buildings, for example, mining camps built to access minerals in remote locations or at sea, and

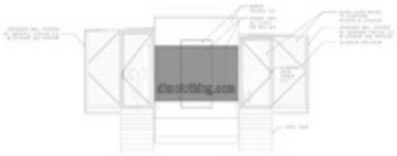
vehicle servicing, logistics support, and medical provision in battlefield locations. Entertainment and commerce are also frequent functions. The circus tent is the archetypal mobile entertainment venue, but mobile banks, catering, and shopping often need to go to customers when they are in locations such as festivals, show grounds, and events away from permanent structures. LOT-EK are a New York-based design team who have developed special expertise in designing mobile buildings, often using recycled industrial components such as shipping containers. Their *DIM mobile clothes store* (Figure 3.8) is, however, built on a truck chassis, which is towed by a conventional tractor vehicle. Once at its location, the trailer converts into a unique building. The sides pull out to create the main shop floor with racks of clothes on either side. Full height video screens show both the clothes within and real-time relays of the shopper standing in front of the rack. Fitting rooms are suspended from the ceiling and drop down for privacy when the shopper wants to try on an item. Although this is a moveable building, it could actually be included in any of the four categories of adapt, transform, move, and interact.

Interact includes buildings that respond to users' requirements in automatic or intuitive ways. Interaction is a key aspect of human existence. Our ability to interact with our environment, to change our actions in response to developing situations and then to make changes to things around us with these actions is crucial. Developing artefacts that also respond in this way has been an important driver in technological advance, culminating in microprocessor-controlled "intelligent" machines that act independently from conscious human management, anticipating our needs and actions. The building industry lags behind vehicle manufacturing, entertainment, and commerce in its adoption of interactive technology; however, some buildings are now being made that engage with both the environment and inhabitants in order to automatically improve the way they

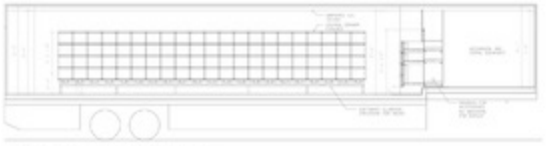


PLAN

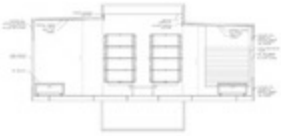
SIDE ELEVATION



REAR ELEVATION

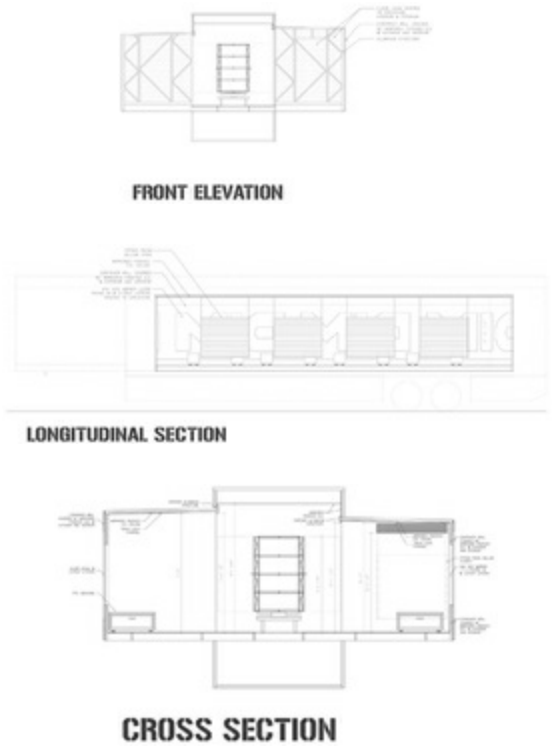


LOGITUDINAL SECTION



CROSS SECTION

SIDE ELEVATION



3.8 *DIM Apparel mobile clothes store* (2004) for the Sarah Lee Corporation, New York, designed by LOT-EK.

operate. Architects Cloud 9 created one of the most ambitious buildings of this type in 2010 with the *Media-TIC* building in Barcelona, Spain, which uses multiple methods to reduce energy demand and control environmental conditions. Internally the building incorporates 300 sensors that sense the presence of occupants to adjust the performance of services according to the level of occupancy and the ambient light levels. However, it is the external skin of the building that is most innovative. On the south-facing façades two systems using ethylene tetrafluoroethylene (ETFE) cushions provide flexible, and highly dramatic, sun shading that are triggered by sensors in the façade. The southwest façade uses vertical cushioned panels, which contain a nitrogen and oil mixture that temporarily coalesces into a "cloud." The south-east façade has triangular cushions with three inflatable chambers. Two of the layers have a reverse design pattern which are brought together to provide full shading when the inflation is actuated.

Why we Need Flexible Architecture

Flexible architecture can be found in every area of human activity, and what it can achieve in terms of increased performance and operational ambition is still developing. By definition, flexible architecture takes on a variety of forms and fulfils different functions – it is not a style and there are many different designers and builders/manufacturers around the world involved in its creation. However, the best examples do share similar characteristics and benefits. Flexibility allows buildings to remain in use longer, thereby preventing costly and wasteful comprehensive demolition and rebuilding. These buildings fit their purpose better by enabling modifications to be made as needed to respond to changes in the function they support. They accommodate users' experience in a more responsive manner by enabling the buildings to be "completed" by the occupants' interventions as they adapt it to their needs. Because flexible architecture is able to change relatively quickly compared to conventional building, it can take advantage of technical innovation more quickly – rather than having to be rebuilt completely, retrofit technologies can be added with less disruption. Also because of this responsive capacity it can remain relevant to cultural and societal needs for longer, maintaining pace with what we expect of our buildings and how we use them. All these abilities have operational ramifications that bring economic advantages, however, they also provide the absolutely crucial benefit of enhanced sustainability.

3.9 *Number of Planets Needed* chart (2012) by Global Footprint Network. Source: Global Footprint Network, Earth Overschool Day, 2012

The *Number of Planets Needed* chart (Figure 3.9), produced by the Global Footprint Network, illustrates why we urgently need to use the benefits that flexible architecture can bring.[14] There is an urgent requirement to re-evaluate how the world's resources are being used as each year humanity uses more raw materials than the planet is capable of renewing. The (2012) chart shows the most recent full year's data (for 2008) indicating how many individual nations are "overspending" their share of the world's resources. The USA is in deficit to 4.16 times its share of the Earth's resources. This means that if we think of the resources as an annual salary, the USA has spent all its cash by 28 March. Canada is in credit to the tune of 7.9 times its share of the Earth's resources because of its large land mass area compared to its population/resource use. The UK is in deficit to 2.6 times its share of the Earth's resources. Ecological overshoot day for the whole world is 22 August which is the equivalent of using more than one and a half Earth's worth of resources in just one year – and this is currently happening every single year! Using all our resources economically and sustainably, of which buildings are major components, is perhaps the greatest single challenge that the human

race has faced in its entire existence.

3.10 Pedestrians at the *Grande Arche*, La Défense, Paris (1989).

However, human beings are ingenious. Architecture at the edge of invention such as that described in this book is one example of the search for ways to deal with this issue. Just twenty years ago the building industry was looking towards the future in terms of CAD, integrated digital fabrication, the beginnings of BIM, and the invention of new materials using chemistry and biomimetics. All these elements are now a part of mainstream architectural production, and new ground continues to be broken. In 1953, Francis Crick and James Watson published theirs and Rosalind Watson's discoveries regarding the form and structure of DNA. The double helix consists of two sugar and phosphate strands with four chemical bases that contain the code for all of life – a natural biological data storage device in the form of a binary system. This structure has remained frozen yet continuously variable for billions of years. Now scientists are altering the code, adding in new bases to

provide valuable synthetic mechanisms to solve both old and new problems. In the same way that early builders took a natural form, modified it and used it to human advantage, we now have the ability to do that with the natural template that makes up all life. Evolutionary geneticist Adam Rutherford states:

> There is a visceral belief in some quarters that we shouldn't be fiddling with nature in such fundamental ways. But it is our responsibility to allow DNA technology to flourish, while society makes informed decisions about how its fruit are shared. We are in a golden age, an industrial revolution ...[15]

Rather than making buildings from natural materials that we have grown, then harvested and shaped into a static, relatively inert state, perhaps the future will consist of buildings that will have their shape designed into their genetic make-up. They will grow into their finished form, but not content with that, will renew their worn-out parts as time passes, and even be programmed to change in response to the other biological systems that form part of their eco-system ... us.

There can now be no excuse for creating architecture that fails to cope with current variations and future change, as the reasons for designing with flexibility as a priority are more important now than ever before, and the technical ability to do it this way is more readily available. The functional and operational failings of inflexible buildings indicate how the designers' knowledge and objectives have become separated from the users' experience and needs (Figure 3.10). How can housing that is unfit for habitation by its adherence to a stylistic genre rather than the requirement of its inhabitants be justified? Or "iconic" architecture that is more concerned with its symbolic presence than those who will use it be relevant? The Vitruvian architectural virtues of *firmitas*, *utilitas*, *venustas* (strength, utility, beauty) remain at the core of achieving good architectural design.[16] In the contemporary architectural brief, the first can best be translated as durability, the second as function, and the third remains timeless ... beauty. The critical requirements for good flexible architecture fit within this triad: it needs to be designed for long useful life; to fit its users' needs well; and to beautifully express its

appropriate use of our resources and fit to the environment.

Notes

1 The significance of "place" is a crucial concept that establishes human identity and existence, explored most eloquently by the German philosopher Martin Heidegger. See Heidegger, Martin, *The Question of Being: An Ontological Consideration of Place* (New Haven, CT: Yale University Press, 1958).

2 1995 statistics sourced from the International Data Corporation (IDC) (www.idc.com/home.jsp, accessed 2 May 2014). 2012 statistics sourced from International Telecommunication Union (ITU) (www.itu.int/en/Pages/default.aspx, accessed 2 May 2014).

3 International Organisation of Motor Vehicle Manufacturers (OICA) (www.oica.net, accessed 2 May 2014).

4 Forbes (www.forbes.com/pictures/eglg45gdjd/emergingmarket-growth-beats-us-2/, accessed 2 May 2014).

5 The earliest buildings created by human beings were portable and continued to be so for many millennia until settled patterns of existence developed. For a detailed history of mobile and temporary architecture up to the present day, see Kronenburg, Robert, *Architecture in Motion: The History and Development of Portable Building* (London: Routledge, 2014).

6 For an in-depth discussion of traditional building types, see Oliver, Paul, *Dwellings: The House Across the World* (Oxford: Phaidon Press, 1987).

7 See Ward Jandl, H., *Houses by Mail: A Guide to Houses by Sears, Roebuck and Company* (Washington, DC: Preservation Press, 1986).

8 See Wallis, Allan D., *Wheel Estate* (New York: Oxford University Press, 1991).

9 See McKean, John, "The Crystal Palace," in *Lost Masterpiece*s (London: Phaidon Press, 1999).

10 The UNDRO (Office of the United Nations Disaster Relief Coordinator) has specifically targeted providing better information and feedback regarding shelter provision, coordinating data from numerous agencies into a series of influential reports and online resources. UNDRO, *Shelter After Disaster* (Geneva: UN, 2010), sets out the critical issues associated with appropriate

response in post-disaster situations.

11 See ShelterBox (www.shelterbox.org, accessed 2 May 2014).

12 These themes were first formulated and proposed by the author in his book, *Flexible: Architecture that Responds to Change* (London: Laurence King Publishing, 2007).

13 John Habraken first articulated the Open Building principles in the 1960s. See Habraken, John, *The Structure of the Ordinary: Form and Control in the Built Environment*, ed. Jonathan Teicher (Cambridge, MA: MIT Press, 1998).

14 Global Footprint Network (www.footprintnetwork.org/en/index.php/GFN/, accessed 2 May 2014).

15 Rutherford, Adam, "DNA Double Helix: Discovery that Led to 60 Years of Biological Revolution," *The Guardian*, 25 April 2013.

16 Marcus Vitruvius, *Vitruvius: Ten Books of Architecture* (20–30 bc), trans. M.H. Morgan (New York: Dover Publications, 1988).

4

Devising Design: Agility, Aptness Equilibrium, Imperfection

BRIAN R. SINCLAIR

Prologue

> Technology is the answer but what was the question?
>
> (Cedric Price)[1]

Design and planning in our modern ethos are often confounded by serious and endemic conditions of deep fragmentation, rampant bureaucratization, and ineffective regulation. Such barriers commonly hamper the ability of environmental designers to realize success in the execution of responsive, responsible, and superb projects. Adding to the impressive mix of challenges are cost escalation, outdated technologies/techniques, conservative posturing, and the ever-daunting threat of value-engineering. In such a milieu it becomes extremely difficult for designers to move from concept through construction with clarity, continuity, and even integrity. Left on the editing room floor all too often are the inspiring, enduring, and delightful qualities that elevate projects from building to architecture.

In the past few decades the author has assumed a broad range of positions, roles, and responsibilities connected closely with the conception, design, development, and construction of many large, complicated, and multi-faceted building projects. Through effecting this portfolio of work, including intensive research into and comprehensive review of processes and product, it has become evident that the need for reform proves both urgent and imperative. The present chapter looks at a range of issues surrounding *agility*, including at a general level the pursuit of more successful and sustainable design and planning. Exceptional design is best cultivated when certain characters and conditions are primed and aligned, including enlightened clients, talented architects, and sympathetic authorities with jurisdiction. Modern times, in order to produce effective and efficient solutions to wicked problems, demand more innovative, creative, and experimental approaches. Novel notions pertaining to materiality, constructability, affordability, durability, agility,

adaptability, flexibility, modularity, and accountability loom large in equations for ingenuity in our contemporary ethos (Figures 4.1a–e).

4.1a–e Inherent flexibility and adaptability in traditional Japanese *ryokan*.

A Holistic Framework for Design and Planning

> We are the product of an environment that is disconnected from the natural world, disconnected from the very world that we were evolved to be part of, and we are suffering from a collective posttraumatic stress. That doesn't mean my next door neighbor has post-traumatic stress in the same way I do – but he has grown up in a culture that does not allow him to experience connection to people, animals, stars and the tides as he was meant to.
>
> (Chellis Glendinning)[2]

Unprecedented problems call for novel inspired strategies that can lead to superior and more appropriate solutions. In reaction to such a standpoint the author developed a *Holistic Framework*[3] focused on design and planning – an approach in which key realms operate cooperatively and collaboratively, understanding that all hold equal value. Realms of *agility*, *fitness*, *diversity*, and *delight* (Figure 4.2) are seen as having great "give and take" and capacity for customization. Underpinning the model are philosophical "tactics" of place-making, sustainability, culture, design, and a guidelines strategy. Building directly from each key realm are four *action areas* (Figure 4.2); these are not definitive but rather should be seen as modifiable and explicatory. Openness to a range of options proves essential to the successful deployment of the model and fundamental for the further delineation of context-specific, pertinent, and potent *action areas*.

The following *Holistic Framework*, presenting a series of guidelines and

associated action areas, should be seen as an interrelated set – a rich system of interaction and integration where classification is less important than consideration. The guidelines are intensely inter-connected and entirely complementary. Successful design and planning interventions, and successful environments (e.g., interiors, buildings, landscapes, spaces, and places) thereafter, most regularly arise when attention is given to both poetics and pragmatics. While some argue that environmental design should be tackled with a pragmatic approach only, I believe that all people deserve joy, respect, and dignity in their lives. The *Framework*, comprising the nested components of *holistic guidelines* and *action areas*, proves unconventional and in many ways indeterminate and discretionary. That said, the real value of this set of guidelines and actions comes via looking at the world, and its problems, in fresh ways. For an engineer to consider delight is a good step. For a politician to imagine agility is helpful. For an architect to embrace diversity is beneficial. And for all players to critically envision and ensure fitness of environments and people is vital to the realization of communities that are healthier, more liveable, and more successful. No small charge for sure, yet necessary and important nonetheless.

4.2 *Holistic Framework* for design and planning.

Agility

In the design and planning of urban environments it is essential to pursue, create, and realize greater agility, better interrelationships of components, and more open systems.

A typical approach to design and construction in most jurisdictions globally is to erect purpose-built structures, such as a school, or an office building, or housing. Even within a given building type, the structure itself tends to be very fixed and static – not easily modified or adjusted despite the fact that needs and uses may and do change over time. One result of this approach is that such buildings often cannot readily adapt to changing demands. Another outcome is that buildings cannot easily be reconfigured, expanded or contracted as activities shift. Further, if said buildings can be retrofit, the costs involved are often significant. In many cases the maths demonstrates it is far easier, and more justifiable on the accounting ledger, to tear down the old and build a new. In an era of climate change, rising pollution, growing populations, and dwindling resources, such strategies no longer meet muster. One can and must extend the arguments beyond the building itself to include critical aspects of landscape design and of city planning, including such matters as infrastructure and social systems. Agility calls for thinking (designing and planning) and acting (constructing) that is far more open, malleable, responsive to needs, responsible to society, and systems-oriented. Rather than fixed in time, agile solutions are nimble. Rather than static in form and substance, agile solutions are dynamic.

Fitness

In the design and planning of urban environments it is essential to foster, invent, and implement spaces, buildings, and neighborhoods that are

truly appropriate for the needs of people, the nuances of culture, and the demands of context.

The notion of fitness implies a natural relationship between object and subject, good suitability between building and inhabitant, and above all the correctness of that which is supplied to that which is demanded. In many cities, and indeed in many circumstances within the environment, there are glaring conflicts between the requirements of a given community and the solutions developed to meet the apparent needs. The reasons for the mismatches are many, including the frequent disconnect between building owners and users, between designers and builders, between politicians and citizens, and between the empowered and the disempowered. The overwhelming authority afforded by money, privilege, and power routinely translates into the creation of environments that serve one agenda while discounting or denying others. The notion of fitness, and the guideline addressing the same, serve to underscore the great need for listening well to the array of stakeholders and then executing professional responsibilities and talents with fairness, skill, and grace. While, on one hand, this is common sense, often efforts miss targets. To meet users' needs fairly, competently, and professionally demands intense diligence, prudence, clarity, and equity. To such ends, it is helpful to see through the eyes of the "other." For example, in the exercise of designing a project in another country an architect should be able to envision and understand the ways in which the project might be seen and received – both on the upside and on the downside. Such connection demands a more immersive role and empathetic awareness than is typically afforded or realized in such scenarios. The arm's-length distance that is commonly established contributes to disconnections in the design and planning enterprise. Potent mechanisms to counter such disconnects include community-based design, collaborative planning, and the integrated design process.

Diversity

In the design and planning of urban environments it is essential to consider, cultivate, and ensure a compatible array of land uses, a complementary collection of building types, and a synergistic community of stakeholders.

Designers and planners over the past century were enamored, and at times became obsessed, with clinical zoning. Under such zoning regimes, uses were highly separated and segregated with, for example, residential and commercial far removed from one another. The world of clinical zoning was best understood through two-dimensional maps and plans. Lines of demarcation on a diagram ensured that home and office were separated, that white-collar offices were contained away from manufacturing concerns, that health care was bundled together, shopping was aggregated, and education carefully bounded. Today environmental designers, real estate developers, politicians, and citizens alike are realizing that something is seriously lost when uses and users are arbitrarily divided and estranged. Through history many types of people, doing many types of activities, were tied together in close proximity. Higher density, greater convenience, and richer more fulsome environments were the order of the day. While there were problems, such concerns were eclipsed by the tangible benefits of propinquity and community. In recent years, forward-thinking environmental designers have called for a re-consideration of such distinct zoning and in its place rally for a mosaic of activities and the proffering of messy vitality. Messy vitality is seen as the complex urban milieu that arises when people from different backgrounds come together, when activities in various realms transpire under a common roof, and when opportunities are provided for serendipity and spontaneity.

Delight

In the design and planning of urban environments it is essential to emphasize, envision, and make spaces and places that contribute meaning, comfort, and contentment to the lives of people.

Too commonly today we are willing to separate function (pragmatics) from aesthetics (poetics). In many instances, under the guise of value engineering or cost cutting, we aim to strip out from buildings, landscapes, and communities those features judged to be frivolous, luxurious, or simply unnecessary. However, the decisions about what might be required in our lives, including in this case in our built environments, are commonly in the hands of people ill-informed and inadequately equipped to render such judgments. For example, often sustainability aspects of projects are removed after being determined to be ancillary to a building's core purpose. Or artistic aspects of a project, such as a tile mosaic or a stained glass window, are stripped out after being judged as irrelevant to a building's function. What is missed in this thinking, and left out of the equations used in evaluation, are the significant roles that beauty, delight, meaning, and satisfaction play in our lives. In the view of the present researcher, whose background is in both architecture and psychology, it is often these more intangible qualities such as beauty and delight that matter most. In crafting the present *Holistic Framework* the ethos of *delight* was deemed central and essential. Too often our environments are conceived with a mindset that favors science and technology at the expense of humanities and arts. And too often our environments are evaluated with metrics that advantage quantitative values at the expense of qualitative aspects. For environments to be truly successful, they must respect the Vitruvian trilogy of "strength, function, and beauty."

Agility in Architecture

> Considering architecture in the context of the massive changes currently taking place reveals that our profession is more reactionary and conservative than the rest of the world might suspect.
>
> (M. Shamiyeh)[4]

Having considered a more holistic approach to design and planning it is important to focus attention more specifically on agility in architecture. Despite the pioneering image of architectural practice being highly

progressive and forward-thinking, in reality the vast majority of buildings designed and constructed in the past have been relatively conservative, arguably conventional, and, in the end, hugely difficult to modify. Most buildings are constructed for single purpose use, for example, an office, a hospital, a school, a residence, etc. The architectural program for such structures is usually tightly delineated in terms of spaces, areas, arrangements, and qualities. The nature of the construction process, and especially in North America, is best defined as incremental, fragmented, and even inefficient. A wealth of agents and players, from architects, developers, and financiers to general contractors, sub-trades, and manufacturers, all struggle to find their place, posturing, and timing within an overly complicated, perplexing, and long-established milieu. Factors such as access to materials, availability of trades, market pricing on structural systems, policies and codes, and, of course, approval by regulatory authorities, all contribute to a daunting *modus operandi* regarding the design and delivery of architecture.

While, historically, design and construction processes and products have been quite routine, predictable, and wasteful (e.g., massive contributions to landfills via the building industry), recent concerns about the state of the planet, the degradation of our environments, and the significant damage inflicted through erecting and operating the built fabric of cities, have raised more than a few flags. The rapid ascent of green and the strong subscription to sustainability have put designers and builders under intense scrutiny with regard to ethics, values, and responsibilities. The world is now more urban than rural. Populations in many nations continue to burgeon. Our building stock is aging with pressures to retrofit existing buildings, and requirements to construct new ones, simply remarkable. While many new materials, innovative constructional approaches, and energy-saving systems are emerging, they tend to build upon commonly accepted ways of seeing, thinking, and acting – that is, despite emerging technologies and novel tools, adherence to the status quo remains severe. In light of the urgency regarding climate change, resource limits, and widespread pollution (e.g., air, water, ground, light, noise, etc.), it seems imperative to transcend the status quo. In fact, considering the plethora of variables in flux, including changing

demographics, shifting needs, intensity of churn, etc., it is undeniable that the design and construction sectors must undergo critical and substantive transformations, including a total reconsideration of means and ends with respect to human habitation and city building.

4.3 *Next 21* Open Building demonstration project (1993) in Osaka, Japan.

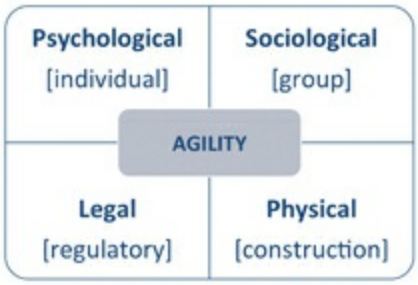
The 1960s were a significant period in the annals of modern architecture, with many theoreticians and practitioners filled with enthusiasm of the modern age, equipped with new materials and technologies, and ripe with ideas on how to construct cities of the future that would usher in harmony, happiness, and utopian lifestyles. The Japanese Metabolists, for example, led by bold and brilliant thinkers like Kisho Kurokawa, imagined cities where the parts were in synergy, where the systems intertwined, and where the lifelessness and the static were swapped with the living and the dynamic. Leading figures such as Cedric Price, Yona Friedman, Gordon Pask, and Constant Nieuwenhuys denied the shackles of the past and sought environments that were fluid, flexible, and responsive. Price's *Fun Palace*, for example, proposed interiors that could be reconfigured based on needs and

redeployed, by users, as demands shifted. It was an era that considered the fantastical opportunities for buildings to accommodate the needs of users, versus the more typical (and certainly so today) arrangements whereby people are shoehorned into spaces (where they must struggle to feel comfortable physically, thermally, psychologically, etc.). The vision of the day was spectacular – that is, to create cities, buildings, and spaces that reacted to needs in real time, that altered composition based on conditions, and that pushed and pulled according to expectations. While the concepts were advanced and inspiring, the main challenge was the serious lag in technology. Simply put, the science and systems of the day were not sophisticated enough to rise to the occasion. Only now, in our present times, have science and technology progressed to the point where the thoughts and theories of these architectural pioneers might be realized in built form.

A relatively recent movement worth exploring, in this regard, is Open Building. Open Building (OB), as an evolving architectural methodology, allows our buildings, similar to ecological systems, to change and adjust over time (Figure 4.3). Embedded flexibility enables such buildings to adapt to different circumstances and be mutable in terms of systems upgrades and ongoing maintenance[5] – hence, in the larger picture, they prove more resilient and less wasteful. The adaptability in OB has become possible through separating the structure or "support" from the interior or "infill" – in essence, ensuring that the systems in a building are independent yet interrelated. This innovative approach challenges the typical "entangled" systems in conventional buildings and provides much greater degrees of flexibility. John Habraken[6] introduced "support" and "infill" as new categories among existing levels in his theory of "decision-making levels in the built field." In this theory, Habraken divides the built environment into different aspects that have varying lifespans and across which the decision-making and control are delegated to different parties. In these various "environmental" levels, users have the ultimate control over the "flexible" interior or infill level to adapt it to their own needs and desires. In this system, "support" is the continuation of urban fabric in the third dimension – its longer life-span and relative permanence support stability with respect to long-term community interests

while “infill” accommodates change in respect to individual preferences in the shorter, more immediate, term.

While serious attempts are underway, and often good progress realized, in green building mantras, methods, and metrics (e.g., Leading in Energy and Environmental Design), even they fall into quite predictable realms of creating and operating. Certainly such systems call for, and even reward, innovation and ingenuity. Some systems move beyond a rather prescribed scheme to promote and pursue regenerative buildings and communities. A key aspect that is missing, however, in the present author’s view, is considerable and meaningful adoption of agility in architecture. As long as buildings remain slow to respond to technological possibilities, stuck in the confines of convention, and staid in their ability to accommodate shifting needs, our buildings will remain a major part of the problem rather than arising as prime players in a more sustainable world.



4.4 Model for agility in architecture.

Pursuing Agility

> Flexible buildings are intended to respond to changing situations in their use, operation or location. That is architecture that adapts, rather than stagnates; transforms, rather than restricts; is motive, rather than static; interacts with its users, rather than inhibits.
>
> (Robert Kronenburg)[7]

Open Building and agile architecture have been almost exclusively focused on the tangible qualities of design and construction – perhaps best illustrated by

attention to support and infill. The author, an architect and psychologist, argues that other less tangible parts of the equation now warrant our serious attention – from a research perspective, from a testing viewpoint, and from an application outlook. Moving beyond concentration on the physical, also key to conceiving and constructing more flexible, adaptable, responsive, and responsible architecture are heightened awareness of regulatory considerations, individual concerns, and group expectations. The proposed synergistic equation for amplified agility in architecture encompasses four areas: (1) physical; (2) legal; (3) psychological; and (4) sociological (Figure 4.4).[8]

Physical

The construction of agile architecture encourages great mutability and adjustability across all realms of the building (and beyond). Such flexibility includes not only moveable walls, fixtures, and fittings, but also structure, infrastructure, and envelope. As noted, the author has written extensively on the more tangible aspects of agility, most recently exploring the limits that the façade can be dynamically configurable, and the unique roles of the envelope as part of the building shell but also part of the urban sphere. In this instance many questions arise concerning opportunities and obligations from both a private citizen and public entity point of view.

Legal

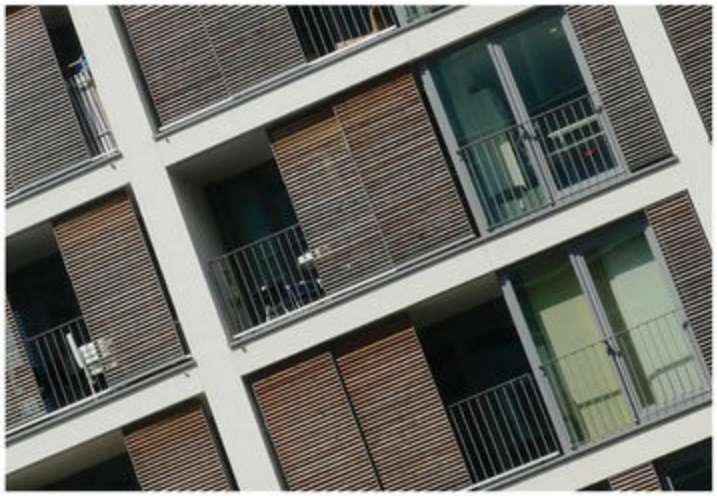
There has been some research conducted, within the academy as well as in practice, concerning the policy, code, statute, and regulatory dimensions of Open Building and agile architecture. Some of this work has considered ownership questions, such as support versus infill, government versus citizen, etc. While such efforts are important and influential, an examination of prevailing legal aspects and development of new systems of regulation are crucial. Legal challenges will need to be realized in order to push Open

Building to new levels, and especially so in traditionally resistant markets (such as North America). In order for buildings to be far more responsive, and by extension responsible, many established ways of working need to be overturned. A key pursuit in this regard is towards performative rather than prescriptive guidelines and measures. Also urgent is reform around litigation on the construction field. In the author's view, movement toward greater agility, modularity, prefabrication, and systems approaches holds promise to reduce building failures, heighten abilities to solve problems (e.g., due to plug and play), and foster more reasonable renewal of buildings (versus the typical age-in-place story of decay, death then landfill). Undeniably this area of the model will require assumption of risks. Exactly how such risk is managed and exposures limited remains to be explored.

Psychological

Individual reaction, resistance, or acceptance to change within agile architecture is a topic that has seen virtually no serious and scholarly consideration. The author, as a psychologist, has begun to study concepts of change, including cognitive and behavioral aspects of living and working in mutable environments. The simple fact of providing the ability of a space to change (even if it is straightforward and effortless) does not translate into spaces that will actually be changed by users. There are many variables that must be considered, including personality, knowledge of systems, understanding of implications, levels of comfort (physiological, mental, cultural, etc.), and willingness to act. Historically, in buildings, limited control has been afforded to end-users. Environmental systems have been centrally driven. Windows have not always been operable. Lighting is typically predetermined. So, when the environment shifts from highly regulated and rigid to highly adjustable and dynamic, it is difficult to determine how people will respond. This realm of inquiry is a significant focus for the author, with an awareness that all aspects of the present model need to be advanced in unison if agile architecture is to see wider deployment and more meaningful

embrace.



4.5 Mutable exterior in an apartment complex in Hamburg, Germany.

Sociological

Finally, it is critical that architects and researchers grasp the relationships, perceptions, and expectations at play at a broader community level (e.g., the residents of a building, the members of a community, the politicians on a council, etc.). Better understanding of the group dynamics, including reaction to agility, resistance to change, willingness to pioneer, etc. proves essential to the successful introduction of more agile architecture. At a sociological level, a given community must be able to overcome fears in order to seize the novel, untried, and untested if consequential change is to occur. We have witnessed impressive cultural swings as society has become more cognizant of the seriousness and significance of global warming. A similar renaissance must occur in the way we conceive of and construct buildings. Rather than fixed objects that deliver service over a set period then see demolition, buildings must be seen as living, dynamic, and mutable entities that can be assembled, reconfigured, upsized, downsized, repurposed then disassembled (e.g., for recycling and/or reuse in subsequent projects). This dramatic shift in mindset will be especially difficult to realize in North America, due in large measure to

a very entrenched, complicated, and conservative *modus operandi*.

Heightened Agility: A Model for Spatial, Functional, and Aesthetic Flexibility

> A concern for greater flexibility in buildings arose in the 1950s as a reaction against the excesses of "form-follows-function", which argued that all parts of a building should be determined by, and destined for, specific uses. In practice, however, even if these uses could be determined, no allowance was made for new developments over time, yet alone the changes of use that happen in many buildings.
>
> (Richard Weston)[9]

Architecture in our present times should arguably be, as has been stressed earlier in this chapter, more flexible, agile, adaptable, and elastic. We live in times of rapid change where advances in technologies are frequent, the expectations of users are shifting, and demands on environments are intense. Into this milieu, architecture and environmental design aim to provide spaces and places which accommodate the needs of increasingly diverse and pluralistic communities. The author previously has delineated a *Holistic Framework* for design and planning.[10, 11] This innovative approach, deployed across multiple scales, considers the symbiotic interplay of fitness, agility, diversity, and delight. The following section expands and explores ways of considering agility with a particular focus on reconceptualizing the manner in which architecture might heighten its resonance with user needs, demands, desires, and expectations. The approach, while acknowledging rich development in the field of Open Building over many decades, proposes a novel lens through which to view and tackle agility, adaptability, and appropriateness of design in our current era.

4.6 Interior view from the Capsule Tower (1972) in Tokyo, designed by Kisho Kurokawa.

Space that is reacting, responding, and transforming enables users, as opposed to more conventional approaches whereby users must adapt to space and conditions, however uncomfortable such accommodations may be. Instead of users adapting to space, the following model advocates for space to be designed with enough flexibility to adapt to users' needs and desires (Figures 4.5 and 4.6).[12] The model, then, changes the user's role in architectural design and practice. The sense of control over the space psychologically empowers the users whereas, conversely, not being able to change the surroundings would result in stress, distress, and discomfort. The strategic model as a mechanism examines agile architecture through the notions of "spatial flexibility," "functional flexibility," and "aesthetic flexibility" (Figure 4.7). The model suggests a means and method to mitigate the social, environmental, and economic problems that have developed as the result of disregarding the dynamic nature of dwelling vis-à-vis the designing of urban places, city blocks, architectural structures, and interior spaces.

While the model elaborates on how each of the three categories of "spatial flexibility," "functional flexibility," and "aesthetic flexibility" contributes to the concept of agility, it further promotes an approach overarching all three as a new and sustainable mindset in designing buildings that prove enduring. "Resilient" design as a hybrid of "spatial," "functional," and "aesthetic" flexibility responds to the users' needs and desires to re-imagine and

reconfigure the space, as they wish, in real time.

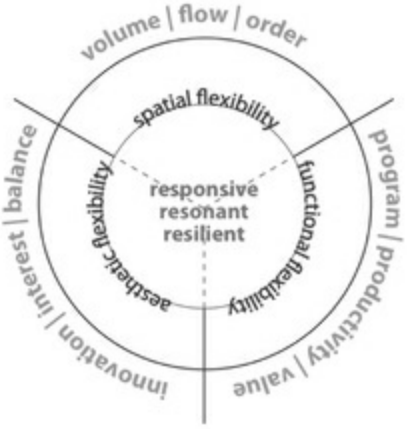
Responsive/Resonant/Resilient

Responsive

The skin, structure, and infill should be equipped with enough elasticity to be able to respond to environmental conditions, adjust to users' needs/ desires, and generate energy from renewable sources to which the building may be exposed. This means that the building is not neutral and stand-alone relative to its users and context. Rather, it is alive and ecologically synergistic with its surroundings.

Resonant

"Open" buildings should be designed with a meaningful balance between interior and exterior, between spatial, functional, and aesthetic aspects. Focusing on the reconfigurable "infill" should not overshadow the potentials of dynamism, customization, and energy generation in the design of an exterior shell.



4.7 Agile architecture strategic model.

Resilient

The building systems should be designed with the capacity to cope with future changes with minimum demolition, cost, and waste and with maximum robustness, mutability, and efficiency.

The "futuristic" architecture, today, ideally proves a hybrid of spatial, functional, and aesthetic flexibility – being able to respond to the need to intuitively reconfigure the space, adapt to future changes in program, and reflect the users' desires in real time. Each of the following three categories of spatial, functional, and aesthetic flexibility contributes to the richness of an expanded and reconsidered "open building" concept; however, each on its own will not be able to resolve the paradox of stability (in respect to long-term community interests) and change (in respect to individual preferences). Spatial flexibility enables rooms to grow and shrink or be subdivided differently to respond to the users' need for space. Functional flexibility allows different functions to unfold within the "support" but it fails to fully respond to temporal needs to spatially change the layout. Aesthetic flexibility is more about the interface between interior and exterior – it is only rational if it reflects the greater adaptability and responsiveness in the infill.

One future architecture, considering all the current environmental, social, and economic issues, would be about designing structures that are fully adaptable from inside out and across scales. Resilience ideally overarches all scales and dimensions. In order to do so, the best designs can be defined as those that spatially, functionally, and aesthetically accommodate change. In this kind of architectural practice, collaboration among all the stakeholders is essential. Design, construction, and building systems, in this methodology, are not distinct entities that develop independently. Rather, they are all inspired by the latest developments in art, science, technology, theory, and practice that

should be thought of and integrated from the beginning and throughout the process.

Spatial Flexibility (Volume, Flow, Order)

In the design of buildings, spatial flexibility realizes the users' needs and desires to make changes in the composition and arrangement of space. It provides the building with greater flexibility and open systems, which ultimately enable the users with more control over the structure of space(s).

In North America, the typical approach to design and construction of spaces tends to be very fixed and static. For each activity, a distinct space is accommodated that may not be efficient especially across the fourth dimension. Delegation of a separate largely immutable space to each function unnecessarily increases the size of the building more and more. This results in more money and materials for construction as well as more cost for maintenance, operations, and energy after construction. Another threat of static spaces is that, as they are physically laid out according to very specific parameters; they resist being adapted to other uses that may happen in the space over time. In other words, fixed spaces are often single function and are usually too rigid.

Spatial flexibility considers the capacity of change in the spatial structures of buildings both in the long term and the short term. Spatial flexibility is responsive to momentary change in users' needs and wants; therefore it accommodates change in the short term. Spatial flexibility permits the unfolding of different functions within a singular space; therefore, it considers long-term change in spatial needs. In this system, the plan should be divided into spaces that change and do not change. The alterable spaces are divided with the use of sliding, folding, retracting, collapsing, and moveable walls that can be reconfigured and rearranged according to the users' wishes. This idea overlaps with Japanese traditional housing where the large rectangular plan

may be easily and readily subdivided into a smaller space with different mutations possible (with minimal effort and limited disruption).

Volume

Spatial flexibility, traditionally, is achieved in "plan" while often the third dimension is dismissed; however, it is essential to consider "volume" in our approach. In other words, spatial flexibility can happen (XYZ coordinates) between the levels in addition to within one level. This consideration allows for greater flexibility and considers the potentials of spatial possibilities also in the fourth dimension (i.e., across time).

Flow

It is crucial to consider the flow between the spaces while users alter the spatial structure. It is important to consider flow of space in all iterations, to delineate which spaces are being shared, and to pay attention to the circulation between those spaces.

Order

In a flexible plan, there is no definite hierarchical order between the spaces. In spatial flexibility the focus is on the three-dimensional (horizontal and vertical) organization and sequencing the spaces in a way that allows for differing compositional arrangements. The spatial order changes as the users alter the plan/volume configurations to match their needs.

Functional Flexibility (Program, Productivity, Value)

In the design of buildings, functional flexibility allows different activities/uses to unfold and be accommodated within the same structure with the minimum amount of demolition and disruption.

Functional flexibility is a remedy for confined space contained in especially smaller structures. In such buildings, the functions may be limited because of the spatial confinement. Functionally fixed spaces also limit the change in the program of the building in the long run. As the spaces in conventional buildings are subdivided into smaller enclosures to accommodate current functions, demolition would be inevitable to accommodate a next-generation and expectedly different program within the same structure.

In this functional flexibility approach, plans/ volumes should be designed in a way that is adaptable and mutable to different needs. This can be achieved by means of specific furniture/ fixtures/fittings such as stackable units and reconfigurable assemblies – space can be easily rearranged to accommodate different functions. In this methodology, the rooms can easily adapt to any future changes in program with minimum or no demolition, as they programmatically remain neutral.

Program

Functional flexibility accommodates a wide range of programs in a singular space. This is achieved through larger divisions furnished with stackable furniture, mutable fittings, and reconfigurable fixtures.

Productivity

The buildings with functional flexible plans are productive, as they address both day and night cycles, an ever-changing number of occupants, the spatial requirements of different age groups, and the need for/of space of different programs. They promote constant and optimal usage of space, which is particularly efficient in terms of a plethora of operational considerations, such

as energy use, for example.

Value

Functional flexibility values the users of space. It respects the dynamic nature of occupants and the fact that their spatial requirements change over time – in the case of residential sectors, the spatial requirements change even from day to night. Rooms designed with this mindset are bedrooms at night, living rooms in the evening, and study rooms during the day. Functional flexibility also preferences value above cost, considers life-cycle impacts, and extends the financial efficiency and viability beyond more conventional approach.

Aesthetic Flexibility (Balance, Interest, Innovation)

In the design of urban structures, applying aesthetic flexibility provides the building with a sense of character that can change, that can communicate with neighbors, and that can animate the greater context.

The "flexible architecture" approaches of the mid-twentieth century, most notably developed in Europe and Asia, were successful in resolving numerous issues of housing demand that emerged after World War II. The flexible infill within fixed structures could re-form and shift to create different spatial configurations according to users' needs and wants. The "open concept" also allowed different programs and functions to unfold within the same structure with minimum demolition and costs. However, the "open building" guidelines soon produced repetitive plans within monotonous structures as primary attention was paid to developing reconfigurable infills. Monotonous buildings and aggregate communities with a lack of identity are not just by-products of "open building" practice; in North America, for example, suburban houses with "cookie-cutter" formula are undeniably boring, banal, and "unidentifiable."

Character flexibility provides the capacity of change in form and façade; it brings about unique identity that can reflect the users' personalities, communicate with the surroundings, and activate the context. Advancements in digital technology and next generation cybernetics have enabled extremely dynamic façades that are often married with clean energy generation techniques and sculptural shifts in form, which further rationalizes this approach. High performance skins that harness solar energy, provide shading, and at the same time allow for appropriate day lighting are becoming more popular. Digital façades that act as an urban-scale message board or night attraction are a trend. Façades populated with minuscule wind turbines and equipped with LEDs and small photovoltaics contribute energy while creating a performative milieu within the city.

Innovation

"Aesthetic flexibility" adapts recent innovations in science and technology to characterize the building and provide icons for the cities. We now see façades in which the automated shading apertures constantly change, not only to provide comfort for the users but also to create interesting dynamic patterns. Small wind turbines populate whole façades to generate energy while their aggregation and moving wings animate the buildings' skins. LEDs, charged via small photovoltaic cells, constantly change a building's color and are proving popular attractions in civic destinations.

Interest

Creating buildings with adaptable character and expressive flexibility is of interest to many stakeholders. Not only are the building users more satisfied, as they are given tremendous control to realize their preferences, but also the community and broader urban realm beyond benefit from the rich aesthetics and poetic dynamism of the building.

Balance

“Aesthetic flexibility” provides a balance between the standardization of dwelling patterns and the individual interpretation of living and working. Such “aesthetic flexibility” is about “customization,” and “design on demand,” which are not necessarily more expensive than the status quo – such inventive systems provide remarkable accessibility to users. Mechanisms for customization and characterization introduce tremendous design opportunities and ensure more flexibility over time (both in the short and the longer term).

Aptness, Equilibrium, Im|perfection

> Above all, architects should think before they create hardware.
>
> (Kisho Kurokawa)[13]

Without question, contemporary architecture – that is, architecture of the twenty-first century – needs to be more agile. Increased agility in architecture invokes approaches such as design-for-disassembly, pre-fabrication, modularity, adaptability, high performance, user-centrism, and customization-on-demand. Agility pertains not only to the building and site, but extends into infrastructure, planning, and the urban realm. The author, together with colleague Somayeh Mousazadeh, is exploring possibilities and implications of the façade (which we refer to as façade plasticity/envelope elasticity) not only for the architecture but for the fabric and function of the city. Agility as a concept, both in theory and application, needs to consider whole systems and integration across scales.

To this end – critically considering the Gestalt – the author underscores three qualities that should accompany our search for greater agility in design and architecture.

4.8 Customizable house in Muji Store, Tokyo, Japan.

These qualities are *aptness*, *equilibrium*, and *im/ perfection*. Aptness refers to a suitability and appropriateness of solution – to the users, context, culture, and conditions at play. I would argue that too many modern environments, including buildings, are out of resonance with the needs, expectations, and demands of modern society. *Equilibrium* refers to a balance – between science and art, between humanity and technology, between physicality and ethereality, and between building and city. I would argue many aspects of modern society are wildly out of balance – a scan of recent environmental, economic, and social catastrophes illustrate the point. Being off-kilter ushers in a spectrum of problems that are routinely incomprehensible and increasingly unsolvable. Finally, *im/perfection* refers to the need to accept that design and architecture can, and in many instances should, be "comfortable" with a greater level of "roughness," "looseness," and "humility." The Japanese can see perfection in environments, objects, and circumstances that seem incomplete and unresolved to the Western mind (Figures 4.8 and 4.9). In our quest for higher tolerances, tighter connections, smoother finishes, more even lighting, and more "engineered" materiality, we often dilute the beauty of our work and the humanness of our solutions. There are many reasons why we might consider at times being more satisfied with more imprecision. Architecture is a social art undertaken in the first instance to satisfy human needs and to improve the quality of life for users. While there are times to

push technology to its logical ends, there are an equal number of times where a human-focus, with all its blemishes and bumps, is apropos. Agility in architecture should endeavor to explore this wide range of factors in a quest for the appropriate. Agility in architecture, moving forward, might best pursue and embrace greater *aptness*, *equilibrium,* and *im/perfection.*

4.9 Board formed cast-in-place concrete.

Moving Forward

> People are very open-minded about new things – as long as they're exactly like the old ones.
>
> (Charles Kettering)[14]

> Its form and structure, resembling a large shipyard in which enclosures such as theatres, cinemas, restaurants, workshops, rally areas, can be assembled, moved, rearranged and scrapped continuously.
>
> (Cedric Price)[15]

4.10 Mutable interior in a traditional Japanese house.

Architecture in the twenty-first century, a period already understood through its dramatic movement and intense change, must be far more responsive, resonant, and resilient than designs for days long past. Rather than requiring users to shift, twist, and surrender to fit into static environments, a new architecture reacts, adjusts, and accommodates (Figures 4.10 and 4.11). The present chapter postulated a conceptual frame with which to better consider, create, and construct such design. It aimed to transition mindsets and methods of architects and architecture, in the spirit of the late Kisho Kurokawa, from the age of the machine to the *age of life*. In this proposition for reconsidered and more appropriate architecture, people must reside centrally and the dynamic, responsive, and meaningful must eclipse the static, staid, and stale. Ingenuity, creativity, and open-mindedness prove vital. Design must be devised to be more *agile*.

4.11 Mutable interior in a modern tower.

Notes

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3 Sinclair, Brian R., "Culture, Context and the Pursuit of Sustainability: Contemplating Problems, Parameters and Possibilities in an Increasingly Complex World," *Planning for Higher Education: Journal of the Society for College & University Planning*, 38(1) (2009).

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14 "Charles Franklin Kettering Quotes," available at: www.quotes.net/quote/14779 (accessed 3 Sept. 2014).

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5
Smart Architecture, Dumb Buildings

MICHELLE ADDINGTON

Contemporary society possesses an unbridled faith in the promise of technology. From the pragmatic – *tablets and laptops will extend educational avenues to more participants* – to the ambitious – *solar energy will enable unlimited growth in energy consumption without carbon dependence* – to the fantastic – *warp drive will eventually be developed to allow interstellar transportation* – we remain wedded to the belief that not only does every problem have some type of technological solution, but that new technology will open up unprecedented possibilities. Everything can be "fixed," anything can become better. As both a microcosm and a mirror of society, the field of architecture shares this faith in technology, but not quite so boldly and perhaps not even with quite as much imagination. We expect our technologies to be available and implementable, and, furthermore, for them to be tangible and demonstrative. Our technological approaches sometimes lean toward the pragmatic, sometimes toward the more ambitious, and they often retain a subtle underlying current of fantasy. Essentially, we want our new technologies to be heroic – directly solving an immediate problem *and* laying the groundwork for an array of possible futures.

Notwithstanding millennia of technological advances in architectural components and systems, and in spite of the rapid proliferation of information and digital technologies, the nexus of our heroic expectations during the late twentieth and early twenty-first centuries centers on surfaces, particularly those that comprise the building envelope. The confluence of glazing with early HVAC systems that marked the beginning of modernism in the twentieth century set up an irreconcilable binary between one side of a material surface to the other as well as an irreducible co-dependence between

the interior environment and the building envelope. Transparent façades only became possible when the advent of environmental systems presumably enabled the complete disconnection between interior and exterior environments. But even though the exterior became objectified into a picture plane view, the inherent bi-directionality of the glazing instead exacerbated the relationship between exterior and interior. Severe heat loss or heat gain, blinding glare or featureless ambient light, the problematic conditions of the interior demanded ever more systems and technologies to compensate for the choice of a glazed surface. Ironically, as concerns with energy have heightened attention toward the façade, the focus has been tautologically constrained to solving the problems wrought by glazing rather than questioning its *prima facie* acceptance. The technological system that was predicated on disconnection is now saddled with resolving the complex inter-connections that it has created.

Transparent, Performative, Dynamic, Responsive … Skin

The problems of the glazed façade produced the contemporary interest in the performative skin. Also known as engineered façade, high performance envelope, or double skin wall, the performative skin essentially refers to a thickened envelope housing many mechanical and electrical functions, of which the most elaborate constructions are highly engineered, from embedded micro-louvers to spectrally selective glazings. Aerogel fills the cavity, adjustable louvers control the amount of sunlight entering the building, secondary fans directly exhaust the solar energy absorbed by the façade before it enters the building, and multiple layers of glass provide wind and noise management. Rather than mediating between interior and exterior, the performative wall is compensating for the environmental penalties wrought by a material choice. If the advent of HVAC enabled the application of the modernist glazed façade, then the contemporary glazed façade demands

additional technologies and systems so that the HVAC systems conditioning the interior environment can adequately function.

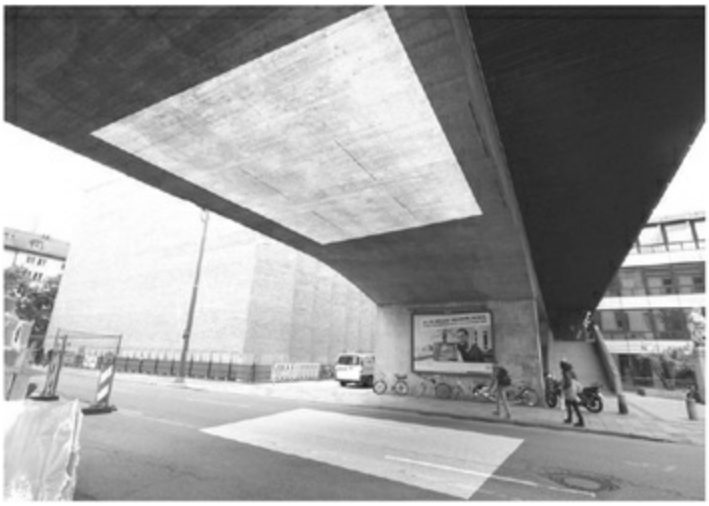
As each version established itself as the hegemonic technology that the next version needed to live up to, the ideal envelope transitioned from transparent to performative and ultimately to dynamic. If the performative envelope was unable to reconcile the inherent conflicts presented by the bi-directional transmission of energy through the façade, then a smarter envelope, one that is changeable for multiple conditions rather than optimized for a single condition, should surely resolve the complex and varying interactions between exterior and interior.

The desire for smart control of functions led to the evolution of the "dynamic" wall. The publication of Mike Davies' "polyvalent wall" in 1981 may not have documented the first of these technological systems, but it was the image that captured the imagination of architects, and, after Reyner Banham showcased it in the second edition of *The Architecture of the Well-Tempered Environment* in 1986, it became the touchstone for most subsequent definitions of a dynamic wall as well as the ultimate goal for its achievement.[1] One of the fundamental differences between the multi-functional performative envelope and the multivalent dynamic wall was the addition of features that were unrelated to environmental mediation. Davies' wall proposed electrically conductive glass, and BIPV (Building Integrated Photo Voltaics) became a standard layer in the common conception and realization of the dynamic wall even insofar as energy generation not only has nothing to do with environmental mediation, but it can exacerbate the thermal conditions that all the other layers are supposedly there to ameliorate. While the energy generation from the photovoltaic (PV) layer cannot be used directly, many designers and engineers certainly imagined that the energy might eventually be available to actuate other active layers in the wall. Actuating capabilities embedded into the wall give us a truly dynamic wall – changeable transparency, color, permeability, and even shape. Coupled with sensing capabilities, the dynamic wall can then be responsive – diffusing light transmission when the sun reaches a particular angle, shape shifting openings to allow ventilation.

What had evolved from a single material choice at the beginning of the twentieth century has now become, by default, the goal. That which was the problem is now tautologically its own solution. So the responsive wall takes on the salient characteristics that mark the technological approach – it solves a "problem," and it poses a tangible, realizable "future." Of course, the problem is rather specious and the future rather murky, but this has not prevented the responsive wall from becoming the holy grail of architecture. Harvard University's Wyss Institute, which houses some of the world's leading scientists, has added the dynamic wall to their list of major initiatives: "The long-range vision is to design entire buildings that adapt their shape and function to continuously optimize energy efficiency, thermal gain, and other properties critical for sustainability."[2] Indeed, this claim that the dynamic envelope is the key to sustainability is the most common justification for many of the initiatives and resources devoted to its development. Ironic, given that many of its features exist to compensate for the energy burden wrought by its foundational element of glazing; and troubling, given that one cannot trace a line of causation from dynamic properties to sustainability. Other architects and researchers are more intrigued by the design potential of responsiveness – the possibility for a more sensual experience for the body or the opportunity for the building to have multiple manifestations. Perhaps this commenter reacting to a Honda Concept Car with a photochromic coating offers an observation that would be applicable to buildings: "Well, the color changing concept is actually rather nice. But then again, how would that be useful for the car, except maybe just to easily change its color?"[3] We want our buildings to be more and to do more, but we are not clear on what we need or why we want it.

This rather long preamble is not meant to be an indictment of buildings with dynamic properties, materials, and components. What it is meant to be an indictment of is the *prima facie* assumption that surfaces, particularly those of the envelope, are the elements that should be dynamic. If we think about the verbs of dynamism – actuate, sense, react, respond, interact – they are all verbs of motion and, as such, they are all forms of energy. What we rarely understand is that the definitive feature of energy is mutable difference,

which is essentially transiency. Transiency denies fixity, and therein lies the dilemma. Transient behaviors are highly unlikely to emerge coincident with any given object, much less to do so repeatedly, yet our desire for tangibility privileges the visual artifact – the surfaces of a building. As a result, when we think about the dynamic, we think of it as the binary opposite of the static. Dynamism has thus been narrowed to activating the static artifacts that comprise the formal elements of architecture. If we are indeed truly interested in solving critical problems in architecture and reaping the full potential of advanced technologies, we must first escape the tautological trap of *surface needs technology/technology determines surface.*

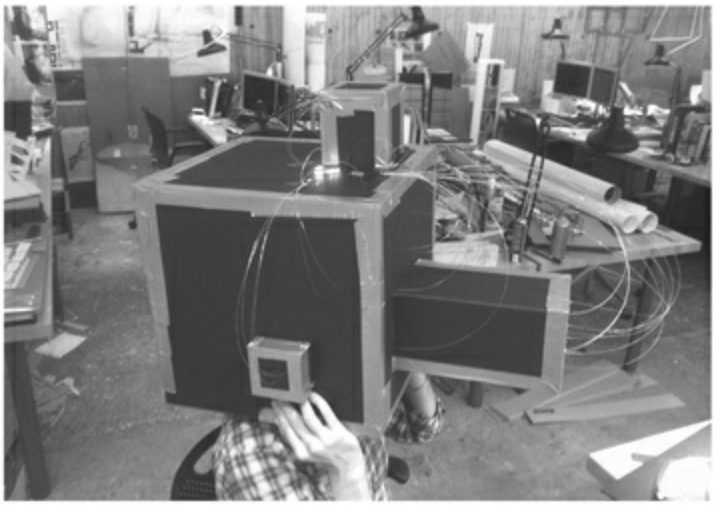


5.1 Design image of Donal Groarke demonstrating the creation of a virtual window on a dark underpass using light projection.

The Three Memes

Our understanding of how things work is constrained by a series of rhetorical abstractions that manifest as uncontested facts. Essentially, they have become memes as they are passed, without question, from teacher to student, from architect to engineer. The following three memes not only hamper us from a more imaginative exploration of new technologies, but they are also

preventing us from getting at the roots of why we consume as much energy as we do in our buildings.



5.2 Experimental headpiece created by Nicholas Hunt in which fiber optic density and lumen emittance determine the apparent depth of surfaces.

Meme 1: The material surface determines physical phenomena (i.e. surfaces produce "effects").

Architectural design, whether as an intent, through an act, or for a result, has an incredible array of possible outcomes, such as from the formal object to the experiential space, or from the functional machine to the political statement. Regardless of what we say we do or what we believe we have produced, we all do so through the same means – by situating surfaces. We presume that the surfaces are responsible for the visual image of the building, and we assume that the surfaces determine the interior environment of the building. The resultant collection of surfaces, however, only demarcates property and constrains the movement of large objects. Nothing more. In regard to the image, human vision responds only to stimuli at the micron scale, and physical stimuli only arise to negotiate differences and then disappear. Our visual perception of the world is entirely created by transient micro-rifts in luminance (Figures 5.1 and 5.2). A highly articulated façade can only appear to have variation if there are tiny directional shifts in light. Bathed in omni-

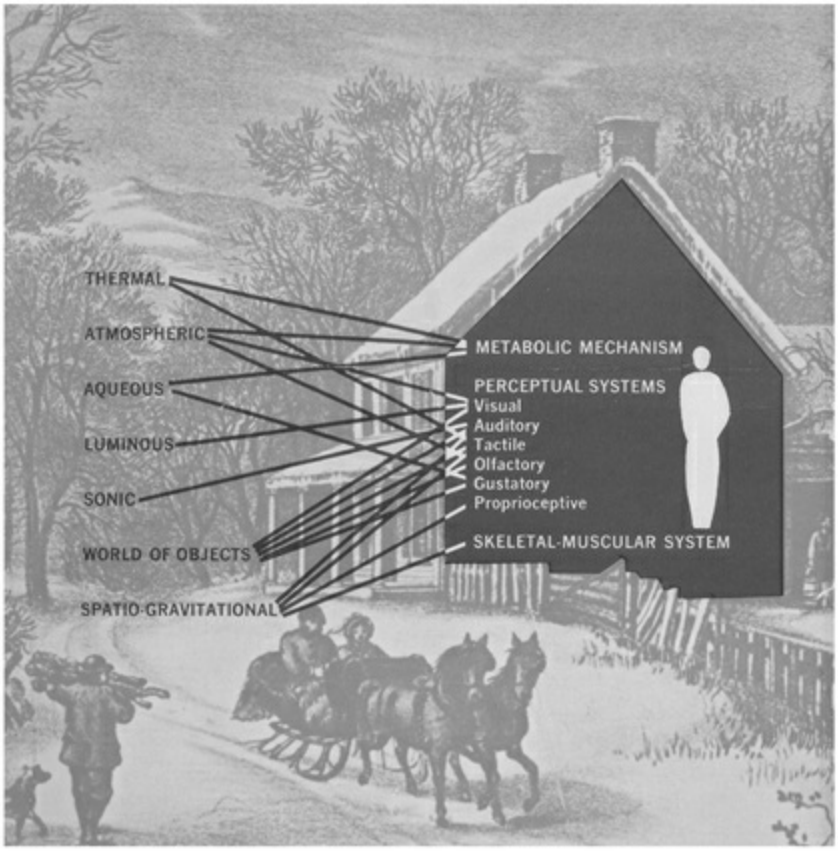
directional diffuse light, the articulated façade will appear completely flat. Indeed, the eye cannot even distinguish between black and white unless these luminance rifts emerge. Visual reality is not determined by, nor is it necessarily coincident with, the artifacts in view. This dislocation of image from object is difficult enough to grasp, but it is even harder for most to challenge the belief that surfaces – our walls, floors, and ceilings – "contain" the environment of the body. They certainly determine the movement of the body, but they don't determine the movement of energy. For example, to deaden sound transmitting from an adjacent room, the typical approach would be to increase the sound insulation on the shared wall. This will certainly help, but so will an increase of absorptivity anywhere else in the room, even in a location that is geometrically the furthest away and completely disconnected from every wall. The thermal environment as well never has been closely coupled to building surfaces. Thermal exchanges operate on some of the smallest geometric scales – none of which coincide with the very large geometric scale of our building components. In regard to the human body, all of the exchanges take place no more than a few centimeters from the skin, with most occurring in sub-micron distances. Blanketing the body in a homogeneous thermal surround only incidentally manages the thermal exchanges, and does so with an enormous energy penalty and not much efficiency. Many of the features being proposed and incorporated into dynamic walls are prescribed as necessary and even optimal for managing the thermal environment inside the "container" surfaces, which is likely so, but these are not the surfaces that matter.

Meme 2: The envelope mediates between interior and exterior environments.

Even though the homogeneous interior environment is a product of one particular technological solution – dilution-based enthalpic mixing of air – it tacitly serves as the standard that all environmental technologies are required to reproduce. The US Department of Energy will not consider homes without dilution-based systems for its highest energy certification; the Passivhaus standard is entirely predicated on the requirement for dilution-based systems.[4]

Given that homogeneity is expected throughout the volume of the building – the same temperature floor to ceiling and wall to wall – the envelope is no longer just the container of this environment, but also must serve as a barrier to any exterior condition that threatens its maintenance. In yet another ironic twist, the dilution-based system was born from the nineteenth-century obsession with bringing in as much outside air as possible into the building, but its twentieth-century application demands that outside air must be limited and controlled so as not to disrupt the ideal functioning of the system. Contemporary architects are quick to point out that we have moved away from the building envelope as a hermetic barrier such as that extolled by Le Corbusier in a 1929 lecture: "at all times there is clean air at exactly 18°. The house is sealed fast!"[5] Most would argue that the current approach is not hermeticism but mediation, with the envelope playing a more active role than just as a barrier. The image put forward by James Marston Fitch in 1972 encapsulates this view, but also its underlying problematic: the building envelope is represented by a series of dynamic exchanges – heat, light, sound – between a transient and active exterior environment and a static and homogeneous interior environment[6] (Figure 5.3). Essentially, the exterior environment is conceived as relatively hostile with moments of usefulness, such as when it can be transformed to serve the interior (i.e. an economizer cycle, or daylight supplementation). In this permutation, the envelope is tasked with doing everything – selective rejection/admittance of exterior climatic conditions or their mediation/transformation – to support the functioning of the interior technological systems, not supplant them. Fitch affirmed this conceptualization when, in the text that accompanied the illustration, he essentially treated architecture as synonymous with the environmental envelope:

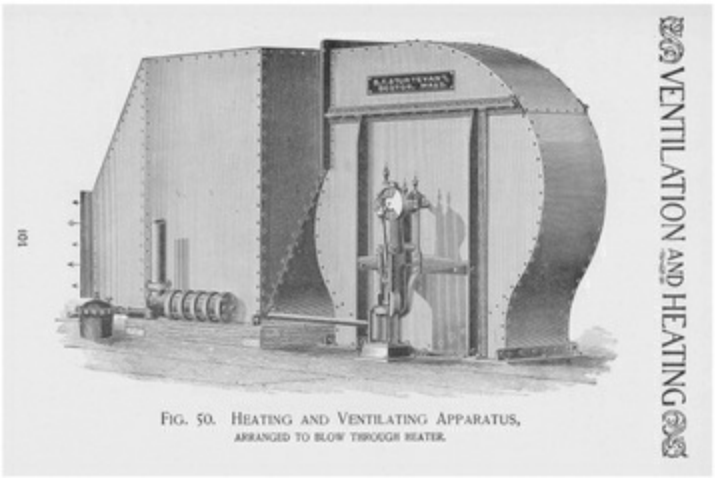
> The task of architecture is not merely to abolish gross thermal extremes (freezing to death, dying of heat prostration) but to provide the optimal thermal environment for a whole spectrum of modern life … to achieve a steady thermal state and a thermal equilibrium across space.[7]



5.3 Cover image of James Marston Fitch's (1972) book, *American Building: The Environmental Forces That Shape It.*

Underlying the attribution of environmental control to the envelope is this message that exterior climatic conditions are not only hostile but also subordinate to man's ideal environment. As such, one of the most common mantras in envelope design is to "build tight, ventilate right."[8] Closely coupled with this is the assumption that the energy expenditure of buildings is the direct result of the envelope design – in cold climates, the envelope supposedly isn't doing its job in protecting the interior from the trespasses of the exterior, in hot climates the envelope isn't doing its job to contain the interior environment in place. The rapid and rather astonishing increase in insulation codes and standards over the last decade results from this unquestioned deterministic connection between the envelope and energy use. Many of the most influential institutions and advisors – from the United Nations to governmental agencies to McKinsey & Company – have singled

out increased insulation as the most important and productive step that nations can take to stem the rise in greenhouse gas emissions, even though energy behaviors are so complex that there is no direct and causal link.[9]

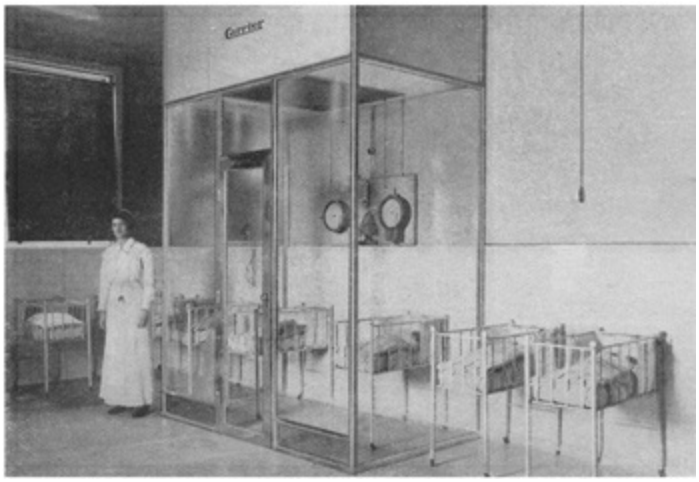


5.4 B.F. Sturtevant combination fan with integrated steam heating coils from their 1895 catalog.

Meme 3: Building technologies should be integrated together and integrated into the building fabric.

In 1886, the B.F. Sturtevant Company introduced a steam-driven fan for ventilation that integrated the spent steam from the fan into a coil embedded in the exhaust.[10] Advertised as "Ventilation with Free Heating," the integrated unit was intended to extend their penetration into the building market (Figure 5.4). The ventilation standards that John Shaw Billings, the Surgeon General of the US, had developed were rapidly being adopted for schools and spaces of public assembly.[11] Building owners and operators were balking at the increased cost, and many complained that the steam needed to drive the fans was resulting in overheating of their buildings. The "free" heating for the winter, for which most major buildings already had less intrusive and more efficient systems to handle, was not enough of a selling point to overcome the negative of overheating in the summer, which many considered to be dangerously unhealthy. Furthermore, the burgeoning open-air movement led many building owners to question the necessity for mechanical systems to achieve the necessary ventilation rates, and a major groundswell of opposition

was building among school superintendents to relax the standards so that open windows would suffice.[12] Willis Carrier patented the air handler in 1911 in the midst of this public backlash.[13] Based on the same integrated concept of the Sturtevant system, although the fan used an electric motor and an external steam source was now required for the heating coils, Carrier's system was still considered an unneeded expense with an unnecessarily complex infrastructure. His air handler may have evolved directly from the Sturtevant fan/ heating system, and certainly follows in its footsteps in terms of the integration of different air behaviors, but its overarching premise was conceptually opposed. Until this point, the *raison d'être* for fan-driven systems was to flush the building with as much outside air as possible. In stark contrast, the air handler was a recirculating system; its ventilation capabilities had little to do with fresh air from outside for the occupants and everything to do with insuring that all the interior air could be pulled though the system. While this brought the ability to control humidity, which other systems were incapable of doing, it was entirely counter to what building owners and the public wanted – open windows and fresh air.



5.5 "Even babies can be manufactured with manufactured weather," from the Carrier Corporation's *The Story of Manufactured Weather* (1919).

The flu epidemic of 1918 produced a dramatic shift in public sentiment as pre-modern ideas about illness and outdoor miasmas resurfaced. The timing

could not have been better for the nascent air handler industry, which was quick to capitalize on the public's irrational fear of outdoor air. The addition of filters and spray washers into the air handler were foregrounded for their ability to clean the air, with the Carrier Corporation even advertising near-antiseptic conditions (Figure 5.5): "[the air handler can] produce manufactured weather that is cleaner and purer than what nature provided."[14] With the addition of cooling coils ten years later, the air handler system became the standard HVAC system that is still used, almost unchanged, today.

Heating, cooling, ventilation, and moisture control are all thermal phenomena that operate at different scales and have different drivers. Integrating all of the functions into a single unit does only one thing effectively – create homogeneity in a large volume of air. As a result, this volume of air is only capable of diluting the bulk heat and moisture emitting from the human body. It is difficult to imagine a more inefficient mode of managing heat and mass transfer than dilution. Nevertheless, this has become the standard that all other technological systems are expected to produce. As the homogeneous environment is a specific result of a particular system, all other systems, by default, also must treat air as bulk matter. The integrated system, born from marketing strategies, has supplanted thermodynamic efficiency and effectively squeezed out newer, more discrete, and substantially more effective systems that embrace transiency and operate on individual phenomena.

Exacerbating our ability to challenge the *a priori* HVAC system is the widely accepted belief that the integration of all building technologies is the primary goal of systems design. Electrical and plumbing systems threaded into walls, HVAC ductwork woven through the structure, material systems knitted into the enclosure. The sentiment expressed by William Caudill about the Centre Pompidou perhaps best sums up what many architects think about systems:

> You see structure; you see mechanical; you see the electrical system; you see everything all in one. That's integration. That is the esthetic system. That is architecture.[15]

Thermal phenomena occur at scales ranging from a picometer to less than one

meter; static structural behaviors are governed at scales at least an order of magnitude larger than the largest thermal scale, and electrical systems are managed at scales yet another order of magnitude larger. Only the structural system behaves at the scale of a building. Enclosure and surface materials can integrate neatly with the structural system, but the other systems need to be conceived, designed, and implemented at their governing scales, which integration often prevents. When architects think about systems integration, they are not thinking about the physical phenomena at all. What they are thinking about are the material artifacts of structure and the material shells that contain the movement of fluids and current. Essentially, all phenomena are narrowed down to the surface characteristics of the static artifacts that shape or contain them.

These three memes – the determinant material surface, the mediating envelope, and the integrated system – not only have constrained technological development for buildings, but have also continued to spawn other memes. The net zero-energy building in all of its renditions (green architecture, carbon zero or carbon positive buildings and communities) treats the building and/or site boundary as the zero sum location for all energy behaviors from generation to conversion to consumption. As problematic as it is to collapse all the heat transfer phenomena from the body into a mono-scaled integrated system, it is irrational to even consider that a boundary determined by private property trumps the boundaries determined by the laws of physics. Yet this is the norm. Another child of the original three memes is the biophillic building.[16] Proponents of building integration have over the years used the human body as a metaphor for architecture – the structural system imagined as the skeleton, the HVAC systems imagined as the lungs and the circulatory system, the envelope imagined as the skin – that readily became an analogy: the structural system *functions* like the skeleton of the body, the HVAC system *functions* like the circulatory system, and the building envelope *functions* like the skin. That eventually became a foundational description of how systems were to relate one another. If the building is indeed a living body, then these systems must be integrated into a seamless whole where each system serves the entire building. Biophillic design takes this a step further by

conceptualizing the ideal building as integrated into nature in order to connect the human occupants back to the natural world. This integration can take many forms – from the use of natural materials like wood to mimicking natural shapes and forms such as shells and ferns to incorporating natural lighting in the interior.[17] Nature is narrowed down to elements comprising park-like and agrarian settings, whereas nature at large is a little too messy and uncontrollable. Humans want to connect to leafy trees; they don't want to connect to a dead forest destroyed by lightning. In perhaps the greatest irony of all, biophillic design strives to match the standardized interior conditions as created by the very environmental systems that were predicated on isolating the interior from the exterior. In so doing, biophillic buildings actually reinforce the disconnect between interior and exterior.

Avoiding Techno-Determinism

So where does this leave us? Continuing to embed more functionality and more dynamism into the things we build does not make our buildings any smarter. Smartness does not reside in the building fabric, and interaction is not between the occupant and the building, rather it occurs at discrete moments wherever and whenever phenomenological differences emerge. Technology can facilitate those discrete interactions but the incorporation of smart and dynamic technology into our buildings without a clear problem to solve will just render buildings even clumsier and more expensive.

We need first to articulate our objectives, and they need to be stripped down to the most fundamental questions. Not a question such as how can we reduce the energy used by our building systems, but one such as what is the ultimate need for these energy-consuming systems to begin with? Not a goal such as making the building dynamically respond to its environment, but rather one such as managing the interaction of the human body with its surrounding environment. Slapping expensive technologies onto the building and seamlessly integrating them into the envelope does not suddenly render

the building smart and more functional. Why do we consider switchable glazing such as electrochromic to be smart, but not Venetian blinds, particularly given that the Venetian blinds have a greater range of performance? If what ultimately matters is the amount of light entering the eye, then why aren't we thinking about how light maps onto the human retina? Why do we assume that we just need to evenly cast daylight throughout the interior? Designing for the eye requires only the minutest changes in angle at the micron scale – which we can do with so many of our advanced technologies deployed in the most discrete of ways. Building surfaces are not discrete. It is much easier to assign determinism to our surfaces and assume that the environmental behaviors will "intelligently" materialize. It is not so easy to directly design the behaviors.

What makes all of this so challenging is that moving forward requires us to completely invert our thinking of design. The things that we make are not the authors of what we see and feel – they are almost incidental in perception and occupation. This is where the real disconnect occurs. How can we foreground phenomena while backgrounding the material artifacts? How can we instrumentalize interactions rather than dynamicizing materials? How can what we make become the armature for what we want to happen? Underneath all of this is a nagging and important question – to what end do we make our decisions, our interventions? Buildings, their systems, and their surfaces do not need to become smarter. We need smart results, not smart materials. But we need to step away from the memes to know what those results should be – and we have to think beyond simply a better way of doing the same old thing. Could our architecture become smarter if we let our buildings become dumber?

Notes

1 Mike Davies, when he was an associate of Richard Rogers, proposed that the exterior wall could be a thin envelope with layers of weather skin, sensors, actuators, and photoelectrics. See Davies, Mike and Rogers, Richard, "A Wall for All Seasons," *RIBA Journal*, 88 (1981). Reyner Banham, in

differentiating the modern from the vernacular, included a diagram of the wall in the second edition of his seminal *Architecture of the Well-Tempered Environment* (Chicago: University of Chicago Press, 1984).

2 The Wyss Institute for Biologically Inspired Engineering is a multi-disciplinary research institute founded in 2008 at Harvard University. Its stated purpose is to use "Nature's design principles to develop bio-inspired materials and devices that will transform medicine and create a more sustainable world." Their initiative on smart building is part of their Adaptive Material Technologies platform. See http://wyss.harvard.edu/viewpage/enablingtechnology-platforms/enabling-technology-platforms.

3 This quote is taken from a comment posted on 17 March 2011 to a review of the 2011 Honda Native Concept car on the TopSpeed site. See www.topspeed.com/cars/honda/2011-honda-native-concept-ar103501.html.

4 The Department of Energy's different certifications and awards for energy-efficient buildings all require dilution-based air systems as the baseline. In spite of what its name might connote, the Passivhaus standard requires a mechanical ventilation system to compensate for its sealed envelope.

5 In 1929, in a lecture in Brazil, Le Corbusier sketched a high-rise building that was treated as a single homogenous volume completely sealed from the exterior, with an air handler as the only device producing the interior environment. He annotated the sketch with "*bâtiments hermétiques" – the house is sealed fast!* See *Precissions on the Present State of Architecture and City Planning*, trans. E. Aujame (Cambridge, MA: MIT Press, 1991), pp. 64–66.

6 The image appeared on the front of the dust jacket of Fitch, James Marston, *American Building: The Environmental Forces that Shape It*, 2nd edn (Boston: Houghton Mifflin, 1972).

7 Ibid, p. 1.

8 The Department of Energy's "Build Tight, Ventilate Right" is a long-standing slogan of its Energy Star program.

9 The fourth assessment report of the Intergovernmental Panel on Climate Change concluded that the Building Sector not only had the largest potential for reducing greenhouse gas emissions, but also the most cost effective. Insulation was singled out as the key strategy. In McKinsey's well-published diagram on greenhouse gas abatement, insulation was shown as the most cost

effective means to reduce greenhouse gases as compared to strategies in all the other sectors.

10 The B.F. Sturtevant Company of Boston introduced the first practical centrifugal fan in 1863. Early versions of the integrated fan with heating coils first appeared in 1869.

11 A brief overview of the onset of ventilation standards in the United States is summarized in Jannsen, John E., "The History of Ventilation and Temperature Control," *ASHRAE Journal*, 10 (1999).

12 C. E-A. Winslough led a multi-year research study investigating ventilation and temperature control with the conclusion that open windows were just as effective as any mechanical ventilation system. The research was published in *Report of the New York State Commission on Ventilation* (New York: E.F. Dutton & Company, 1923). A good secondary source that contextualizes this time period, particularly the protests over mechanical ventilation, is Cooper, Gail, *Air-Conditioning America* (Baltimore, MD: The Johns Hopkins University Press, 1998).

13 The air handler was first introduced in a meeting of the American Society of Mechanical Engineers. See Carrier, W. and Busey, F., "Air Conditioning Apparatus: Principles Governing Its Application and Operations," *ASME Transactions*, 33 (1911).

14 See Carrier Engineering Corporation, *The Story of Manufactured Weather* (New York: author, 1927), p. 5.

15 Cited from a roundtable conversation between architects and engineers in Rush, Richard (ed.), *The Building Systems Integration Handbook* (New York: John Wiley & Sons, 1986), pp. 34–35.

16 The Harvard biologist, E.O. Wilson, coined the term "biophillia" to describe the link between mankind and the rest of the living world. He introduced the term to the public in his landmark book, *Biophillia* (Cambridge, MA: Harvard University Press, 1984).

17 An acolyte of Wilson, the Yale ecologist Stephen Kellert has devoted his research and teaching to applications of biophillic principles, particularly in the design of the built environment. See Kellert, S., Heerwagen, J., and Mador, M., *Biophillic Design: The Theory, Science and Practice of Bringing Buildings to Life* (New York: John Wiley & Sons, 2008).

6
Adaptive, Responsive Building Skins

BRANKO KOLAREVIC AND VERA PARLAC

As the building industry developed new materials and technologies, many of them found initial application in building envelopes, leading to a never-ending tectonic evolution in façade engineering: curtain walls, shading systems, double-skin façades, etc. With the advances in computer hardware and software, building management systems (BMS) that control mechanical and electrical equipment in buildings became commonplace. As the overall goal behind the deployment of BMS was to monitor and manage the buildings' energy demands, their reach quickly extended to building envelopes as they started to incorporate kinetic components that would affect a building's thermal performance, i.e. its heat loads. In the late 1990s, double-skin façades with a BMS-controlled vented air cavity and operable, integrated shades or blinds became popular. With the greater incorporation of electronically controlled, mechanically activated shading and ventilation systems came the kinetic or dynamic façades, active and high-performance building envelopes. Whatever term is used, the principal idea behind these new systems is that buildings should respond in dynamic fashion to constantly changing environmental conditions and do so in energy-efficient ways. Buildings thus became *adaptive*, with building envelopes playing a key role in how they adapted, i.e. responded to the ever-changing external environment.

The key focus in designing adaptive envelopes is better management of energy flows, both from the exterior environment into the buildings and from the interior spaces of the building to the outside, with the overall goals being the improvement of the building's performance and the user comfort inside the building. The adaptive behavior of the envelopes can be visible or invisible

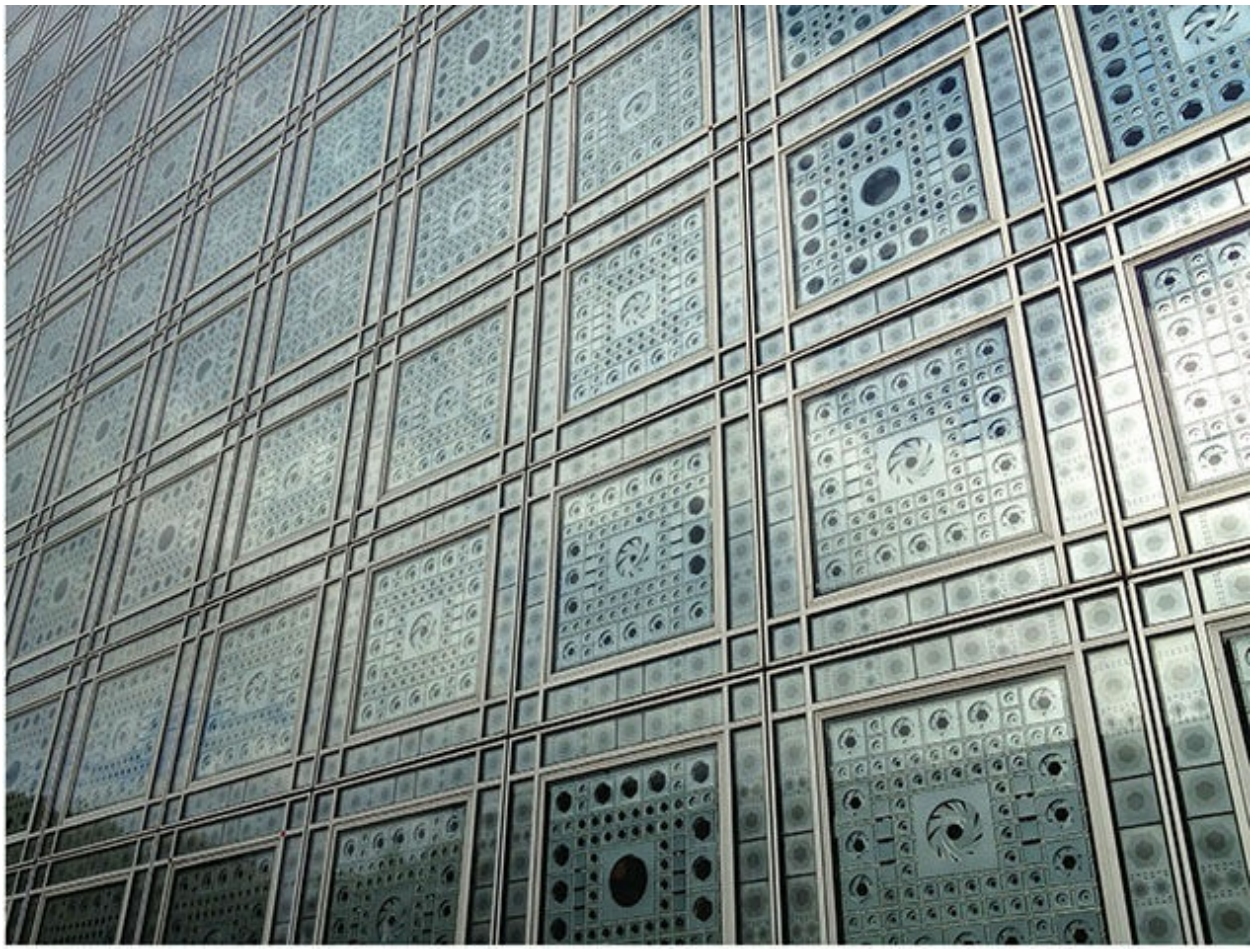
(or both); in addition to components that move literally, such as the shades or vents, air (or water) would move as directed, and thermal energy would flow through different materials as designed. The visible adaptive behavior could lead to an urban spectacle that can add performative dimensions to the project that go beyond the scale of the building. While the literal movement of components is not an end in itself in many architectural projects that incorporate environmental responsiveness, it is often exploited to make the buildings appear "alive."

6.1 The *KfW Westarkade* (2010) in Frankfurt, Germany, designed by Sauerbruch Hutton, features a double-skin façade with an automated Venetian blind system.

The building envelope can act as a "living" part of the building – its "skin," a semi-permeable membrane that mediates between the building and the

environment. It is a layer – or more precisely a set of layers – where architecture and environmental engineering intersect as disciplines. Whereas the focus is traditionally on blocking heat gain or heat loss – effectively creating energy barriers – the new façade designs attempt to harvest energy from the environment and channel it to where it is needed. For example, in double skins, the air contained in the space between the two layers is heated by the sun during the winter months; conversely, in summer months, cold air is drawn in at the bottom of the cavity and as it heats up, it is exhausted at the top using natural convection. The dynamic control of energy flows (manifested as light and heat) is at the center of innovation in adaptive building envelopes, facilitated by new materials and the latest advances in sensing, control, and actuation systems.

To imbue building skins with dynamic, changing behavior, their elements need to be *actuated*, i.e. moved, rotated, expanded, shrunk, twisted, etc. so that the desired performance objectives are met. What differentiates adaptive building skins is not so much what is actuated (and that matters greatly), but how that actuation is produced. There are essentially four different methods of actuation in building envelopes: (1) motor-based; (2) hydraulic; (3) pneumatic; and (4) material-based. Most of the automated adaptive façade systems deployed to date rely on motor-based, i.e. mechanical actuation. Recently, we have seen increasing use of pneumatic actuation, primarily with patterned, multi-layer ETFE-based[1] systems in which hermetically sealed air chambers can be inflated or deflated to create different shading densities. There are also ongoing experiments in material-based actuation, which offer the promise of "zero energy" dynamic building envelopes, which are years away from large-scale commercial applications.



6.2 Kinetic curtain wall at Jean Nouvel's *Institut du Monde Arabe* (1989) in Paris, France.

Mechanical Actuation

A mechanized Venetian blind system inside an air cavity, often in a double-skin façade system, is the most common motor-based actuation system in use today. It can significantly reduce glare and solar heat gain. It is often automated, whereby a central building management system (BMS) tracks the location of the sun and monitors the light conditions and can lower and tilt (or raise) the blinds as needed. The blinds are housed between two layers of glass, one on the outside providing protection from the elements, and the one on the inside protecting it from potential damage or interference with its

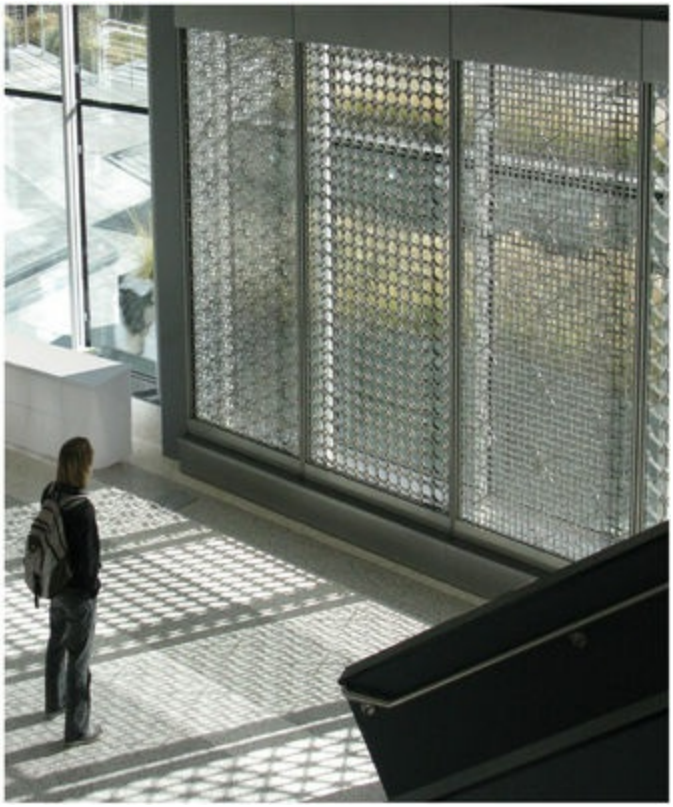
operation (and both providing protection from particulate matter). The *KfW Westarkade* (2010, Figure 6.1) in Frankfurt, Germany, designed by Sauerbruch Hutton, features such a system.

Other automated, active shading systems sandwiched between two sheets of glass have been developed and deployed in the past. Jean Nouvel's *Institut du Monde Arabe*, completed in 1989 in Paris, was the first significant, large-scale building to have an adaptive envelope (Figure 6.2). The building's kinetic curtain wall, a technological interpretation in glass and steel of a traditional Arab lattice screen called a *mashrabiya*, is composed of some 30,000 photosensitive diaphragms that control light levels and transparency in response to the sun's location (the system no longer works due to mechanical problems).

6.3a and b *Adaptive Fritting* adaptive façade system designed by ABI.

Hoberman Associates (led by Chuck Hoberman) is perhaps one of the best-

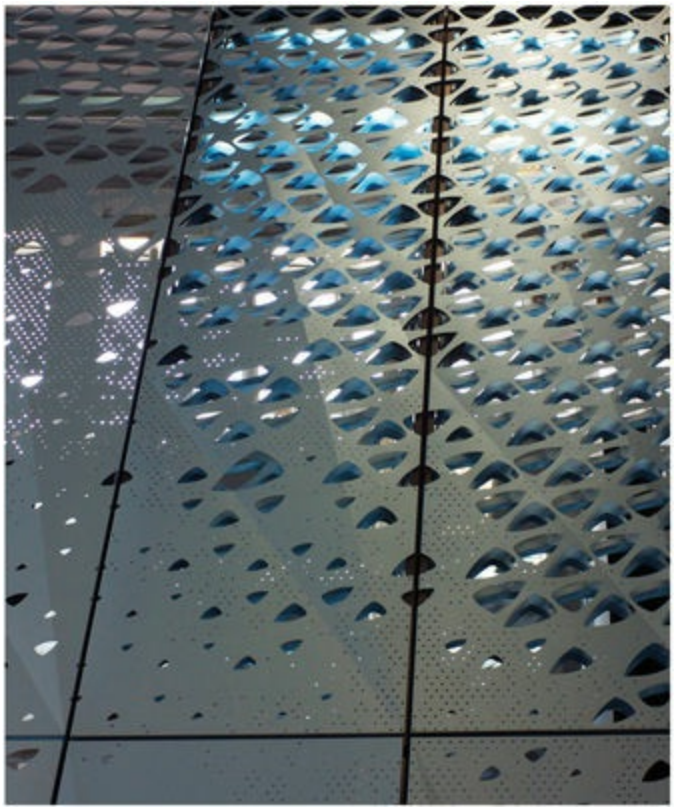
known contemporary practices to have designed several kinetic, performance-based adaptive shading systems in collaboration with the New York office of Buro Happold, a global design and engineering firm, with whom they allied in 2008 to form the Adaptive Buildings Initiative[2] (ABI). One of the systems they designed is based on "adaptive fritting" that produces movable patterns of varying density (Figure 6.3a and b) and could be thus used to control transparency, light transmission, solar gain, and views. The variable patterning is accomplished by shifting several layers of fritted glass[3] relative to each other. The glass layers are housed in an integrated glazed unit; their motion relative to each other is accomplished by a simple motor-based actuation. The shading patterns are highly customizable and could be uniform or non-uniform, repetitive or not, etc.



6.4 The *Tessellate* adaptive façade system designed by ABI in collaboration with A. Zahner Company.

In collaboration with A. Zahner Company from Kansas, ABI (i.e. Hoberman and Buro Happold) has developed an adaptive façade system called *Tessellate*,

a self-contained, framed perforated screen that consists of stacked panels that move and overlap, creating kaleidoscopic patterns (Figure 6.4), which control light and solar gain, ventilation and airflow, privacy, and views. The changing pattern density is accomplished in the same way as in adaptive fritting, by shifting the patterned layers relative to each other. In this case the perforation patterns are CNC-cut from sheets of metal (or other material). The perforated sheets are then housed in an integrated unit with a motor that provides for the rotational translation of the sheets, resulting in a constantly changing light-diffusing screen.



6.5 The *KAFD Spas* in Riyadh, Saudi Arabia, is to feature an adaptive façade system designed by ABI and made by A. Zahner Company.

The *Tessellate* dynamic perforated screen system was incorporated by the architectural firm WORKSBUREAU in the façade design for twin luxury spas (Figure 6.5) that is to become the gateway to the King Abdullah Financial District in Riyadh (construction was scheduled to begin in 2014). The system's

modules consist of three layers of perforated color-interference titanium, two of which are motorized, so that the perforated patterns create overlaps and thus regulate light and heat in a continuous reaction to external conditions. According to the designers' estimates, this façade system should reduce the cost of cooling the building by 15–20 percent.

Some of the motorized adaptive façades are applied externally to the building façade, i.e. they are external to glazing units. Many of them involve some kind of retractable mechanism that can either expand or contract the shading surface. The *Strata* adaptive shading system, also designed by ABI in collaboration with A. Zahner Company, is made of modular units that consist of telescopic fins that can retract into a single slender profile or extend to form a nearly continuous surface (Figure 6.6a–d). The *HelioTrace* System, which ABI has developed in collaboration with SOM and Permasteelisa, is based on the telescopic motion of stacked fins that can retract to a slender square shape or expand to an almost closed square surface. This kinetic shading system could be programmed to follow the location of the sun and adjust its square aperture as needed. The fins do not need to be completely opaque; they could be perforated, fritted, and made from different kinds of materials. According to ABI, the system is capable of reducing the heat gain by up to 80 percent.[4]

6.6a–d The *Strata* adaptive shading system designed by ABI in collaboration with A. Zahner Company.

6.7 *Q1 Headquarters* building (2010) in Essen, Germany, designed by Chaix & Morel and JSWD Architekten, has a kinetic façade made of 1,280 motorized louvered shades.

As these examples show, active adaptive shading systems could be either internal, i.e. embedded in the building façade, or be external to it. Whether they are internal or external depends on the scale, materials, means of actuation – and the maintenance regime. Encasing the shading system between two sealed layers of glass eliminates dust particles (and sand), which can get into lubricated areas that reduce friction in mechanized assemblies. Mechanically activated systems that are external to the façade are not only exposed to the elements but particulate matter could get into the mechanisms causing greater wear and tear, and thus resulting in a shorter lifespan of the systems; there is also increased chance of malfunction in the system, resulting in more frequent and more costly maintenance than is the case with the

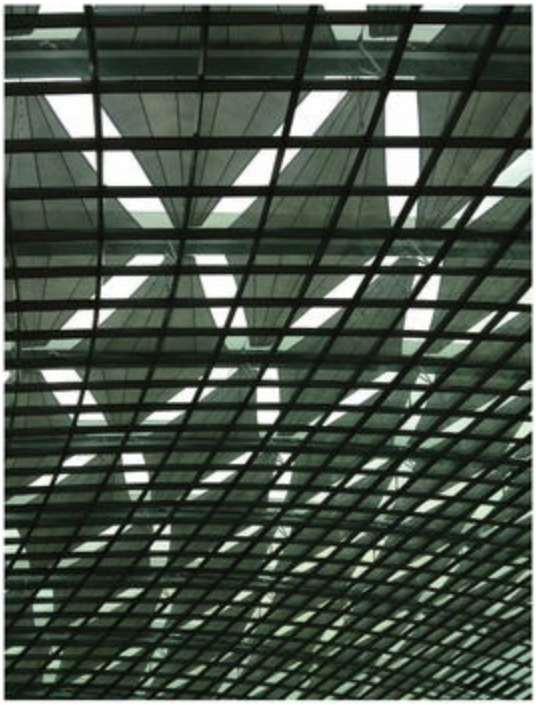
internal, embedded systems.

The *Q1 Headquarters* building (Figure 6.7) for ThyssenKrupp in Essen, Germany, completed in 2010 and designed by Chaix & Morel (Paris) and JSWD Architekten (Cologne), is shaded by an external kinetic system that consists of 1,280 feather-like motorized louvered shades made from stainless steel. The "feathers" come in different shapes, from triangles and rectangles to trapezoids, that can move from open to closed positions (and in between) as the control system tracks the sun moving across the sky. Besides shading the building's interior, reducing its solar heat gain and modulating daylighting, the "feathers" produce a finely textured façade. The feather-like pivoting elements can move in unison or independently, i.e. they can be individually controlled.

Another notable, recently completed building with an external adaptive shading system is the *Al-Bahr Towers*, two 29-story buildings in Abu Dhabi, UAE, designed by AHR and completed in 2012 (Figure 6.8). The responsive façade is based on a traditional Arab lattice-screen called a *mashrabiya*. It consists of approximately one thousand triangular "umbrellas" organized into hexagonal units, which are attached to a conventional glass façade (Figure 6.9). The umbrellas can change their configuration from open to closed through linear actuation and origami-like folding, which is controlled by the building's management system that tracks the movement and location of the sun. According to design estimates, the external shading system should reduce cooling loads by as much as 25 percent. The design team developed a parametric geometric description of the external system and simulated its operation under different incidence angles over the course of a year, measuring its impact on the building's thermal and energy performance. By minimizing the solar heat gain, the system reduces cooling requirements thus reducing the energy consumption. It also diffuses direct sunlight with its translucent, fiberglass surfaces, which do not block the views to the surrounding cityscape. It performs in multiple ways, as is the case with most active shading systems.

6.8 *Al-Bahr Towers* (2012) in Abu Dhabi, UAE, designed by AHR, features an adaptive external shading system.

6.9 *Al-Bahr Towers*: operable triangular "umbrellas", organized into hexagonal units, shade the sun-exposed surfaces of the two towers.



6.10a and b Conservatory buildings in *Gardens by the Bay* (2012) in Singapore, designed by Wilkinson Eyre, are covered by an automated fabric-based external shading system.

Gardens by the Bay in Singapore has a conservatory complex designed by Wilkinson Eyre Architects and completed in 2012, featuring a double-glazed

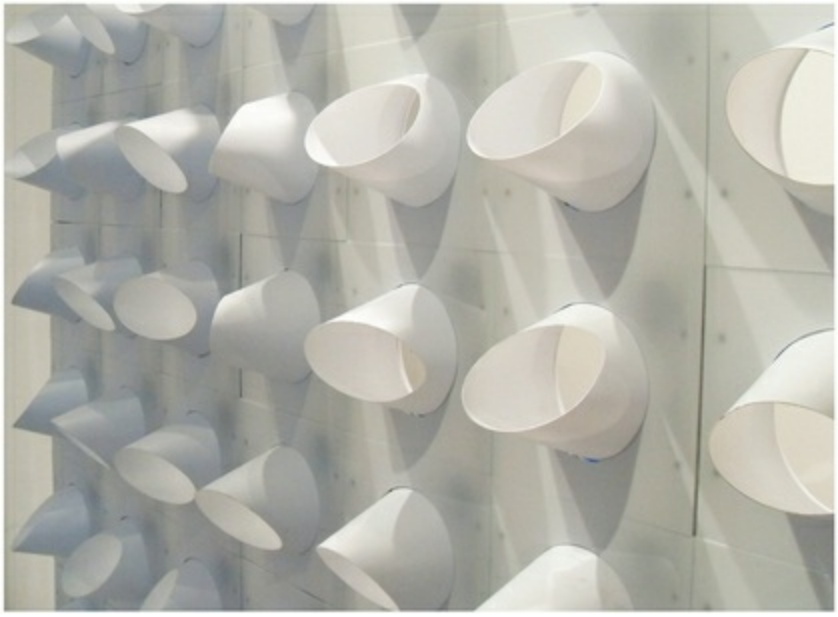
roof with a mostly horizontal external shading system that is composed of triangle-shaped fabric shades (Figure 6.10a and b). Each shade can be fully extended or rolled up depending on solar conditions, thus modulating daylight and reducing heat gain in the glazed buildings. Sensors inside the conservatories monitor the environmental conditions, i.e. the temperature, humidity, and the light levels. As light levels increase and reach a certain threshold, the external shading system is deployed. The shades, which when deactivated are rolled up and concealed under structural members on one side, are pulled by a cable towards the opposite side, creating a visually dynamic "pineapple" pattern when fully extended. The adaptive shading system also provides a degree of spectacle for the visitors as it expands and retracts across the glass surfaces of the conservatories.

The *One Ocean* pavilion for Expo 2012 in Yeosu, South Korea, designed by SOMA from Vienna, Austria, features an external kinetic façade system that mimics the movement of a fish's gills (Figure 6.11). The kinetic façade, developed in collaboration with engineering consultants Knippers-Helbig from Stuttgart, Germany, is 140 meters long, with the height changing from 3 to 13 meters. It consists of 108 vertical lamellas made from glass-fiber reinforced polymer (GFRP). The lamellas are both strong and flexible, allowing for reversible elastic deformations; when actuated by motors along the top and bottom edge, the lamellas bend asymmetrically, creating gill-like openings that allow light into the buildings and afford views to the outside. Each lamella is individually controlled; the bending of the lamellas is choreographed to create wave-like patterns as they open and close along the length of the façade, producing a dynamic effect that animates the building's organic form.

In 2010, our research group, Laboratory for Integrative Design (LID), created *iConic*, a prototype of a building façade system comprised of mechanized, electronically controlled truncated conic modules (Figure 6.12) that rotate independently, altering the orientation of elliptical apertures and producing different performative effects during the course of a day, from dynamic sun shading and regulating outward views to urban-scale performances across the exterior field. Even though various tests were

performed on the rotating conic modules, the prototype started producing squealing, whirling, and scratching noises soon after it was publicly exhibited. The main challenge in its design was not the geometry, electronics, or the actuation, but *friction*, which to this date remains an issue in almost all mechanically, i.e. motor-based actuation systems. Friction, i.e. the required frequent maintenance of malfunctioning apertures, is the primary reason why the kinetic façade on Jean Nouvel's *Institut du Monde Arabe* building is now "permanently frozen." It is also why designers of adaptive systems are looking into other ways of actuation besides motor-based ones, such as hydraulics, pneumatics, or material-based actuation.

6.11 The *One Ocean* pavilion in Yeosu, South Korea, has an external, gills-like kinetic façade system.



6.12 *iConic*, prototype of a dynamic building façade system designed in 2010 by Matt Knapik, Eric and Mike Kryski from Laboratory for Integrative Design (LID), University of Calgary.

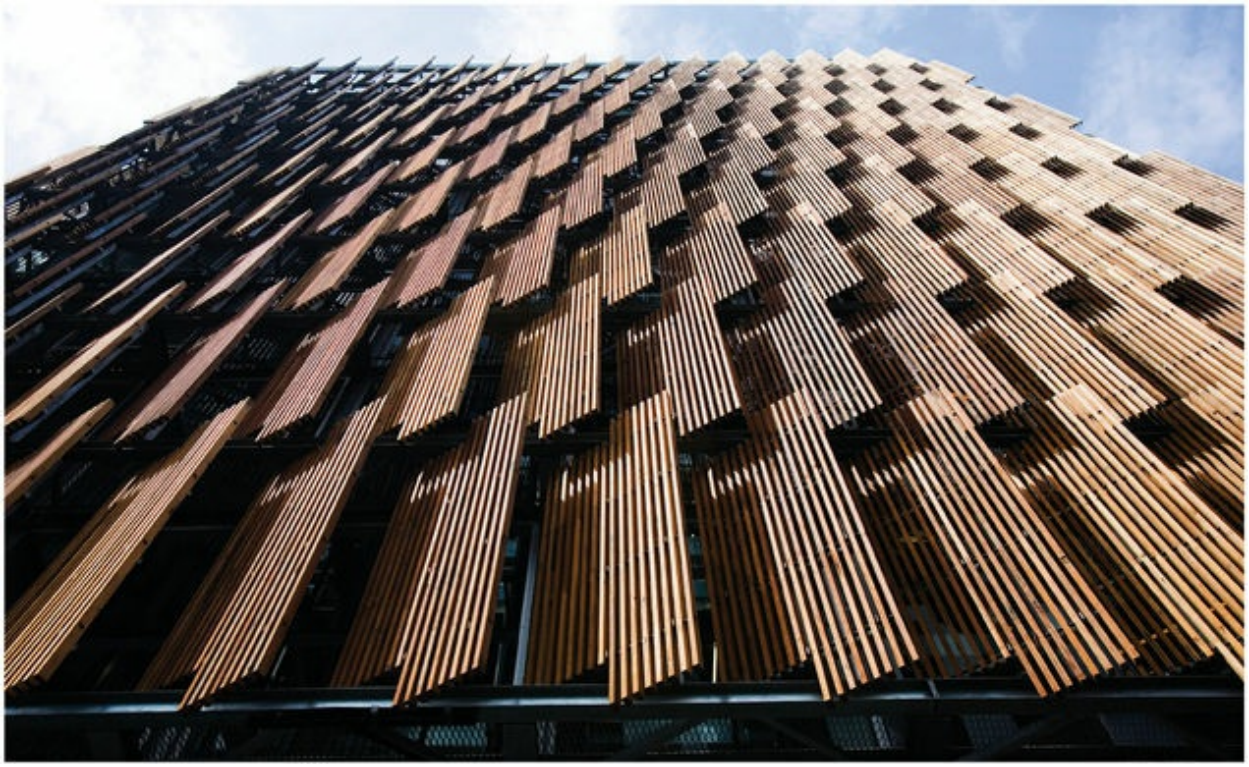
6.13 The *Media-TIC* building (2011) in Barcelona, by Cloud 9, features a dynamic façade made of "breathing" ETFE air cushions.

Pneumatic Actuation

The *Media-TIC* building in Barcelona, designed by Enric Ruiz-Geli of Cloud 9 and completed in 2011, features a dynamic façade made of lightweight ETFE air cushions that provide pneumatic sun shading (Figure 6.13). The cushions consist of three layers of plastic with two air chambers between them that can be inflated or deflated as needed; the first layer is transparent; the second and third layers have a reverse pattern that creates shade when inflated and joined together. On the west side of the building, the ETFE air cushions are filled

with nitrogen (mixed with tiny oil droplets) in the afternoon, transforming a transparent into a translucent façade that blocks 90 percent of the sun's radiation, thus reducing substantially the building's heat gain. In addition, the building features a number of other control systems (based on over a hundred networked Arduino[5] boards) that can sense various changes in the environment and then produce a corresponding reaction not only in shading but also how the building is lit, etc.

ETFE cushions were previously used in the *Eden Project*, designed by Nicholas Grimshaw and completed in 2003, and in the *National Aquatics Center* (the "*Watercube*") in Beijing, designed by PTW Architects from Sydney in collaboration with Arup, and completed in 2008 for the Summer Olympic Games. ETFE is an incredibly lightweight, inexpensive and thermally effective building enclosure that weighs about 1 percent of glass with the same area. Typically, the sheets of ETFE are precisely cut using CNC cutters, heat-welded along the edges, and then inflated to create "cushions." The cushions need to be inflated continuously by air pumps, which consume energy and may require periodic maintenance. The cushions also require a separate support structure, which was given a honeycomb pattern on both Grimshaw's and Enric Geli's buildings; the *Watercube* in Beijing features hexagons and pentagons. ETFE is finding increasing use in all types of buildings, from school courtyards to football stadiums (such as Bayern's stadium in Munich, designed by Herzog and de Meuron).



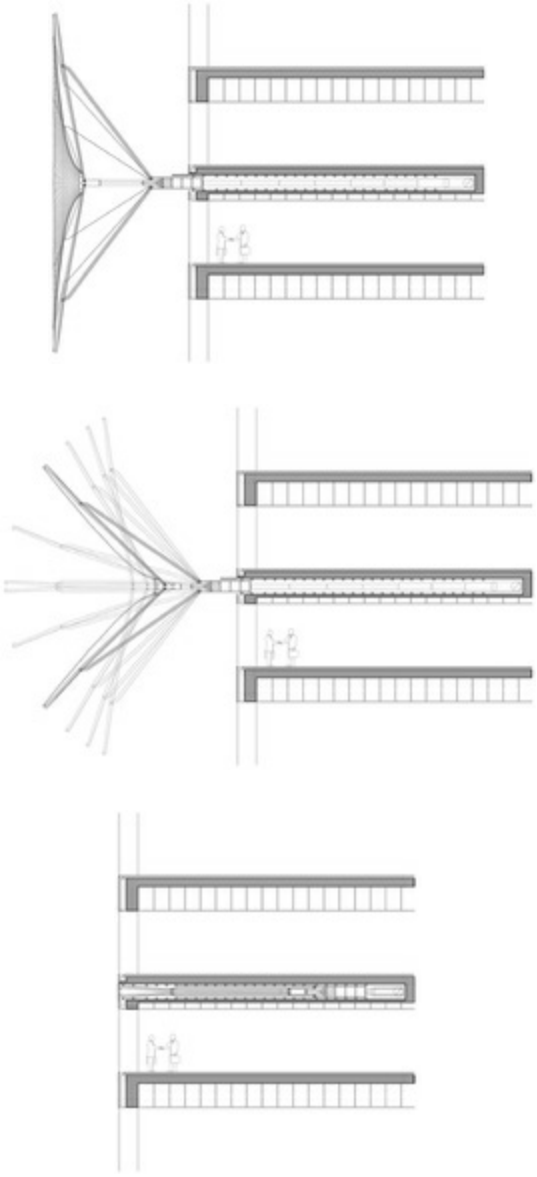
6.14 The *CH2* building (2006) in Melbourne, Australia, is covered with timber shutters driven by a computer-controlled hydraulic system.

Hydraulic Actuation

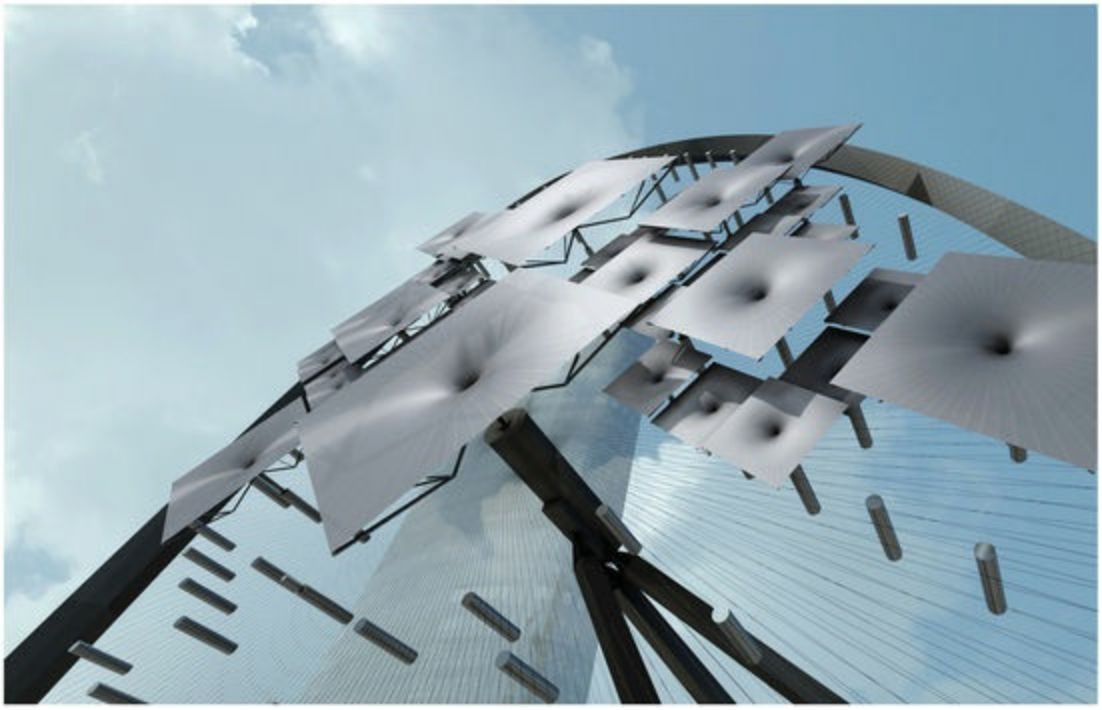
The *Council House 2* (CH2) building in Melbourne, Australia, designed by Mick Pearce and completed in 2006, features an external adaptive shading system that consists of pivoting timber shutters that are moved by a computer-controlled hydraulic system (Figure 6.14). The shutters respond to the amount of direct sunlight hitting the western façade; they open fully in the morning and then slowly close up as the sun moves overhead to the west. This adaptive shading system is a rather simple, straightforward way to reduce solar heat gain. The building also features other systems that control lighting and ventilation, further reducing the building's energy footprint, making it one of the "greenest" buildings in Australia. Its wood-textured façade provides a noticeable, yet subtle presence along one of the main streets

in downtown Melbourne.

6.15a and b The REX-designed towers in the Middle East with retractable sunshades.



6.16a–c Nestled in cavities between floors, the shades can expand or contract within 60 seconds.



6.17 The *Surya* shading screen, designed by REX, is comprised of variably dimensioned umbrellas that "blossom" as needed to provide protection from reflected sunrays.

REX designed two "thin" towers for an undisclosed location in the Middle East that would be protected from the intense sunlight by an array of retractable sunshades (Figures 6.15a and b), whose geometry was inspired by the *mashrabiya* shading screens common in traditional architecture in the region. The umbrella-like overlapping sunshades would be 14.5 m in diameter; however, in spite of their size, they could quickly be deployed from the cavities embedded between floors (Figures 6.16a–c), transforming the buildings' façades into two large, vertical "blossoming" fields. The courtyards surrounding the building also feature deployable umbrellas that are automatically retracted when the courtyards are in the shadow of the building or, conversely, expanded when exposed to sunlight. A similar shading system was devised by REX (in collaboration with Front, Inc.) for the sun-responsive *Surya* shading screen (Figure 6.17) that would protect the interior of an art center in Dallas from the sun's rays reflected from the nearby glazed tower. The shade, mounted on an oval ring resembling a bicycle wheel, consists of variably dimensioned umbrellas that "blossom" in a precise configuration as

needed during the day, when intense reflections from the tower are detected, and retract when not. Besides having a purely utilitarian function, *Surya* can also perform as an ever-changing urban-scale sculpture.

6.18a and b The *BIQ House* in Hamburg, completed in 2013, is covered with over a hundred bio-reactive panels.

Material-Based Actuation

The glazing itself could adapt to changing environmental conditions. The so-called "smart" or "switchable" glass can change its light transmission properties if electrical current is applied to it (electrochromic) or under light (photochromic) or heat (thermochromic). This kind of glass can change from being transparent to translucent and back. In electrochromic glass, electricity is required only when switching from one state to another, but once change is effected, no electrical current is required to maintain it.[6] Recently developed electrochromic materials can become reflective rather than absorbing, and thus change between transparent and mirror-like states. These new glazing materials effectively eliminate the need for mechanically activated blinds and shades.

Other kinds of adaptive building materials are emerging out of research labs.[7] For example, Joanna Aizenberg at the Wyss Institute at Harvard University has been experimenting with super-hydrophic surface materials that can prevent or slow ice formation, can adapt from hydrophobic (non-wetting) to hydrophilic (wetting), and collect rainwater efficiently; light-sensitive materials that control transparency and thermal gain; surface materials that can harness energy from the environment, etc.

Several researchers are looking into the "organic" or biological paradigm of kinetic adaptation, which also relies on material instead of mechanical actuation. For example, Achim Menges has recently designed *HygroScope*, a prototype that relies on the innate capacity of thin strips or sheets of wood to produce an actuated response (bending) when exposed to changing levels of humidity.[8] In this case, the material structure itself is the machine, as Menges notes. Another trajectory in material-based activation is to create laminates made from materials that react at dimensionally different rates to

environmental changes. For example, Doris Sung is experimenting with bimetallic panels in which two laminated sheets of metal expand and contract at different rates when exposed to heat, i.e. direct sunlight, producing changes in geometry, again through bending. Other researchers are working with shape-memory materials, in which deformation can be induced and recovered from through temperature changes. David Benjamin experimented early on with shape-memory alloys (SMA) and Nick Puckett has used various shape-memory polymers to create material-actuated prototypes. These experiments in material-based actuation could potentially lead to "zero-energy" adaptive building envelopes, if and when they are fully developed into commercial products.

While these experiments are harbingers of future building skins that will look "alive," Arup's engineers have developed collaboratively (with SSC Ltd. and Colt International) a photo-bio-reactive façade prototype called "*SolarLeaf*" that is actually alive. It features a layer of microalgae between two sheets of glass that generates biomass and heat as renewable energy resources. The four-story *BIQ House* (Figures 6.18a and b), built for the 2013 International Building Exhibition (IBA) in Hamburg, has installed 129 of these bioreactor panels on the south-east and south-west façades, each measuring 2.5m x 0.7m. Solar thermal heat and algae are harvested over approximately 200m^2 of surface area in a closed loop system, in which they are stored and then fermented to generate hot water.

The future of dynamic building skins will likely belong to low-energy systems that can harvest the heat from the sun or the kinetic energy of the wind. In many experiments described in this section, the "sensing" and "actuating" capacities were built into the material, eliminating the need for complex mechatronic assemblies. Such passive systems of dynamic activation that rely on innate properties of materials are perhaps the most promising direction for developing adaptive building envelopes.

6.19 The transformable façade of the *Storefront for Art and Architecture* in New York (1993), designed by Steven Holl and Vito Acconci.

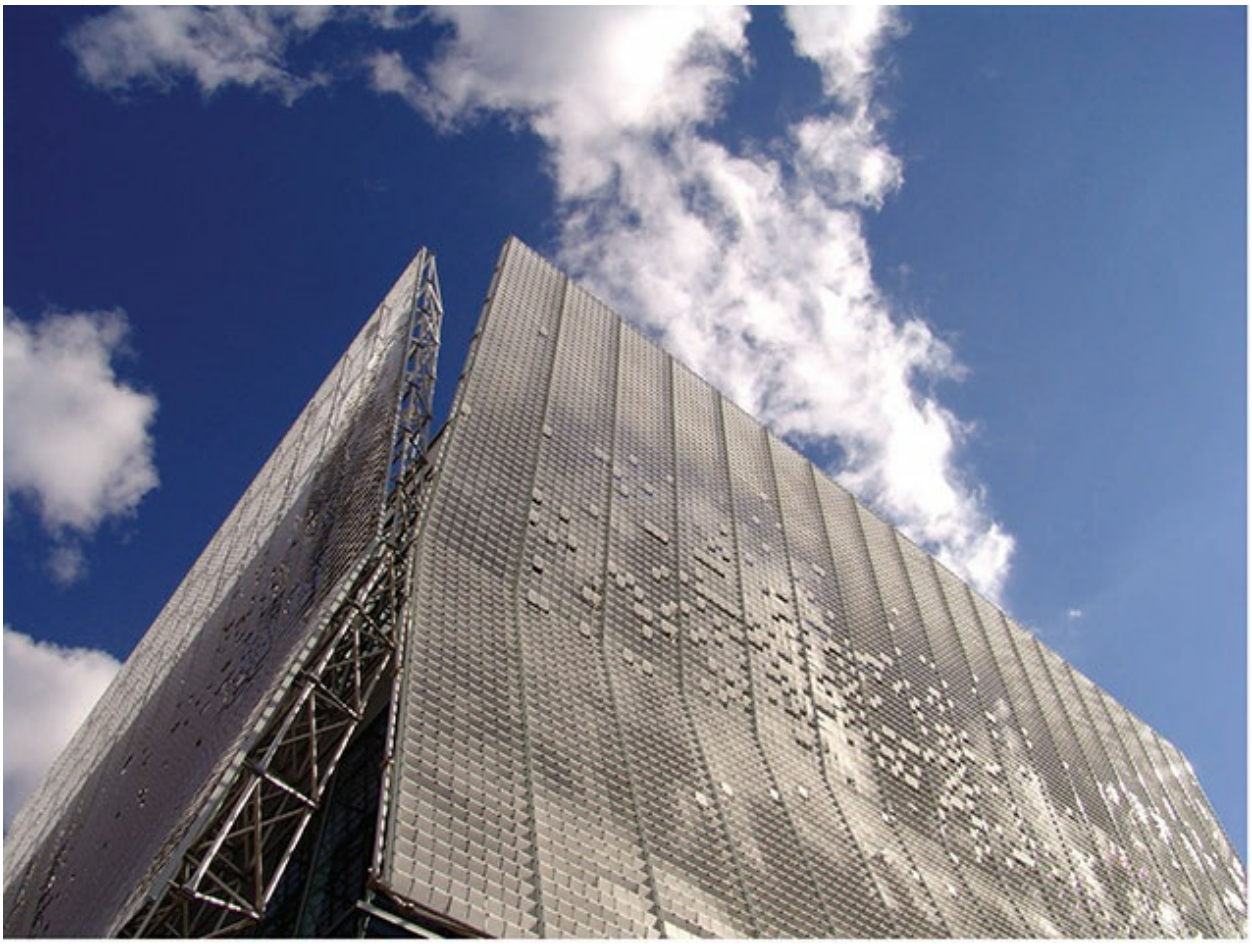
Adaptive Skins Using Simple, Lo-Tech Strategies

As more and more designers and firms begin to experiment with innovative sensing, control, and actuation technologies embedded in the layers of building skins, it is worth noting that the notion of adaptive building envelopes is not new. Buildings used to have adaptive façades with hinged and louvered shutters fixed outside the windows that were used to provide security, privacy, or to modulate light. Sliding, externally mounted shading and privacy screens are still widely used; they are not mechanized and are moved (i.e. "actuated") by people who occupy the spaces behind them. Such simple low-technology, low-maintenance, and low-cost solutions still have a place in contemporary architecture that seeks to provide user-controlled adaptability in buildings.

Ordinary wheels and hinges – if used imaginatively – could create very potent transformable environments that need not rely on any fancy mechatronic set-ups. By relying on hinged panels Steven Holl and Vito Acconci created an incredibly effective, puzzle-like transformable façade of

the *Storefront for Art and Architecture* in New York (1993, Figure 6.19). The *Sliding House* in Suffolk, UK, designed by dRMM and completed in 2009 (Figures 6.20a–d), features an enclosure that can move along recessed tracks to cover or uncover different buildings along its 28m-long linear path: the house, garage, or the annex (and a swimming pool that could be added in the future). The four electric motors that move the enclosure are integrated into its wall thickness; car batteries that are charged by mains or PV solar panels power each motor.

6.20a–d dRMM's *Sliding House* (2009) in Suffolk, UK.



6.21 For the *Children's Museum of Pittsburgh* (2011) Ned Kahn designed a sunscreen made from tens of thousands hinged resin flaps.

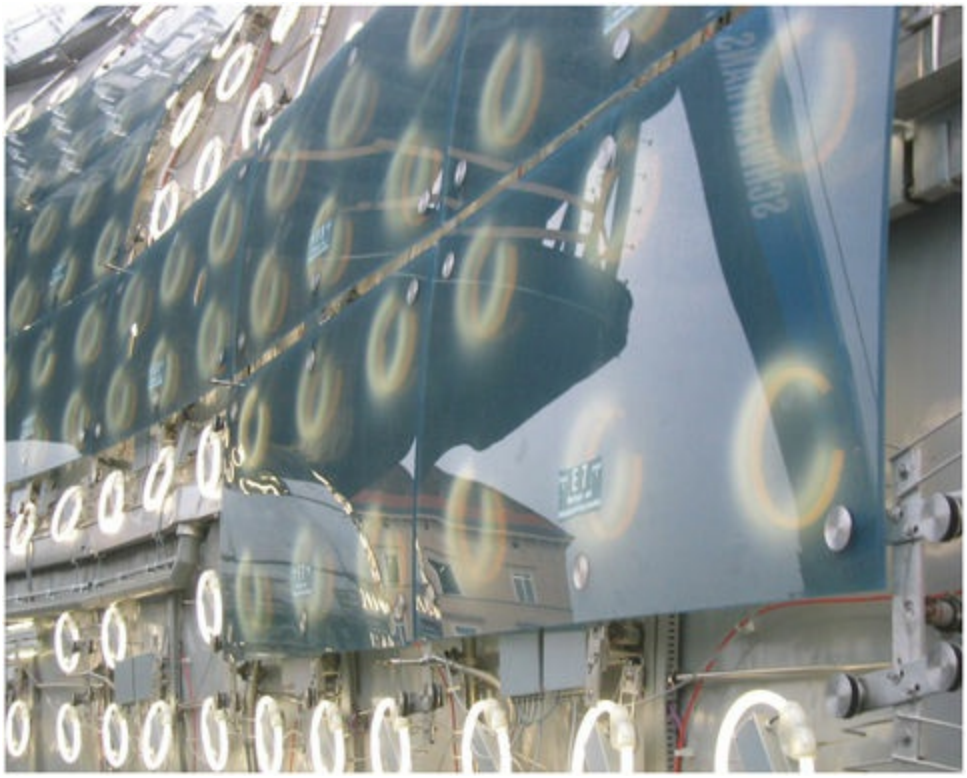
The new pavilion added to the *Children's Museum of Pittsburgh* (2011, Figure 6.21) offers a compelling example of a dynamic yet tectonically and technologically simple façade. Koning Eizenberg, architects of the pavilion, deployed a sunscreen called "*Articulated Cloud*," designed by Ned Kahn, that consists of tens of thousands of hinged resin flaps that flutter in the wind; during the day, their color depends on the sky conditions; at night, they are illuminated, emanating bright white light like a large lantern. The architects have managed to produce a dynamic building skin that registers and responds to environmental conditions (light, wind) without any sophisticated mechatronics. It represents an excellent example of minimalist, simple tectonics producing complex, subtle spatial and surface effects. Such

simplexity – complexity attained through simple means – is perhaps another promising trajectory for dynamic building skins.

Challenges Ahead

We should not lose sight of "lo-tech" solutions in the current quest for adaptive building skins infused with the latest sensing, control, and activation technologies. Oftentimes, simply adding wheels and tracks (and/or hinges) to façade elements that are then moved by people is all that is necessary to create effective – even "zero energy" – adaptive building skins. Where and when it becomes impractical for people to reach those moveable elements, for example, due to a building's height, severe weather, or the element's weight, they could be mechanized and activated with an on/off switch.

Automating building skins bring a host of other issues into play that go beyond available state-of-the-art materials and technologies, affordability, durability, low-maintenance requirements, and other various performance targets (energy savings, uniform light levels, etc.). User override is potentially a critical issue in the design of any highly automated adaptive, responsive building envelope system. Social and cultural factors need to be taken into account. For example, louvers in an automated, "high-performance" façade could automatically come down in bright sunlight to shade the interior spaces but that action could not only be distracting to people who might be in an important meeting but could also block a highly desirable and attractive view to a nearby park or lake. If an installed, automated system requires frequent manual overrides by annoyed users, its "life" is not going to be that long; a simple, people-activated "high-performance" and lo-tech solution would probably more than suffice in such cases.



6.22 The *BIX Façade* at *Kunsthaus* in Graz (2003), designed by realities:united, was built using round neon lights that were ubiquitous in the 1960s.

There is also a good chance that any mechatronic solution that depends on the current state-of-the-art technologies could become obsolete relatively quickly. One way of addressing this challenge of obsolescence is to rely on solutions that are already seen as "obsolete" – as such, they won't become obsolete – because they already are. For example, Jan and Tim Edler from realities:united, who took on the challenge of designing the media façade for the *Kunsthaus* in Graz by Peter Cook and Colin Fournier, considered all sorts of the latest and the greatest contemporary technologies, such as LEDs, plasma screens, projections systems, etc. but were concerned with their potential life span. In the end they settled for the humble but utterly "obsolete" round neon lights that were ubiquitous in kitchens in the 1960s (Figure 6.22). They discovered that the intensity of those lights could be controlled with a simple capacitor that could be connected to a custom-designed controller board with a user-friendly screen interface. Thus, a lo-tech, low-resolution monochrome "BIX façade" (BIX stands for the "building

pixel") made from technologically obsolete components was devised to withstand these inevitable challenges of time and technological progress.

There is also the ever-present danger of creating "gimmicky" architecture that becomes "boring" very quickly; that should be a primary concern for the designers of dynamic building skins who aim to provide a novel urban experience by adding computer-controlled LED lighting systems (i.e., the technology of the day) that can display images across buildings at night. What is "new" today becomes "old" sooner than ever before, which is why we didn't cover "dynamic" building skins with embedded, computer-controlled lighting systems.

We must not forget that any cutting-edge technological system of today can become obsolete rather quickly. This dimension of time is rather critical for the designers of adaptive, responsive – and interactive – building envelopes of tomorrow.

Acknowledgements

Parts of this chapter have been previously published by the authors.

Notes

1 ETFE stands for ethylene tetrafluoroethylene.

2 See www.adaptivebuildings.com/.

3 Fritting is a pattern of ceramic glazing fused to the glass layer; this is a well-known surface treatment for solar control.

4 The *Strata* adaptive shading system was supposed to be deployed on several projects in the Middle East, which, however, had to be put on hold during the last financial crisis.

5 Arduino is an inexpensive open source microcontroller that was released in 2005 in Italy. It can be connected easily to a variety of sensors detecting light, motion, touch, sound, temperature, etc.

and also to all kinds of actuators that can be controlled, such as lights, motors, and other devices.

6 The Boeing 787 "Dreamliner" airplane has electrochromatic windows instead of pull-down window shades.

7 For a more detailed discussion of adaptive materials, see Chapter 12 by Vera Parlac in this book.

8 See www.achimmenges.net for more details.

7
Dynamic, Adaptive Building Envelopes

EDWIN B. HATHAWAY

7.1 *Lever House* (1952) in New York, designed by Skidmore, Owings and Merrill.

It is time to look at the impact that buildings have on the environment and how we can make use of new technologies to create more adaptive building

envelopes. Today, we can develop building envelopes designed to accept or reject *free energy* from the external ecosystem, and as a result, reduce the costs required to achieve a comfortable, internal environment.

While we can look back to Mies van der Rohe's drawings of the 1920s for the first instance of skyscraper design, it was really during the 1950s and 1960s that the curtain wall was born. Some of the first curtain walls were made with steel mullions, and the "plate glass" was attached to the mullions with asbestos or a fiberglass modified glazing compound. Eventually, silicone sealants or glazing tape were substituted. Some designs included an outer cap to hold the glass in place and to protect the integrity of the seals. This type of construction approach was used on Skidmore, Owings and Merrill's *Lever House* (Figure 7.1), the first curtain wall building installed in New York City in 1952.

At that time, energy costs were low, allowing for air conditioning to conquer building design, and as a result, most buildings ended up with façades that featured fixed windows and contained or "sealed" environments. However, by the 1980s, harsh weather conditions had caused the Lever House glass façade, sealants, and original fabrication design to deteriorate. By the mid-1990s, only 1 percent of the original glass curtain wall remained. Buildings designed and constructed during this era underperformed and now have become energy-inefficient.

It is not an exaggeration to say that Willis Carrier's (1902) invention of modern air-conditioning shaped twentieth-century America. In the 1930s, the use of air conditioning increased from very limited domestic use to movie theaters, department stores, rail cars, and offices, sending workers' productivity soaring in the summer months.

Residential air-conditioning was slower to gain popularity and as late as 1965, just 10 percent of US homes had it, according to the Carrier Corporation. By the 1980s, the USA – which then housed only 5 percent of the world's population – was consuming more air-conditioning than all the other countries combined. In fact, by 1979, essayists lamented people's reliance on the electricity-devouring invention. "It is thus no exaggeration to say that Americans have taken to mechanical cooling avidly and greedily," wrote

TIME magazine writer Frank Trippett in 1979. "Many have become all but addicted."[1]

By 2007, 86 percent of US homes had air-conditioning. As cool air spread across the country, Sun Belt cities that had been unbearable in the summer became more attractive places to live and work, thus facilitating a long-term shift in US population.

Over the years, air-conditioning has been credited with the survival of institutions and industries: the heat-sensitive world of computer networks and the US Federal Government, which often had to shut down in humid, swampy Washington, DC. Even Las Vegas was revitalized after the introduction of man-made coolness.

But the cool bliss of air-conditioned environments has raised the temperature of some critics. Environmentalists who are concerned about global warming have long called for a cutting back on the proliferation of air-conditioning.

With buildings consuming approximately 50 percent of the US total energy, we should re-examine past practice and make use of collaboration and new technologies to create more dynamic and adaptive building envelopes. Building envelopes can no longer be passive; indeed, they must become more dynamic and adaptive. In fact, 50 percent of the 8,000 buildings owned by the US Government constructed between 1950 and 1995 are almost all in need of significant upgrading. Commercial buildings account for 75 percent of carbon emissions on the planet. If we are serious about reducing greenhouse gas effects, we should re-examine how we design, construct, and retrofit buildings to achieve improved energy performance.

One of the real pioneers of holistic thinking about buildings was R. Buckminster Fuller. One of his many predictions about the future was that societies would rely on renewable sources of energy, such as solar and wind-driven electricity. He introduced a multi-faceted system known as "Synergetics"[2] that used geometric modeling to explore interrelationships between the facts of experience and the process of thinking. Fuller stated, "Synergetics endeavors to identify and understand the methods that Nature actually uses in coordinating the universe both physically and

metaphysically."[3] Fuller believed technology would have to follow nature's design as illustrated by the ingenuity of a spider's web, which can float in a hurricane because of its high strength-to-weight ratio. Fuller wanted building designs to incorporate principles found in nature.

The geodesic dome was the result of Fuller's exploration of nature's constructing principles. Introduced in the 1940s, the sphere used Fuller's concept of "doing more with less" in that it encloses the largest volume of interior space with the least surface area, thus saving on cost and the volume of materials. The spherical structure of a dome is one of the most efficient interior atmospheres for human dwellings because air and energy are allowed to circulate without obstruction, enabling heating and cooling to occur *naturally*. Geodesic shelters have been built all around the world in different climates and temperatures and they still have proven to be the most efficient human shelter. The net annual energy savings from a dome is typically 30 percent more than traditional, rectilinear homes.

Modeling Geometry/Simulating Performance

Energy modeling has become very important with respect to new building design and retrofits; including calculating peak heating and cooling loads; ventilation options; façade design and solar shading; and the use of ventilated and unventilated double façades. Energy analysis provides the critical insight that promotes buildings existing in their environment in the most energy-efficient manner – in essence, to act as a "climate moderator." Today, there are tools that conduct high-level analyses and provide feedback regarding energy performance at the very early stages of design.

Technology and collaboration are two crucial elements that will lead the way to creating more adaptive building envelopes. The technology from the manufacturing and software industries is driving this new design/build process. Building Information Modeling (BIM), with programs such as Revit,

Rhino, Grasshopper, CATIA, Navis Works, Horizontal Glue, and even applications on smart phones/tables, are revolutionizing the way buildings are designed. This technology creates new opportunities for innovative collaboration at all stages of the design/build process. As Fuller predicted, energy-efficiency, sustainability, and environmental stewardship are informing the technology, and as a result, changing the way buildings are designed.

One reason why there has been a huge surge in demand for computer-simulated design is the advancement of computational hardware to provide massive, high-speed calculations. Such innovations have enabled professionals to tackle complex scientific problems in such diverse fields as climate change, earthquake prediction, and medical research. In a recent *Wall Street Journal* article, Don Clark wrote:

> The increased use of super computers underscores the increasing popularity of computer simulation as a way to conduct science, augmenting theoretical research and in many cases replacing physical experiments. As super computers become more powerful, scientists can examine animated models of objects and phenomena with much greater detail than before.[4]

Video games have been around for years, but it's really only been in the last five years that the quality of their graphics and their ability to render photo-realistic environments have exploded with accelerating, new technology. One example is the Australian company, Euclideon, who in 2011 ignited YouTube and the international gaming industry with a short teaser of its "Unlimited Detail" 3D engine.[5] Euclideon has an unconventional "atom-based" approach to building 3D worlds. This new technology can increase the current, graphic visual fidelity by a factor of 100,000 times. Euclideon's Unlimited Detail (UD) technology removes *all* limits that have traditionally restricted the amount of 3D data that you can capture, visualize, and virtually experience. No longer are 3D visualizations and rendering technologies restricted by expensive, high-cost hardware with expensive RAM capacities.

At the heart of this technology is a 3D search algorithm that can render unlimited quantities of point cloud data in real-time. As this algorithm efficiently grabs only one point for every screen pixel, it can display models of

previously unimaginable sizes at interactive frame-rates, without the need for powerful CPUs or multiple graphics cards. This revolutionary ability to render such massive 3D detail has game-changing implications for the AEC community.

The biggest hurdle we face in creating adaptive building envelopes is collaboration. Our industry is at the forefront of game-changing technology. We have to be able to engage our knowledge with architects, engineers, and owner/developers in a more direct, effective, and efficient process.

We have the expertise and innovations that can provide critical insights at the very earliest stages of design. There are no longer technical reasons why we cannot produce integrated drawings. More importantly, there are no technical reasons why we cannot build *virtually* before we build *physically*.

Enabling Collaboration with BIM IQ®

In 1987, when Building Information Modeling (BIM) was introduced, it was seen as the beginning of a significant technological breakthrough that would enable collaboration in the design, documentation, and construction of buildings. Oldcastle BuildingEnvelope® wanted to advance BIM further, to make it more intelligent. BIM + Intelligence = BIM IQ® (patent-pending) is a revolutionary interactive design and energy application for the architectural and construction industry (Figure 7.2).

7.2 BIM + Intelligence = BIM IQ®, a revolutionary 3D interactive design and energy application for the architectural and construction industry.

The BIM IQ® rendering aspect of the application generates physically-accurate visualizations of buildings from any view point outside or inside, at any time of day or night, and on any day of the year, with any one of our architectural glass substrates and curtain wall designs. BIM IQ® features an energy analytics engine that accurately calculates the energy-performance data of any given change in glass substrate or curtain wall design substitution. BIM IQ® is a game changer in how buildings will be designed to enhance energy-efficiency and achieve compelling aesthetics within the context of the existing, built environment.

Three relevant case studies illustrate the power of BIM IQ®: *The Bow*, Encana's Headquarters in Calgary; *Aura*, Canada's tallest (78 stories) condominium tower; and DFR's *West 57th Street*, a residential, rental project in New York. These three buildings have taken a variety of approaches to the design of their respective building envelopes, and BIM IQ® can be used to show how different architectural elements, such as glass type and curtain wall designs, can enhance energy efficiency.

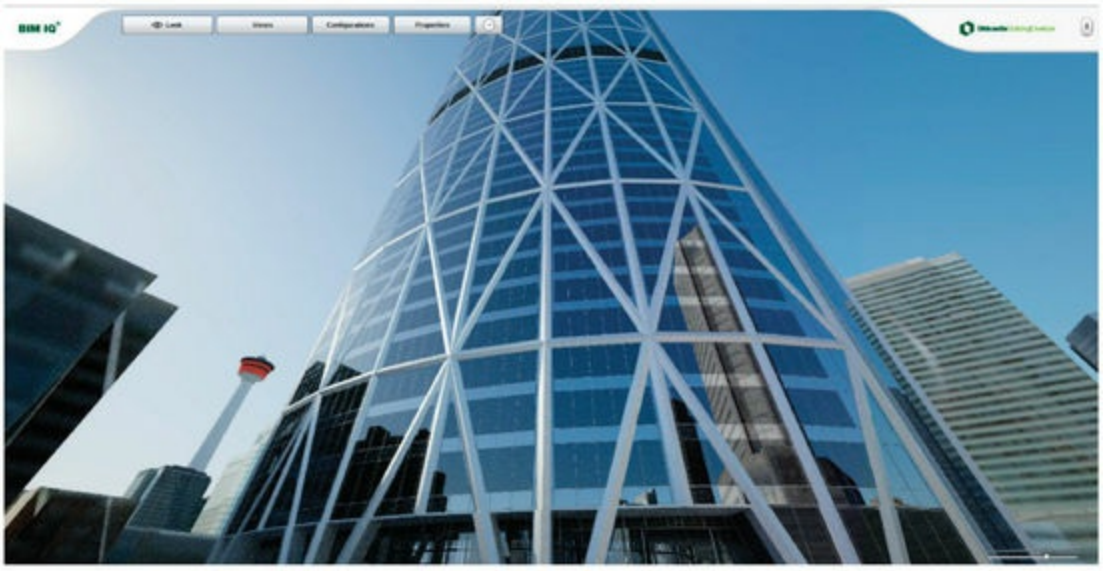
At 58 stories, *The Bow* is Calgary's tallest mixed-use development, providing an environmentally sustainable headquarters for Encana, one of Canada's leading corporations (Figure 7.3). Designed by Foster + Partners, the development comprises an office tower for Encana, a new public plaza with cultural and retail facilities, and a podium building between 6th and 7th Avenue. The building's form was shaped by both environmental and organizational analysis. The tower faces south, curving towards the sun to take advantage of daylight and heat, while the resulting bow-shaped plan gives the tower its name and maximizes the perimeter offices with Rocky Mountains views. By turning the convex façade into the prevailing wind (Figure 7.4), the structural loading was minimized, reducing the amount of steel required for the inherently efficient diagrid structural system. Where the building curves inwards, the glazed façade is pulled forward to create a series of atria that run the full height of the tower. These spaces act as climactic buffer zones, insulating the building and helping to reduce energy consumption by approximately 30 percent. The large curving floor plan provides a window office for roughly 70 percent of the staff. These office placements, combined with floor-to-ceiling glazing, reduce the need for artificial lighting. Heat produced within the offices is also recycled through the atrium to further reduce heating costs and "excessive" energy consumption. Foster used a similar system for *The Gherkin*, located in London.

7.3 *The Bow* (2012) in Calgary, designed by Foster + Partners.

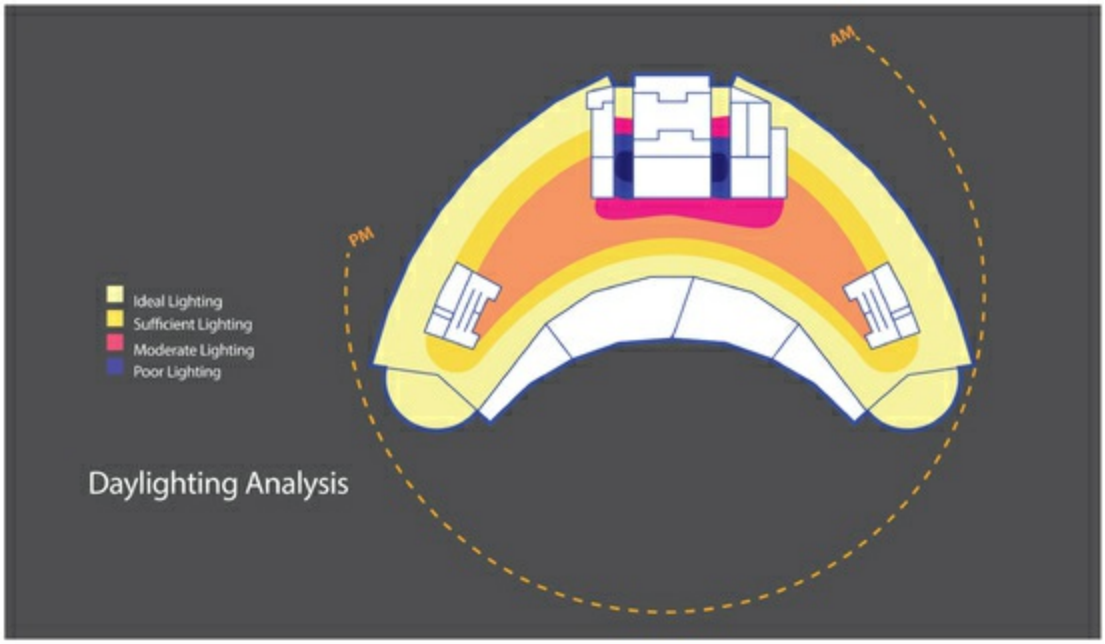
BIM IQ®'s energy analytics can evaluate the climate specifics of a local environment to determine the impact of external temperatures, solar intensity, and wind speed, and direction on the initial stages of a building's design. An energy analysis shows that Calgary, Canada, has very few weeks with temperatures above 20 degrees Celsius, so heating is more of a prevalent cost factor than cooling with air-conditioning. The orientation of *The Bow* building was key in optimizing energy usage. The shape of the building is designed to serve as a giant solar collector. The south elevation of the building has a high-performing double-skin façade with vents connected to the building's maintenance system for automated control. This creates a high degree of energy-efficiency and a dynamic, adaptive structure. A BIM IQ® daylighting analysis (Figure 7.5) shows that 70 percent of the interior space has adequate daylight penetration. A wind analysis illustrates the speed and direction of the prevailing wind that strikes the building over the course of a year. This analysis is used to assess the possibility of incorporating natural ventilation into the building envelope's design; and to determine the number of vents and

louvers that would be needed to maximize natural ventilation. With greater natural ventilation, the size and cost of the HVAC system would be reduced for this adaptive building design.

BIM IQ® technology can also be used during the design process to create realistic comparative visualizations. Design changes, such as glass and curtain wall framing options, can be modified and these scenarios can be seen from varying viewpoints, at different times of day, to gain physically-accurate visual representations.

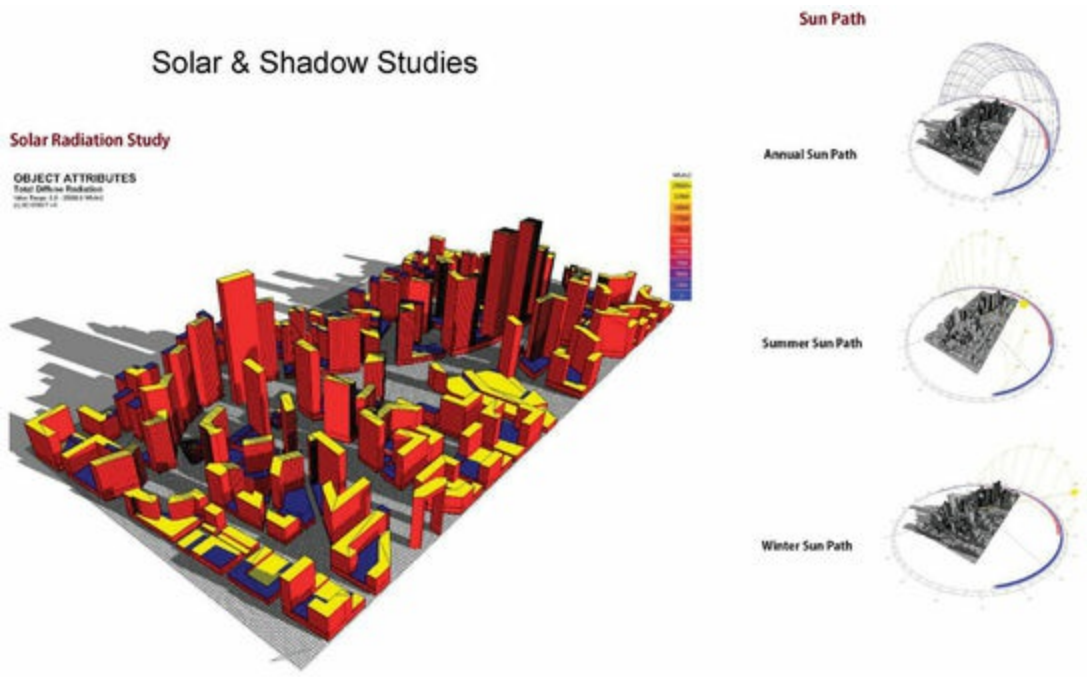


7.4 *The Bow* has a convex façade facing the predominant wind (image rendered in BIM IQ®).



7.5 BIM IQ® daylighting analysis of the interior of the *The Bow*.

7.6 *Aura,* a mixed-use building in Toronto, designed by Graziani + Corazza.



7.7 Solar studies.

Aura (Figure 7.6) at College Park is located in downtown Toronto, at Young and Gerrard Streets. It is a mixed-use building consisting of lower-level podium retail space with the balance being residential units. At 78 stories, it is the tallest residential building in Canada. Designed by Toronto architects Graziani + Corazza, this residential tower contains 985 residential units and features a 40-foot-tall glass enclosed lobby. The residential portion of the tower has been built above a three-story podium that will contain approximately 14,000 m^2 of retail space. Each residential condominium unit features an individually controlled in-suite heat pump system featuring on-demand central heating and air-conditioning, as well as individual unit metering for electricity. Double-glazed, low-E windows with pre-finished aluminum frames surround the building's exterior.

As seen with *The Bow* project, the energy analysis of BIM IQ® can show the effects of temperature, solar, and wind impacts on the building's external environment (Figure 7.7). Toronto's climate has very few weeks with temperatures above 20°C; therefore heating will become more of a factor than cooling in the optimal design of the HVAC systems. A solar radiation analysis

will help to determine what type of glass is best suited to complement HVAC design to either shield the sun's radiation or to make use of it for internal comfort and lighting requirements. This analysis will also help in designing the exterior of the building with respect to sunshades and glass colors. A wind analysis indicates the speed and direction of the prevailing wind on the building's environment. Such analysis assists in making the best use of and to locate vents and louvers to maximize natural ventilation. As seen with *The Bow* project, it also helps ensure the appropriate size of HVAC system is designed for the building.

A BIM IQ® analysis will also be important in determining the amount of natural daylight that will enter the space and therefore the amount of additional light that would be needed. Similar to *The Bow*, the impact of the choice of glass for the *Aura* building affects the structure's energy performance. With BIM IQ®, the aesthetics of changing glass types can be reviewed instantly, and BIM IQ® can represent accurate images with respect to reflections as the environment changes. The choice of glass impacts the building's solar gain, energy consumption, and visible light. Changing the glass has a significant impact on the energy loads and therefore cost to heat the building. For the *Aura* building, BIM IQ® shows that it is better to use a lesser-performing glass to maximize impact from the natural environment. BIM IQ® will also allow for material and color changes with materials other than glass, and has the ability to demonstrate changes to sizing of curtain wall elements.

7.8 The *West 57th Street* apartment building in New York designed by BIG.

The Danish architect firm, Bjarke Ingels Group (BIG), has designed an unusual apartment building on *West 57th Street* (Figure 7.8) in New York for the developer Durst Fetner Residential (DFR). The project, stretching the entire block between 11th Avenue and the Hudson River, will include 750 rental apartments in a pyramid-shaped, 32-story tower. As BIG's inaugural North American project, the building is a hybrid between European perimeter block residential buildings and a traditional Manhattan high-rise. The *West 57th Street* building has a unique shape which combines the advantages of both: the compactness and efficiency of a courtyard building providing density, a sense of intimacy and security, with the airiness and the expansive views of a skyscraper. By keeping three corners of the block low and lifting the north-east corner up towards its 32-story peak, the courtyard opens views towards the Hudson River, bringing the low western sun deep into the block and graciously preserving an adjacent building's views of the river. Each apartment has a water-to-air heat pump. Each apartment is also mixed-mode

ready, which means that each apartment has operable windows, which the occupants can use to control the internal environment. This allows the mechanical systems to be switched off for periods where the natural external environment can be used to maintain comfortable conditions in the living spaces. Because the building is located within the FEMA floodplain for a one-hundred year storm (similar to the recent superstorm Sandy), the building's mechanical systems could not be placed in the basement and have been positioned above ground on the north side of the building.

Again, the choice of glass for a building envelope has a huge impact on the structure's energy performance. By changing to a lesser-performing glass, thereby maximizing the impact from the environment, the energy consumption is reduced by approximately 20 percent. A model of *West 57th Street* was provided to Oldcastle BuildingEnvelope® by the owner. The balance of the model, which is the cityscape, is a combination of aerial photography and mass modeling to create the surrounding built environment.

BIM IQ® is capable of making property changes to materials and glass types on demand, and interior views can be investigated to demonstrate how the project will look from the inside. BIM IQ® can reveal unforeseen issues including those that affect energy use. One notable discovery, specifically on the *West 57th Street* project, was that direct sunlight and direct solar heat rarely impacted the northern-facing units of the building. This elevation has restricted access to natural daylight and solar gain throughout the year. For example, in an effort to assist the designer to leverage natural resources on this façade, we highlighted one design feature on the north wall, that being privacy panels, which was included to prevent adjacent apartments from seeing into each other. After the BIM IQ® analysis, our recommendation was to replace these panels with simple capillary-filled glass, thus maintaining the required privacy of the tenants, as capillary glass only allows views through perpendicularly. With the elimination of the privacy panels, and introduction of a higher light transmittance/higher solar heat gain coefficient glass substrate on the north facade, the entire system allows much needed additional daylight and solar heat into these north-facing apartments.

Towards Integrated, Performance-Based Design

These three important project case studies demonstrate how – with integrated collaboration and technology – architects, engineers, developers, manufacturers, and other industry experts can apply performance-based design and achieve more intelligent energy-efficient buildings. The development of adaptive buildings requires early design collaboration to examine trade-offs versus energy costs for heating and cooling. Achieving optimized building envelopes requires design to be integrated across various disciplines. The selection of curtain wall, glass substrates, solar shading devices, fixed/operable windows, and window sizes requires critical analysis relative to the building's global site positioning and solar orientation, as well as weather, wind, and context within its built environment.

R. Buckminster Fuller once said:

> I am enthusiastic over humanity's extraordinary and sometimes very timely ingenuity. If you are in a shipwreck and all the boats are gone, a piano top buoyant enough to keep you afloat that comes along makes a fortuitous life preserver. But this is not to say that the best way to design a life preserver is in the form of a piano top. I think that we are clinging to a great many piano tops in accepting yesterday's fortuitous contrivings as constituting the only means for solving a given problem.[6]

Whether we think about buildings as unique structures or investigate how we can harvest more energy from a building envelope, or design the envelope to breathe and capture daylight, the future of our industry is very much upon us. As Fuller's quote suggests, we need to rethink the way we design buildings. Their performance is not just measured in isolation; buildings are now part of an ever-increasing energy ecosystem that affects communities and our environment. Just because buildings designed up until this point have tried to build on better design, technology and improved construction materials does not mean we can rest on our laurels. Fuller stated, "Architects, if they are really to be comprehensive, must assume [...] the total world pattern of needs, its resource flows, its recirculatory and regenerative processes."[7]

It is our collective responsibility to continually explore ways of making

more dynamic and adaptive buildings and building envelopes. The AEC industry can bring intelligence to performance-based design and achieve more energy-efficient buildings.

Notes

1 Frank Trippett in 1979, as quoted by Katy Steinmetz, in "Air-Conditioning," *TIME*, July 12, 2010.

2 Fuller, R. Buckminster, with Applewhite, E.J., *Synergetics: Explorations in the Geometry of Thinking* (New York: Macmillan, 1975).

3 Ibid.

4 Clark, Don, "Demand Surges for Supercomputers," *Wall Street Journal*, March 28, 2013.

5 See www.youtube.com/watch?v=00gAbgBu8R4.

6 Fuller, R. Buckminster, *Operating Manual for Spaceship Earth* (New York: Simon and Schuster, 1969).

7 Fuller, R. Buckminster, *Ideas and Integrities: A Spontaneous Autobiographical Disclosure* (New York: Macmillan, 1969).

8
Tranformable: Building Structures that Change themselves

CHUCK HOBERMAN

Introduction

Our firm, Hoberman Associates, Inc. (HAI), is a multidisciplinary practice that specializes in transformable design – the development of products, structures, and environments that change their size and shape. We believe that a world undergoing accelerating change needs an adaptive, interactive approach to design. Whether that means inventing a rapidly deployable shelter, re-defining portability for children's products, or collaborating with architects to develop next-generation adaptive buildings via our Adaptive Building Initiative (described later in this chapter), our clients seek us out to *shape change* – and inspire it. We aim to *design behavior* – to create objects that have the living qualities of organisms.

Since its founding in 1990, HAI has focused on fostering a dynamic relationship between product and user, seamlessly fusing art, design, engineering, and architecture. In recent years HAI has embarked on a series of architectural collaborations to create adaptive buildings. Working with architectural firms in America, Europe, and Asia, HAI is creating responsive shading and ventilation surfaces, operable roofs and canopies, and retractable façades for multiuse spaces. The primary motivation for our architectural projects is to achieve energy savings and enhanced building environments within the context of advanced sustainable strategies. Our role is concurrently

creative and technical, and our work is justified by its performance, including environmental impact, architectural integration, and visitor experience.

This chapter presents an overview of practical methods for designing objects that can change their size, shape, and surface. It draws on my own practice of building large-scale kinetic installations, as well as those of other practitioners, exploring a range of applications in architecture and design.

Theory of Tranformation

Hoberman Associates' work is centered on the fundamental idea that a designed object can transform the way a natural organism does. While the smooth transformation of size and shape is ubiquitous in the natural world, it is rare among man-made objects. The creation of transforming objects requires a new design theory, a conceptual framework that draws on mathematics, mechanics, and structural engineering to integrate *change* as a basis for design.

Through years of exploration and experimentation we have identified critical parameters for the successful creation of transforming objects. The process of transformation should be complete and fully three-dimensional, smooth and continuous, and reversible and repeatable. These attributes result in functional benefits for products, such as ease of use, fluid responsiveness, and adaptability. They lead to an integrated design approach where structure and mechanism are combined, which offers the ability to build transforming structures at both the large and the small scale.

Our creations are experiments in *adaptive behavior* – we believe that behavior itself can be designed into a product or place. By doing so, an indelible experience and connection are made with the user or occupant. Our design medium is behavior itself. For us, elegance and economy remain the pre-eminent values of good design. An elegant mechanism translates a simple push or pull into rich and complex behavior. Sustainability fundamentally requires us to do more with less, which is the very definition of design

elegance.

There are transformable typologies, i.e. families of structures that share functional characteristics, such as patterns of connectivity and modes of transformation (e.g. expansion, surface modulation, shape-morphing). Geometric and mechanical principles underlie these typologies, rule-sets allowing the designer to consider two types of transformation – parametric within the design process, and kinematic as expressed in actual movement and real-time behavior.

The idea is not so much to just make something go from A to B, but to make a structure where the process of going from A to B is actually the subject of the design. The challenge for us is how to design transformability, how to design the process of change within a structure or within an object.

So if we consider why a subject like transformability is interesting, we need look no further than nature, where everything transforms. All organisms transform. We are transforming as we read this; our bodies are changing from birth to death. Those changes in our bodies are also reflected over much longer time scales, in evolutionary time spans, where species change their form to adapt, to survive. But we also see shape changes occurring in organisms in realtime. An octopus changes its size, shape, color, and texture – all with the goal of grabbing little fish. For me, as a designer, this is the idea of what I want to create – something that transforms in as complete a way as possible. It is the design of the transformation that I am after.

Over the years, I have worked in many different sectors at many different scales, from miniature medical instruments up to architectural scale. The common theme is not really the change in shape or size or color or some other design parameter but the process of transformation itself.

8.1a–c *Tutu Rattle* (2007).

8.2a–c *Brain Twist* (2003).

8.3a–c *Boom-O-Ring* (2008).

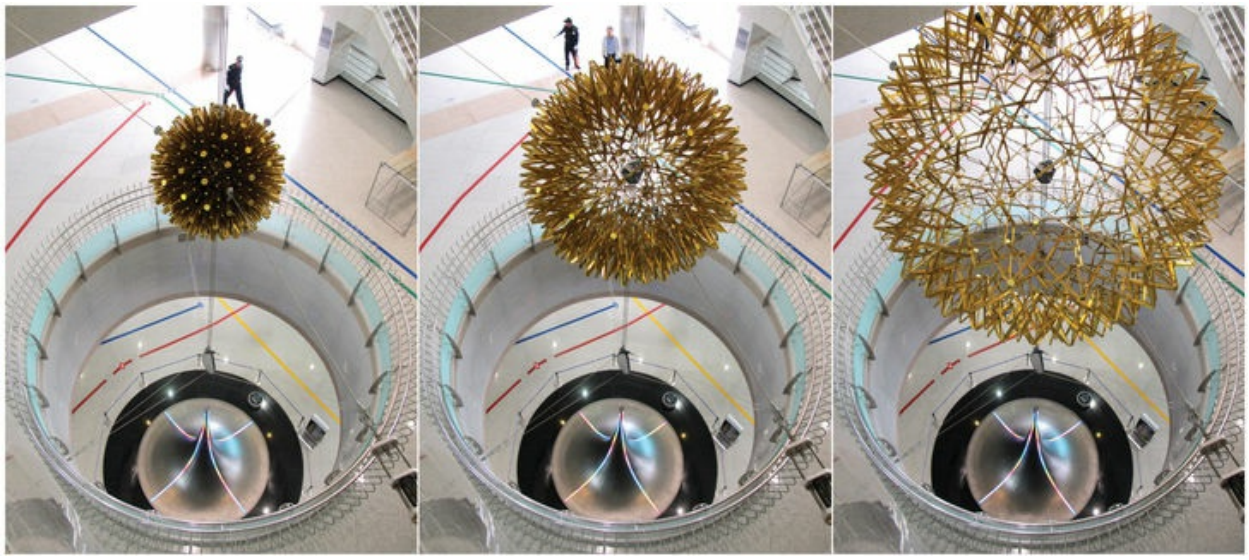
8.4a–c *Switch Pitch* (2004).

Transformable Design

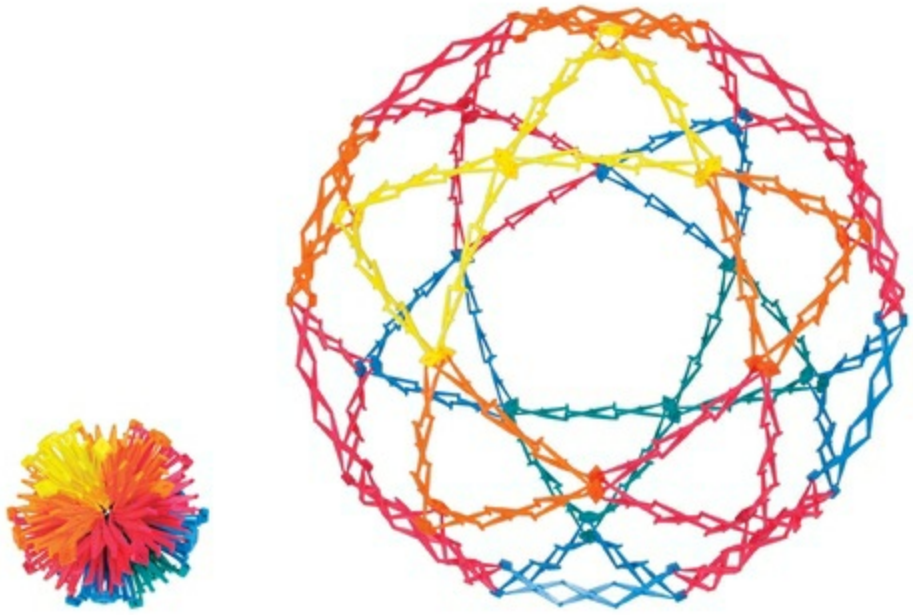
Today, we are used to designing shape transformations digitally rather than physically. When the movie *Terminator 2* came out, morphing was introduced into the lexicon and all of a sudden we could think about design in a new way. So, my interest is to combine the physical transformation of the kind that we see in nature with the design transformation that we might see digitally. My approach to this is from a mechanisms standpoint (I trained as a mechanisms designer). But I try to generalize that mechanisms approach into a broader idea of designing objects that change by defining an object not as a single form, but as a sequence of forms; the object then has the means within itself to self-transform, to change itself.

One of the things that I always loved about mechanisms is that they are very tactile; I love touching them and feeling the movement in my hands. There is something about a mechanism where as physical and specific it is, there is always something beyond the physicality, something ineffable, which, of course, is the movement itself. I see a mechanism as *embodied relationships*. It is an object that holds all those movements within itself in potential form, and then, as soon as an actuation force, such as my hands, is applied to it, everything transforms synchronously. I have designed a number of expandable, colorful, transformable toys, such as *Tutu Rattle* (2007, Figures 8.1a–c), *Brain Twist* (2003, Figures 8.2a–c), *Boom-O-Ring* (2008, Figures 8.3a–c), and *Switch Pitch* (2004, Figures 8.4a–c), all of which share a tactile, almost addictive quality. These are the result of a longstanding experimentation with flexible, manipulative forms that can be changed and flipped. These toys have developed alongside larger-scale works, as studies at full-scale in themselves, not necessarily models for larger works (although the themes often reemerge).

While the medium I have been working with is mechanical, the mechanical means of transformation touches on many other processes of transformation not only in nature but also in other types of technologies, which are covered later in this chapter.



8.5a–c *Expanding Sphere*, Korea Aerospace Research Institute (2011).



8.6a and b *Hoberman Sphere* (1999).

8.7 A close-up view of the *Expanding Sphere*.

Expanding Sphere

When I first designed the *Expanding Sphere* (Figure 8.5a–c) in 1992, as a 318-kg kinetic aluminum centerpiece for the atrium of New Jersey's Liberty Science Center,[1] I was doing it as an inventor, as a structural designer. It is a very interesting object and I thought that if we made a toy, maybe kids would like to look at it. So, the *Hoberman Sphere*,[2] mass-produced as a colorful children's toy in the form of a lightweight, flexible plastic dome that opens and closes (Figures 8.6a and b), hit the market in 1999 and has since sold in millions around the world. What is interesting about this toy is actually when you see how somebody interacts with it, they just don't look at it – it completely engages the people. I have learned a lot about the potential for transformable design after seeing so many people play with the sphere.

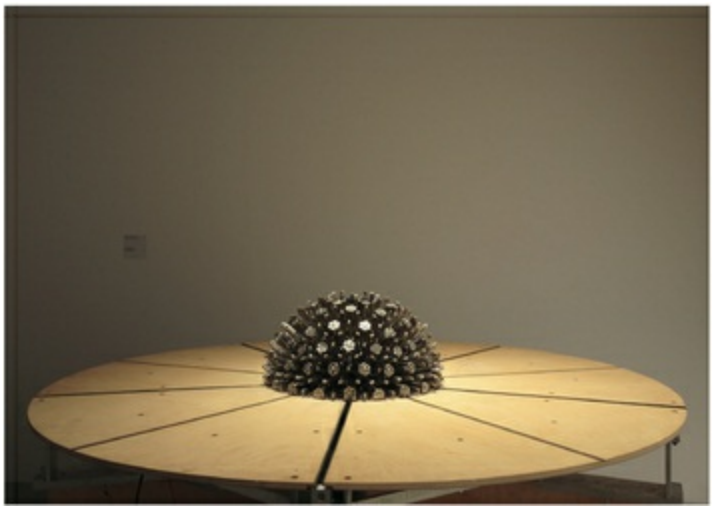
The *Expanding Sphere* has been installed in a number of buildings around the world, including Estonia, Germany, Korea, Japan, etc. The sphere installed at the AHHAA Science Centre in Tartu, Estonia, expands from 1.5 to 5.9

meters in diameter in approximately three seconds. Weighing 340 kg, it consists of 244 hubs and 1,440 linkages machined out of aircraft-grade aluminum, and connected with 2,880 pins and 5,760 bearings (Figure 8.7). Hub-linkage sub-assemblies form triangulated facets, with the entire sphere approximating the geometry of a geodesic sphere. Twin actuator cables control the diameter of the sphere by alternately pulling the sphere's opposing polar hubs.

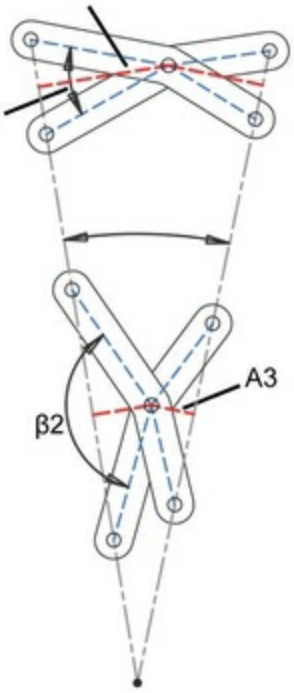
In addition to adding a dynamic element to the building, the *Expanding Sphere* also serves as an educational tool. Geometric principles such as symmetry, surface tessellation, and the structural integrity of triangulated shapes, are apparent in the Sphere's form. In both form and behavior, the Sphere demonstrates the concept of biomimicry. Its continual expansion may be likened to the smooth, continuous growth patterns seen in nature – the opening of a flower blossom, or the expansion and contraction of the iris of an eye.

The best thing about the *Expanding Sphere* in a Science Museum is seeing how kids react to it as it expands. I have seen kids looking at the sphere and just falling backwards, on their backs – they feel like this thing is coming at them. They don't react in an intellectual way; they are reacting in a physical, visceral way. It shows the power of transformable relationships in an object and how it engages the people who interact with it in a fundamental way.

The *Expanding Sphere* has had many lives – as a popular children's toy, a piece of public art, and also as a satellite. We adapted it for use as a radar calibration satellite for the US Naval Research Laboratory (NRL). Navy scientists approached us because they were seeking a perfectly spherical target that could be packed tightly into a rocket payload. Unlike inflatable structures, the *Hoberman Sphere* will last much longer in orbit and produce a superior cross-section for calibration of radar arrays.[3]



8.8a and b *Expanding Geodesic Dome* at Centre Pompidou (1997).

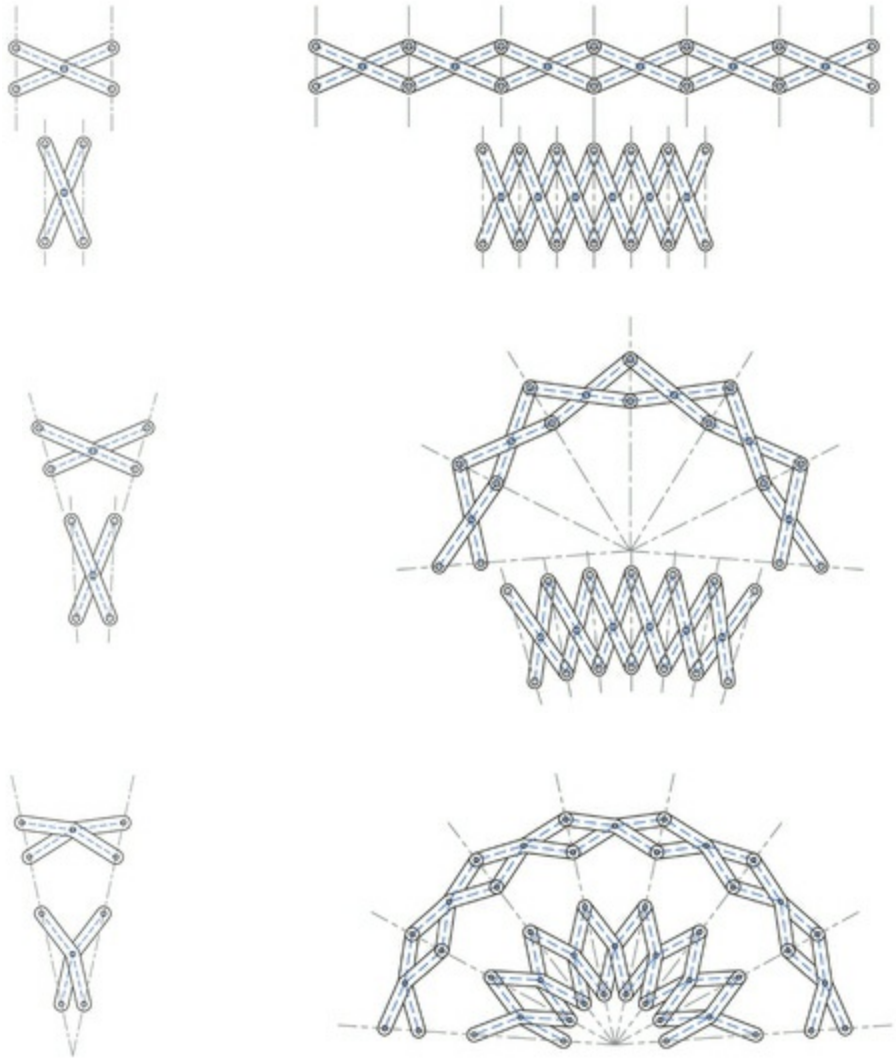


8.9 Angulated scissors mechanism.

Designing Mechanisms

When you design a transformable structure, you can think of it as a mechanism. The *Expanding Geodesic Dome* (Figure 8.8a and b), which I designed fairly early, in 1991, expands from a 1.5-meter cluster to a 6-meter structural dome when pulled open from its base. When deployed, it has the same shape and triangulated pattern as Buckminster Fuller's static, geodesic dome. It has what we might call a kinematic mode, but then as soon as the dome opens, it goes into a structural mode: it has triangles, it is dome-shaped, it sits on the ground – structurally it is virtually equivalent to Buckminster Fuller's geodesic dome. So, even though it seems the *Expanding Geodesic Dome* goes from a kinematic to a structural mode, in fact it has to negotiate both the motion and the structural support simultaneously. That dual nature is very much part of the transformable designs we do.

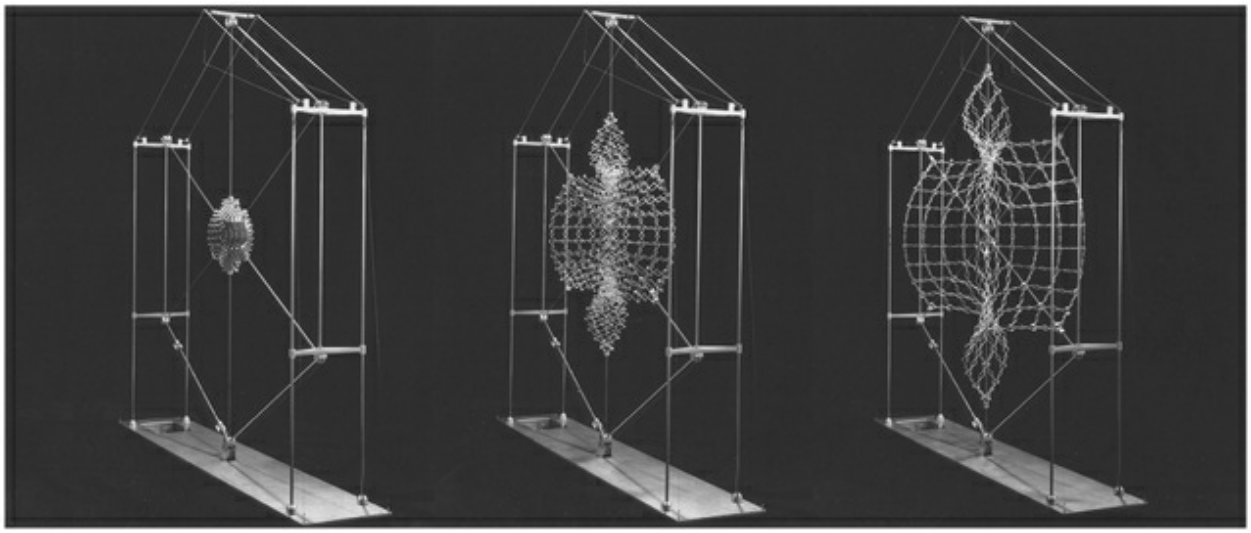
The conventional view in engineering is that structures resist forces and mechanisms convert force into motion. In my view, that is an artificial divide: even the most stable structure does in fact move a bit and every mechanism resists some forces. For a structural engineer a stable structure is equivalent to having very small deflections. In our designs we consider simultaneously structural and mechanical performance – a transformable structure is constantly deflecting as it expands, and the scale of deflection depends on the spans. For us, stability is dynamic – it is a process rather than a state.



8.10a–c Different scissors mechanisms produce different motion paths.

The mechanical performance of an object that we design is that it

transforms itself, by itself. For us, motion is not about a physical quantity — it is about changing relationships; a mechanism is an *embodied system of relationships*, whose changes through motion are carefully designed. To describe motion, kinetics studies the trajectories of points and lines (and other geometric objects) and their differential properties such as velocity and acceleration. In kinetics one designs the motion path, i.e. what mechanism does. While trajectories and paths matter, it is the relationships that are essential for mechanism's performance. Key to many of our transformable structures is one of my main inventions – the *angulated scissors mechanism* (Figure 8.9). In a typical scissors mechanism there are two straight, pivoting components connected at the center that form a criss-cross X pattern; the two lines that connect the endpoints remain parallel as the mechanism moves (Figure 8.10a). Now, if the connection point is moved off-center, i.e. if it is no longer at the middle point, the lines through the endpoints produce a changing angle (Figure 8.10b). My discovery more than 20 years ago was that if you bend or angulate the linked components, the angle between those lines connecting the endpoints no longer changed, i.e. it became invariant (Figure 8.10c).

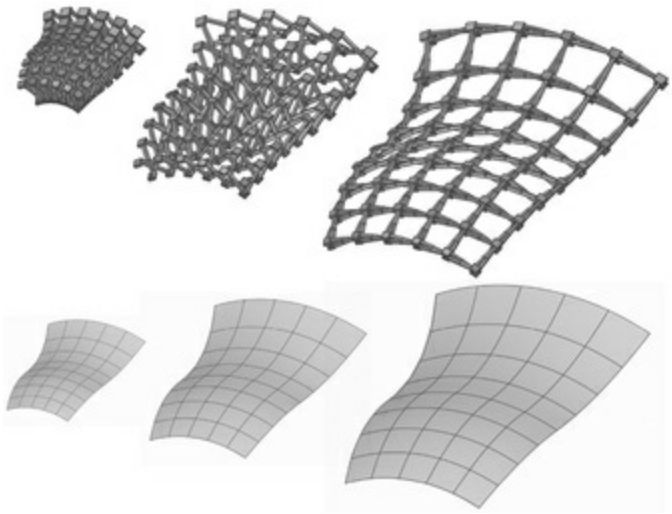


8.11a–c In the *Expanding Helicoid*, the points on the spiral shape move along straight-line trajectories.

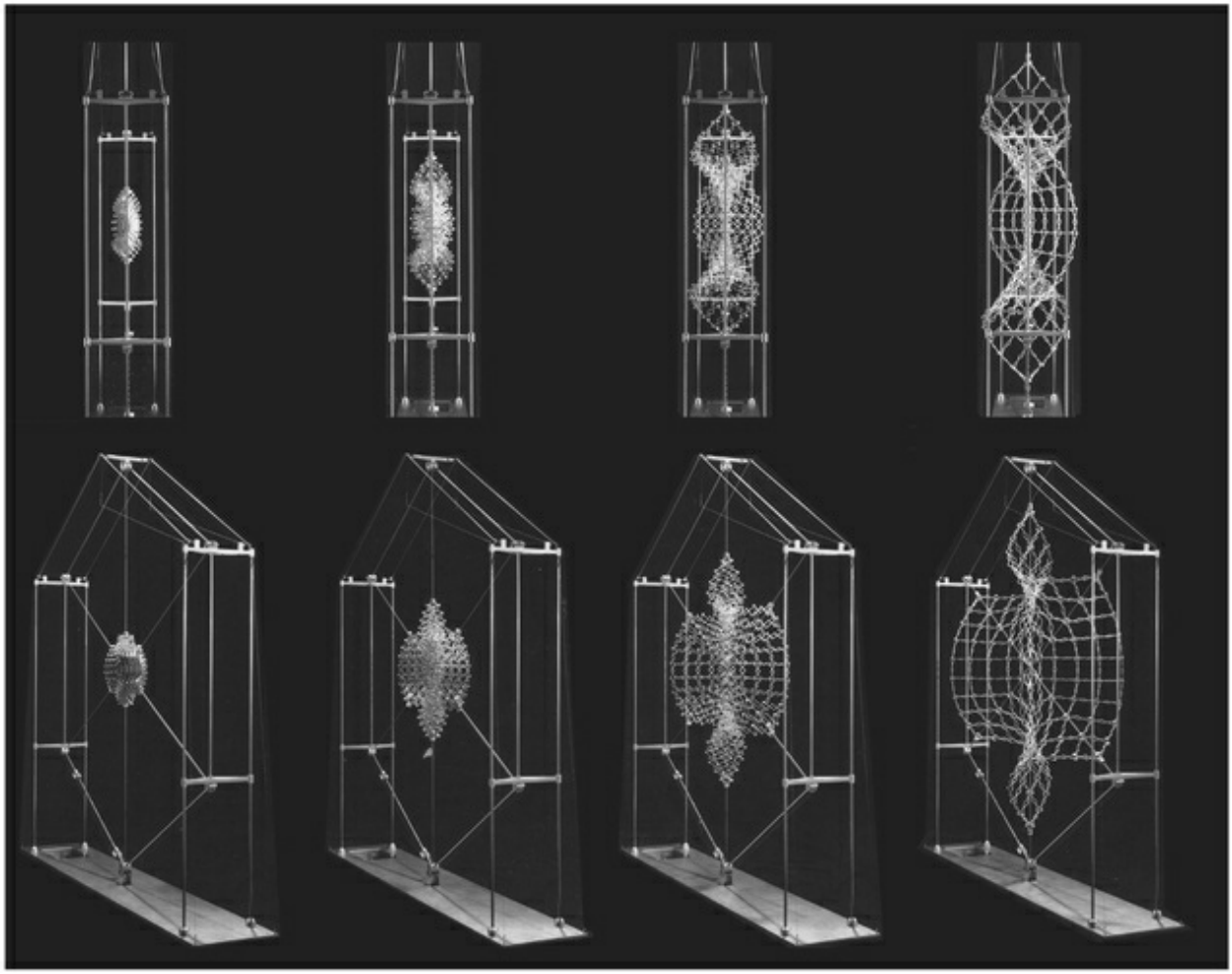
Once you have this quantity that doesn't change even as the mechanism folds

and unfolds, you can connect it to others of its type to create an expanding ring or other expanding shapes including spheres. While the angulated scissor mechanisms are moving, the overall shape remains unchanged. The shape's points move along straight-line trajectories during radial expansion from the center. For example, in the *Expanded Helicoid* (Figures 8.11a-c), the spiral shape moves along straight-line tracks, in and out. The motion is along straight lines even though the form is all made of curves.

Such a two-dimensional expanding mechanism can be parametrically defined and applied to different forms. When taken into the third dimension, the lines that define the invariant angle of the angulated scissors mechanism could be related to the normals of any three-dimensional surface; vertices can be created with intersecting normal lines and then populated with the folding and unfolding linkages (Figures 8.12a-c). Basically, the process involves moving from surface properties in their pure mathematical form and translating them into linkage properties.



8.12a–c Angulated scissors mechanism could be applied to any three-dimensional surface.



8.13a–d *Expanding Hypar* (1998).

Transforming Size: Expanding Structures

As an inventor, I usually think about inventing not a single device, but a class of devices. I am interested in mechanical typologies. I have spent decades working on expanding structures based on a scissors mechanism; such transformable structures have a long history and were done by some really great designers. What I came up with when I began to work with these expanding scissor structures was what I refer to as *shape-invariant expanding structures*, i.e. objects that get bigger but their shape doesn't change – a sphere remains a sphere and a spiral remains a spiral (see Figures 8.11a–c), etc.

Key to this shape invariance was the use of angular scissors mechanisms.

Making objects that expand but don't change their overall shape or profile has some other interesting qualities in terms of motion itself. The points on the expanding shape move radially outwards by following straight-line trajectories from the center, resulting in radial expansion. We use those straight-line trajectories to create support points and motion paths.

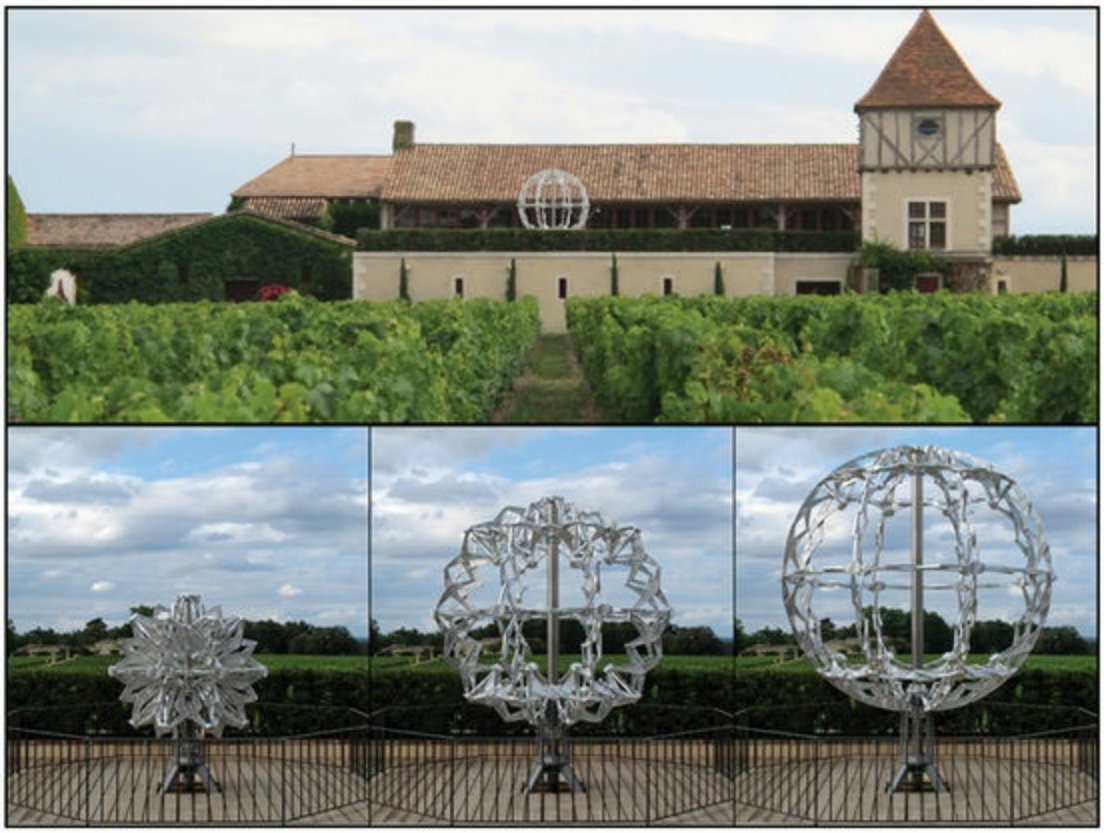
In 1998, we designed the *Expanding Hypar*[4] (Figures 8.13a–d), a permanent exhibit at the California Science Center in 1998. The *Expanding Hypar* forms an undulating plane that bisects the museum's wedge-shaped atrium. It changes with the viewer's perspective – resembling from different angles, a star, a saddle, or a bow. Regardless of the form, the profile expands and contracts continuously while maintaining its overall shape.

8.14a–c *Expanding Helicoid* (1998).

Another shape-invariant expanded structure we did is the *Expanding Helicoid* (Figures 8.14a–c), which was originally commissioned in 1998 by Inventure Place, the National Inventors Hall of Fame in Ohio. The helicoid's shape is a surface generated from two spiral profiles, similar to the double helix structure of DNA. In 2006, another *Expanding Helicoid*,[5] a 40-ft-high

transformable structure, was installed within the spiral staircase at the center of Discovery World's permanent biotech exhibit in Milwaukee. Visitors have the remarkable sensation of being inside the sculpture: as it contracts, the structure seems to disappear into the stairwell; as it expands, it seems to grow like an evolving living organism. We have designed and installed several suspended expanding spheres over the past two decades. Clients like them because they are an effective way to dynamically activate what is otherwise a static architectural space. In the *Expanded Sphere* we built for Deutsche Telekom for a series of trade shows, we managed to join the digital and the physical, creating a potent physical-virtual combination: the sphere was "the heartbeat of the stand," rhythmically pulsing and casting shadows onto the curved walls of the trade booth.

Most of our expanded spheres are placed indoors. The first permanent outdoor installation entitled *Nouaison* (First Growth)[6] is at the notable Bordeaux vineyard Château Smith Haut Lafitte (2012, Figure 8.15a–d). Situated on the main terrace of the winery, directly overlooking the grapevines, the freestanding expanding sphere begins at a very human scale, retracted to eye-level for viewers in close proximity. As it transforms, the sphere both extends outward and rises off of its pedestal, growing to nearly 4 meters tall. Created as a site-specific artwork, the sculpture combines graceful curves with precise details and strong patterning that both conceptually reflects the Château's *terroir*, and visually reflects the lighting and coloring of its lush surroundings. Fabricated out of aircraft grade aluminum with CNC machining, each of the 224 struts and 54 hubs are given their hatch pattern through deep-set, exaggerated passes of the milling tool. A seemingly random disbursement of deeply engraved hatch patterns creates a varied surface reminiscent of Cubist sculpture or stippled Impressionist painting. As the sculpture transforms, its individual parts rotate and pick up the direct and reflected sunlight in different ways – catching and transmitting colors from first the bluebird sky, then the terracotta roof of the winery, then the deep greens and mahoganies from the surrounding countryside.



8.15a–d *Nouaison* (First Growth) at Château Smith Haut Lafitte, Bordeaux, France (2012).

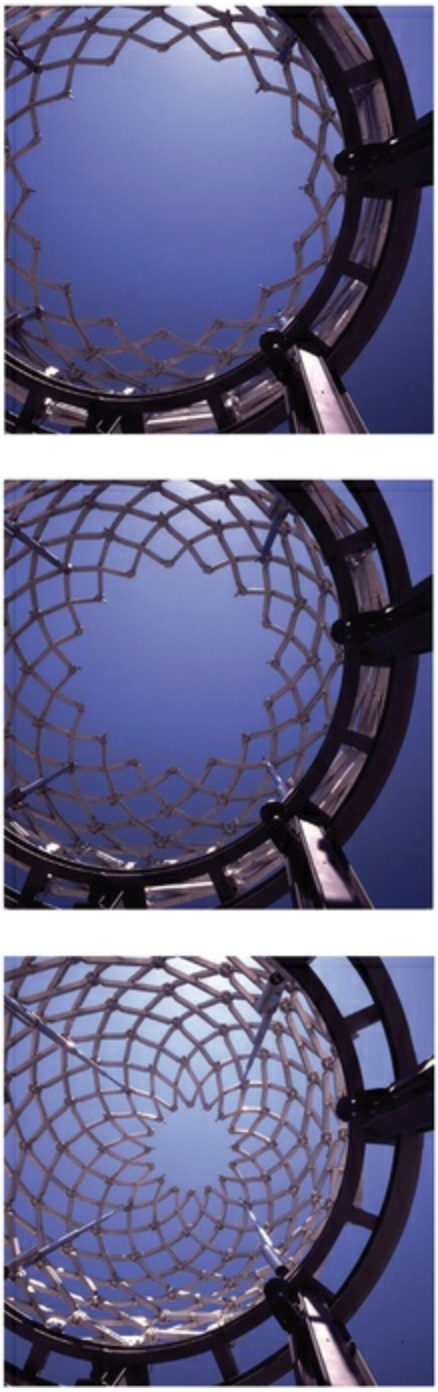
Transforming Space: IRIS Structures

Once I got into transformable objects and structures, it was a natural extension to think about how to *make space itself transform* because structures and objects within a space define our sense of it. One of the ways to do that is with what I call an iris structure, which in some ways is an inversion of an expanding object, where the focus of the expansion is on the opening – the oculus – and not on the structure itself.

In 1994, I designed the *Iris Dome* (Figure 8.16), an exhibit at MoMA in New York, as a new type of retractable roof that opens and closes like the iris of an eye, transforming the space inside between indoors and outdoors. The Dome has rigid covering panels attached to its structure; they glide smoothly over

one another to form a continuous skin covering the Dome when fully extended. The first outdoor installation of the *Iris Dome* appeared beside the German Pavilion at Expo 2000, the World's Fair held in Hanover, Germany (Figures 8.17a–c). The *Dome* celebrated the reconstruction of Dresden's legendary Frauenkirche Cathedral, which was destroyed during World War II. The bell-shaped structure recalled the dome of the original cathedral. It is assembled from machined aluminum extrusions, suspended on a colonnade about 20 feet across and 35 feet high, and powered by hydraulics. The project was a reinterpretation of the classicist notions of the oculus, as a transformable opening between earth and sky.

8.16 *Iris Dome* (1994).



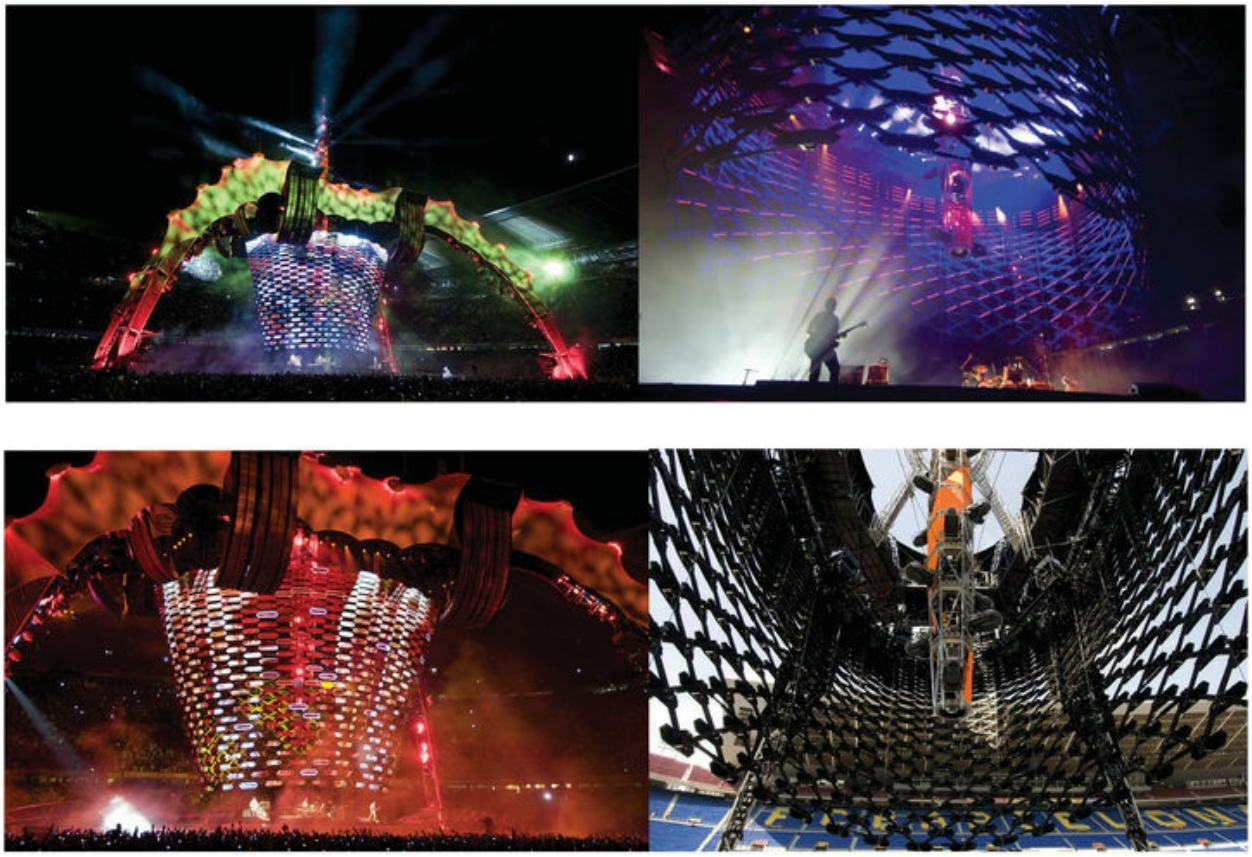
8.17a–c *Iris Dome* at the Expo 2000 in Hanover, Germany.

For the 2002 Winter Olympics in Salt Lake City we designed the *Arch,* a 35-foot tall, 72-foot-wide transforming curtain (Figures 8.18a–d), installed in front of the stage at the Olympic Medals Plaza. It provided a magical, artistically engineered performance – including music, lighting, and dancers –

to signal the start of each evening's medal ceremony. When open, it revealed the Olympic flame. The screen is both a mobile mechanism and load-resisting structure.[7] It consists of 48 panels, made of aluminum extrusions backed by polycarbonate backing called *Lumicite*, which was lit from behind during the evening ceremonies; there is a track below the stage that pulls the screen open. The *Arch* is an example of structure/mechanism synergy in that the main struts provide the operational geometric symmetry and mechanical impulse, and also have the required strength to carry panel loads.

The Olympic Arch was our introduction to the world of live entertainment. In 2009, in support of Innovative Designs and its parent company Barco, we created the *Expanding Video Screen* (Figures 8.19a–d) as the centerpiece for the U2 360° tour. While large video screens are a familiar fixture for arena-style rock concerts, U2 was looking for something unprecedented for its 360° tour – a giant screen that could change its size and shape. We collaborated with U2's creative team of Willie Williams and Mark Fisher, and Frederick Opsomer of Innovative Designs, to conceptualize this fusion of architecture, stage scenery, and extreme technology. We came up with a design for an elliptical video display, approximately the size of a tennis court that could morph into a 7-story-high cone-shaped structure, enveloping the band as it extends. The screen is constructed of stainless steel and aircraft aluminum; the display is made of 888 LED screens, with 500,000 pixels spanning across them, providing concertgoers with clear and visually stunning images. It has a screen area of 3,800 square feet, and weighs approximately 120,000 pounds. To create the *Expanding Video Screen*'s atypical design, we and our structural engineering partners, Buro Happold, had to overcome multiple technical challenges. These included designing a structure that could withstand high winds and inclement weather, last the rigors of an 18-month tour, and be able to assemble in eight hours and disassemble in six hours for transport. It is the largest and heaviest transformable structure we have designed so far.

8.18a–d Transformation of the *Arch* at the 2002 Winter Olympics in Salt Lake City.



8.19a–d *Expanding Video Screen* for the U2 360° tour (2009).

Transforming Architecture

After about a decade or so of working on transformable structure, I started to think more and more about transforming architecture, of figuring out how to make buildings transform. The idea of time-based, transformable buildings is not new. Architects have long imagined a built environment that is fundamentally dynamic. Portable buildings, retractable coverings, kinetic façades, and spaces that morph: these transformable structures have become part of the lexicon of architectural possibilities. Despite this persistent interest, examples of truly dynamic buildings are few. Accordingly, architectural

design remains focused on developing objects that are essentially static.

But why should the building itself be static? A building mediates between the occupant and the environment, both of which are highly dynamic. Media need not be limited to bandwidths of light and sound. Permeability, density, solidity are all parameters of what we might term "material media."

In my view, there are two overarching factors driving building design today: (1) the critical need for sustainable solutions; and (2) the power of computation. The convergence of these two is leading to a new generation of adaptive technologies. Real-time computation can continuously control response to an ever-changing environment. What are the systems themselves that are being responsively controlled? What are they made of? How are they organized in space? Which physical quantities are changing?

In this "information era" we tend to view physical mechanisms as being somewhat quaint and old-fashioned. Yet what I find most interesting in mechanical systems are their non-material qualities: their trajectories, degrees of freedom, transformative behavior. How can we understand transformation itself as a design parameter that can be shaped, crafted, and optimized?

In 2008, after working with Buro Happold, a global engineering firm, we launched the Adaptive Building Initiative (ABI), as a joint venture between Buro Happold and Hoberman Associates, dedicated to designing and delivering a new generation of buildings that optimize their configuration in real time by responding to environmental changes. In our view, *adaptation* is essential to managing the problem of climate change. To meet this growing challenge, ABI creates the systems and tools that achieve new levels of sustainable performance. ABI designs and produces adaptive façades and building envelopes. By controlling light levels, solar gain, and thermal performance, our adaptive systems reduce energy usage, enhance comfort, and increase the flexibility of the built environment. Additionally, we develop adaptive strategies that can be effectively applied to a wide range of other building systems.

We realized that a building façade perhaps provides more opportunities for transformability rather than the entire building that would change its volume. So, we focused on developing transformable surfaces and transformable

window mechanisms. With what we call *adaptive control*, we could change the permeability, the opacity, or just the degree of covering the skin in order to control environmental quantities. It is essentially an adaptive layer within the other layers of the façade that delivers the desired adaptive performance.

We developed a number of systems that we call *Intelligent Surfaces*. This is a suite of adaptive shading and cladding solutions that help connect an occupant to their environment in new ways. When a building physically transforms, it in turn transforms the viewer's surroundings, through spatial impact or shifting play of light from kinetic surfaces. Our systems create this visual impact while providing performance benefits suitable for any building geometry, climate, or context, and can be customized by pattern, size, and configuration for specific building designs and requirements.

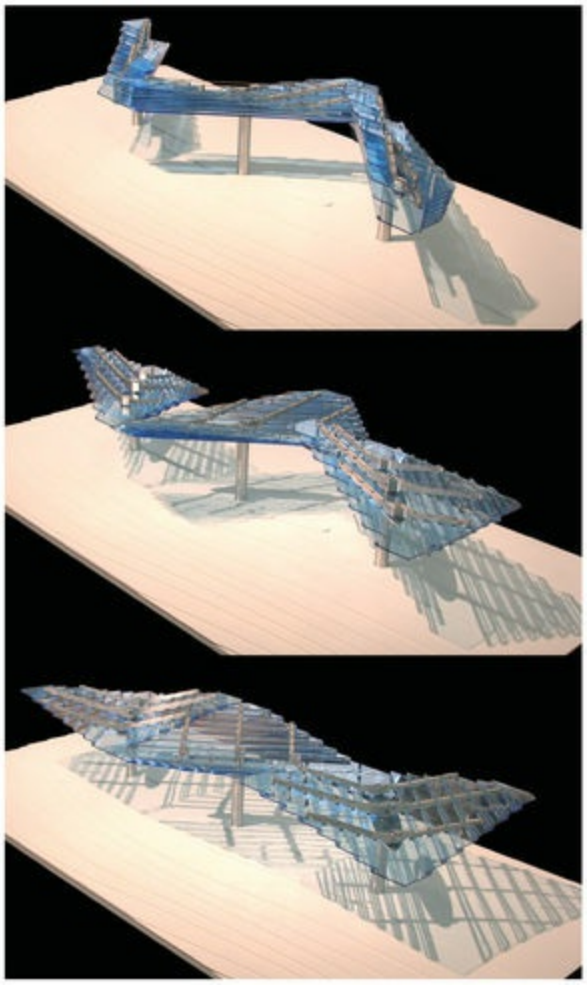
One of the first systems we developed is called *Strata™* (Figures 8.20a–c), which consists of modular units that hide within a single slender profile when retracted. When activated, they extend to form a nearly continuous surface comprised of a series of slats that may be constructed of different materials, including metal, plastic, and wood. This system is well-suited to applications for which the shading device is needed to "disappear" into a building's underlying structure. Advantages of *Strata™* include the ability to be designed into non-rectangular shapes, to match three-dimensionally curved surfaces when extended, and to visually disappear into a building's underlying structure when retracted. Additionally, it can be installed in non-vertical orientations or as a freestanding, structural awning. Adaptivity benefits are shading control, reduced solar gain and glare, and ventilation and airflow control.

8.20a–c *Strata™* consists of modular units that hide within a single slender profile when retracted.

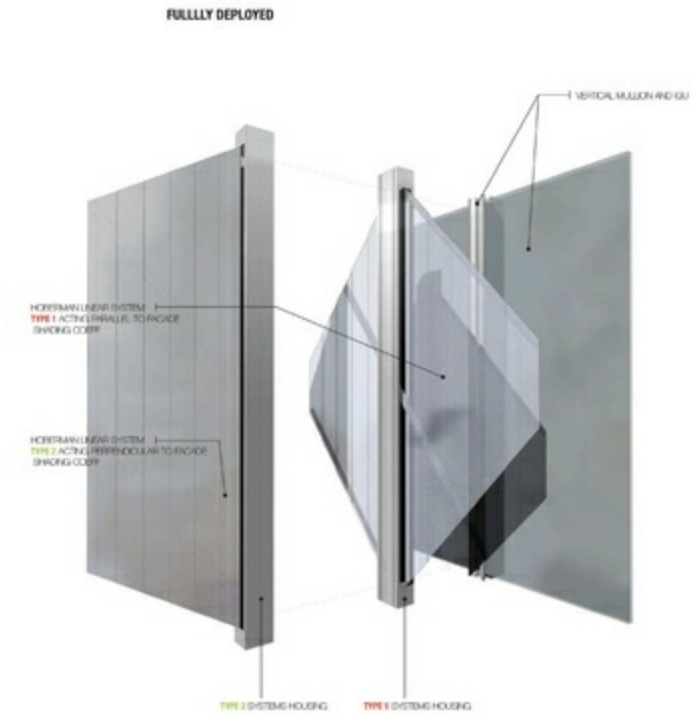
Using similar mechanisms, moving parallel linkages rendered as a roof or as a series of structural umbrellas, in 2006 we designed the *Adaptive Shading Esplanade* (Figures 8.21a–c), a freestanding, structural implementation of ABI's *Strata™* system. This series of structural umbrellas was commissioned for the exhibit "100 Years of Construction Innovation" at the Building Centre Trust in London. Three kinetic shading units were created, each having a square plan that retracts into a slender profile. The shading surfaces are treated in transparent blue glass; the structural members are constructed from aircraft aluminum. The units can be arranged in a variety of ways – as a rectilinear esplanade, for example, or a square configuration. They can be either freestanding or integrated into the building structure, creating a courtyard that can transform from indoor to outdoor use.

In response to the Center for Architecture's competition "Open Call: Innovative Curtain Wall Design," ABI teamed up in 2010 with Skidmore, Owings, and Merrill (SOM), and the Permasteelisa Group to create the *HelioTrace* façade concept (Figures 8.22a and b). The goal of this collaboration was to develop an advanced building enclosure prototype that could leverage contextual, environmental inputs to inform a responsive kinetic curtain wall

system. Architects and enclosure experts at SOM envisioned a configuration that would improve the wall's performance relative to daylighting and glare, and that would reduce solar heat gain by as much as 81 percent. The kinetic shading system was developed and integrated into the overall façade by ABI, utilizing its patented *Strata™* system. SOM's Sustainable Engineering Studio prepared ecological analyses that leveraged empirical data to inform the position and operation of the kinetic shading system. The Permasteelisa Group, a curtain wall fabricator, worked with the team to engineer the system and resolve issues of constructability and performance. The final design utilizes an adaptive kinetic solution to respond to ecology, form, and function.



8.21a–c *Adaptive Shading Esplanade* (2006) is a freestanding, structural implementation of ABI's *Strata™* system.



8.22a and b *HelioTrace* façade system (2010).

8.23a–c *Strata™* system was used in the design of the shading units in two buildings designed for the Campus of Justice in Madrid (2011) by Foster + Partners.

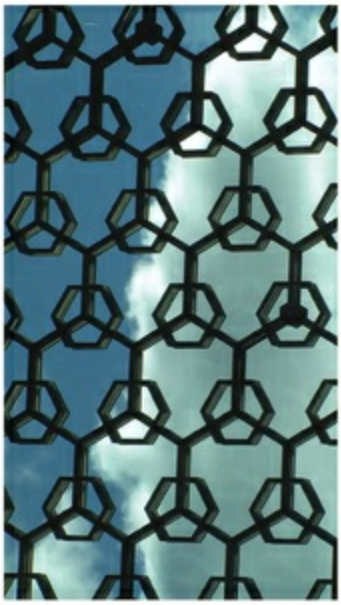
ABI's *Strata™* system was used in the design of two buildings in the new Campus of Justice in Madrid (2011). Foster + Partners designed two distinct circular buildings: Tribunal Superior de Justicia (the High Court) and Audiencia Provincial (the Appeals Court). Both buildings have been designed to minimize unwanted solar gain, while allowing natural daylight inside. As a key part of this environmental strategy, ABI's systems were used to develop a customized shading scheme. In the Audiencia Provincial, the shading units will occupy the central circular atrium as well as the eight peripheral atria. For the Tribunal Superior de Justicia, the shading units will occupy the

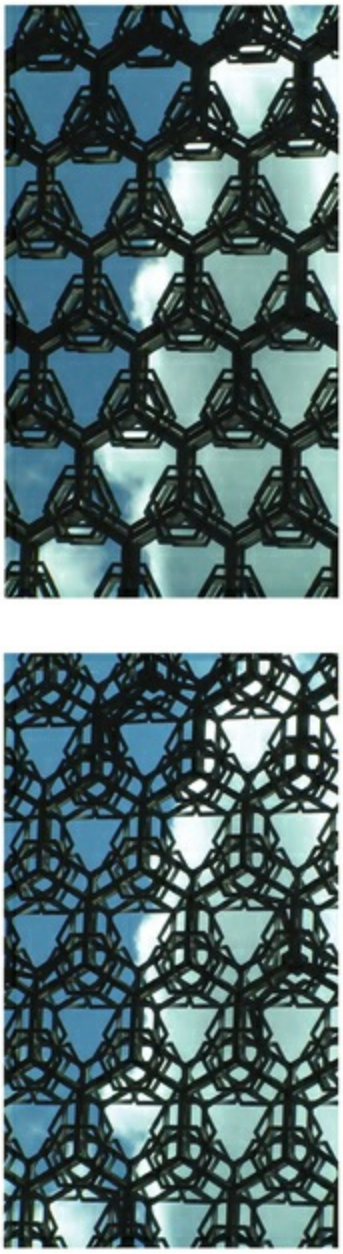
trapezoidal central atrium. When extended, the ABI's *Strata™* system will cover the triangulated roof grid (Figure 8.23a). When retracted (Figure 8.23b), their profile will "disappear" into the structural profile of the roof (Figure 8.23c). During the day, the primary function of the system will be sun shading. A custom algorithm combining historic solar gain data with real-time light-level sensing will control the shading units.

Another system that was developed by ABI is *Permea™* (Figures 8.24a–c), a unitized, self-contained system that controls its permeability, varying smoothly between a completely covered and a largely open state. It can be configured to create a seal to protect against dust and debris over large areas; and customized for non-rectangular shapes and installed in a non-vertical orientation. *Permea™* panels move parallel to the building's surface, allowing its layers to be completely hidden when retracted. Additional benefits include unitized integration with the building, and an unprecedented level of control over patterning. Adaptivity benefits are ventilation and airflow control, dust and debris protection, reduced solar gain and glare, shading control, and privacy control.

Foster + Partners' design for the Aldar Central Market in Abu Dhabi (2010) uses ABI's *Permea™* system as exterior shading roofs (Figures 8.24a–c) in three public squares within the retail complex on one of oldest sites in the city. The kinetic design is based on an operable grid. In its covered configuration, the shading roof resembles a traditional coffered Islamic roof (Figure 8.24a). When retracted, the roof becomes a slender lattice (Figure 8.24b) that complements the Foster team's designs for fixed shading (Figure 8.24c). The adaptive shading system covers an area of 1,000 sqm. and consists of eight operable units made from steel and aluminum; each unit is driven by a servo-motor with custom array control.

8.24a–c *PermeaTM* system used in the exterior shading roof for the Aldar Central Market (2010) in Abu Dhabi, UAE, designed by Foster + Partners.





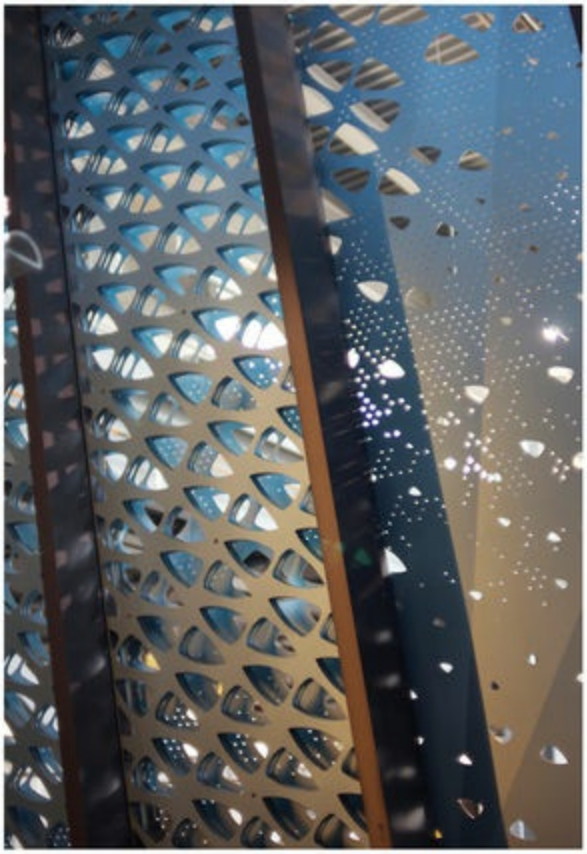
8.25a–c *Tessellate™* consists of a series of stacked panels. As these layers overlap, the result is a kaleidoscopic visual display of patterns aligning and then diverging into a fine, light-diffusing mesh.

Tessellate™ is a self-contained, framed screen whose perforated pattern can continually shift and evolve, creating a dynamic architectural element that regulates light and solar gain, ventilation and airflow, privacy, and views. *Tessellate™* consists of a series of stacked panels (Figures 8.25a–c) that can be constructed of various metals or plastics.[8] As these layers overlap, the result is

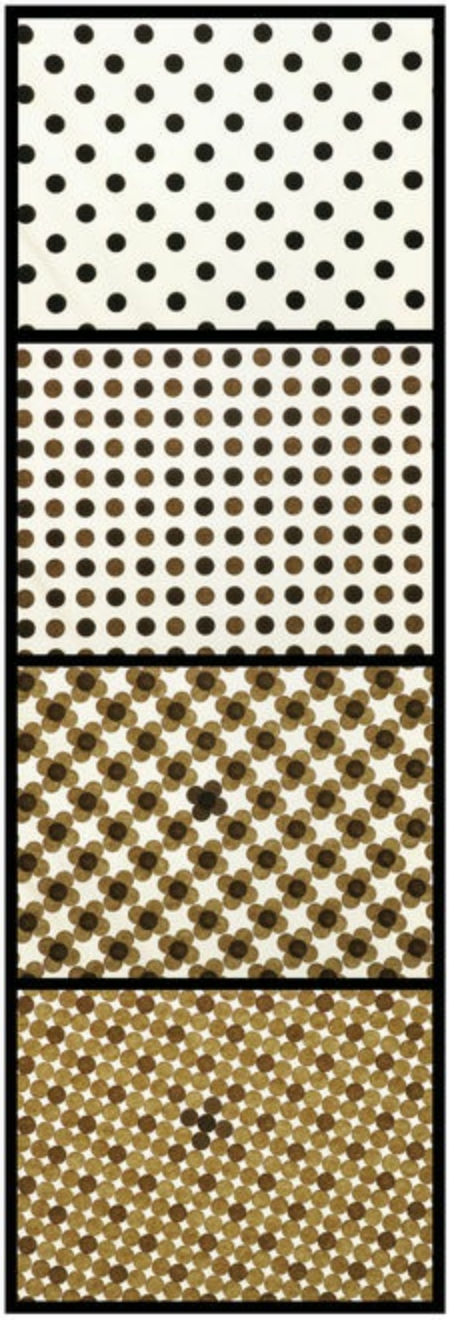
a kaleidoscopic visual display of patterns aligning and then diverging into a fine, light-diffusing mesh. ABI works closely with its clients to customize *Tessellate™* to fit their architectural vision – from geometric grids, to non-standard free-form patterns. Adaptivity benefits are fully variable shading control, reduced solar gain and glare, privacy control, and ventilation and airflow control.

An early installation of *Tessellate™* was at the Simon Center for Geometry and Physics at the State University of New York in Stony Brook (2010) where there are eight panels, 5 feet by 12 feet in size, each of which has a different perforation pattern based on hexagons, circles, squares, or triangles that align and diverge, creating different visual effects. The first-ever major building project that would feature the *Tessellate™* system is the KAFD Portal Spas in Riyad, Saudi Arabia (Figure 8.26). Planned for a 2014 construction, the architectural firm, WORKSBUREAU, has completed detailed design for twin luxury spas to become the gateway to the King Abdullah Financial District in Riyadh. Each building will be wrapped in a perforated titanium rainscreen incorporating the kinetic *Tessellate™* system to continuously adjust its opacity in response to changing environmental conditions. About 80 percent of the building skin is just static, perforated metal and about 20 percent consists of active *Tessellate™* panels. Another key member of the team, the A. Zahner Company, has fabricated and tested a full-scale working mock-up made of color-interference titanium that demonstrates the dynamic performance of this unprecedented façade (Figure 8.27).

8.26 *KAFD Portal Spas* in Riyad, Saudi Arabia (2014), designed by WORKSBUREAU, should feature the *Tessellate™* system.



8.27 A. Zahner Company has fabricated a full-scale mockup out from color-interference titanium that demonstrates the dynamic performance of the *Tessellate™* system.



8.28a–d *Adaptive Fritting™* can modulate between opaque and transparent states by shifting a series of fritted glass layers so that the graphic pattern alternately aligns and diverges.

Adaptive Fritting™ is an integrated glass unit (Figures 8.28a–d) with a custom-moveable graphic pattern that can modulate its transparency to control transmitted light, solar gain, privacy, and views. While conventional fritting relies on a fixed pattern, *Adaptive Fritting™* can control its

transparency and modulate between opaque and transparent states. This performance is achieved by shifting a series of fritted glass layers so that the graphic pattern alternately aligns and diverges. Glass fritting is an established architectural treatment for passive solar control; *Adaptive Fritting™* imbues this treatment with the expanded functionality of movement. Panels can be composed of fritted glass or plastics, at scales ranging from 0.5 to 3 meters. Patterning options are infinite: geometric grids, color variations and images, non-uniform fields or gradients, even organic and non-repeating patterns are possible. An early adopter of ABI's *Adaptive Fritting™* system is the Wyss Institute for Biologically Inspired Engineering at Harvard, which commissioned in 2010 an ABI installation in two parts, the main sliding glass doorway and an adjacent moving glass partition-wall. The Institute's door is adorned with a graduated pattern of hexagonal dots in slender floor-to-ceiling panels that continually shift in transparency.

I have been collaborating for several years with the Wyss Institute on adaptive materials. The mission of the Institute is to discover the engineering principles that nature uses to build living things, and to harness these insights to create biologically inspired materials and devices that will revolutionize healthcare and create a more sustainable world. Understanding how living systems build, recycle, and control is also guiding efforts focused on the development of entirely new approaches to construct buildings, convert energy, control manufacturing, and improve our environment. The Wyss Institute organizes itself around five so-called Enabling Technology Platforms. The Adaptive Architecture[9] and Bioinspired Robotics[10] Platforms will develop biomimetic materials and processes for the construction industry, which will enable buildings to respond and adapt to environmental cues like living organisms.

8.29a–c *Morph* (2014) changes shape from a cube into a sphere (design model).

Morphing Shapes

I am increasingly interested in the morphing of shapes, that is, turning one

shape into another. We are exploring a variety of spinning shapes and forms, so that we could turn a cylinder into a sphere, a sphere into a cube, or simply create a dynamically undulating surface.

In fact, there are many examples of physical objects that, in some sense, change their shape. The question for me is whether it is possible to develop a general method where one could specify a first shape A, that smoothly morphs into a second shape B, whereby A and B can be arbitrarily specified. Such a method would be a physical version of morphing methods widely used in digital media.

While we are still some distance from a fully general method, I have come up with a technique utilizing spinning elements that gets us closer to it. To make a transformable shape, we create an array of customized elements, each of which follows a free-form spline and rotates on its own individual axis. To effect the transformation, the elements rotate synchronously. In a first position, all of the elements align with shape A, and then, having rotated into a second position, they align with shape B. The effect is a smoothly morphing form between the specified shapes. The underlying mathematics has intriguing aspects, where each freeform spline is defined by the intersection between the two surfaces represented by the two specified shapes.

One of our first installed sculptures transforms from a cube to a sphere, made up of 32 metal parts each rotating on a separate axis. As the parts synchronously rotate, they align first with a cubic surface (Figure 8.29a) and then with a spherical one (Figure 8.29c), thereby creating the smooth transformation from cube to sphere and also producing an interesting Moire effect. The *Morph* was commissioned by Liberty Science Center for their "Beyond Rubik's Cube" exhibit, as a playful homage to Erno Rubik, inventor of the eponymous cube.

Conclusion

The projects described in this chapter are predicated on the conviction that

innovative insight arises from constant prototyping and testing. By fabricating different types of mechanisms, designers gain a hands-on understanding of various modes of physical behavior, control, and interaction. Such exploratory mechanisms became the basis for actual projects. They all share the ability to exhibit physical transformation. Their value, in my view, extends beyond the very real craft and visual interest that they display, pointing towards new classes of objects capable of self-transformation and new ways of thinking about design itself.

Experience of watching an object transform is about flow, in some sense. We see something in front of us, it changes, and in some ways that brings us into harmony with the reality that we are changing all the time as well.

Architecture is highly dimensional and even kinetic; you are meant to see it from different angles and move through it. I want to invert that relationship. Rather than depending on the viewer to synthesize all the relationships in the architecture by moving through it, I want the architecture itself to transform, and you to just sit there and see it happening.

Physical transformation is all around us in nature, constant and ubiquitous. Embedding a building with physical intelligence is the future.

Notes

1 One of our best-known museum pieces, the original *Hoberman Sphere* was installed in 1992 as the central exhibit in the Liberty Science Center's atrium. The sphere was re-installed in 2007 in the newly renovated museum's entry hall. Suspended by cables, the 700-pound aluminum sphere expands and contracts smoothly and continuously. Throughout its long history, the sphere has become the icon for Liberty Science Center, logging millions of cycles.

2 In 2010, the *Hoberman Sphere* was added to the Museum of Modern Art's permanent collection and was included in the exhibition "Action! Design Over Time."

3 NRL's global network of radar arrays study the Earth's upper atmosphere, ionosphere, and connection with space. We developed a comprehensive program for launching the satellite into space including exploring various geometries to optimize radar cross-section, developing

proprietary software for analyzing advanced kinetic structures with our partners Buro Happold, developing assembly and testing procedures to ensure successful launch, fabrication and assembly of the satellite, and designing and engineering the launch capsule that protects the sphere during launch.

4 The *Hypar* is a hyperbolic paraboloid. It belongs to a special class of shapes called minimal surfaces, which occur in nature as soap bubbles and spider webs.

5 The *Expanding Helicoid* was awarded a Silver IDEA 2008 Award for excellence in the Environments category by the Industrial Designers Society of America and *BusinessWeek*.

6 The sculpture takes its name from a French term describing the stage of growth when grapevines first develop their fruit – a critical moment in wine production.

7 The project required intense collaboration between Hoberman Associates, who conceived the *Arch*'s artistic design and mechanical technology, and Buro Happold, who devised the structural systems. For Buro Happold, the creative challenge was in developing new analytical tools to explore structures that can exist in multiple configurations. The final cumulative design was successful as it incorporated members as both operable machinery and load-carrying components.

8 Developed by ABI, *Tessellate™* is delivered in partnership with A. Zahner Co.

9 The Adaptive Architecture Platform group is led by Joanna Aizenberg.

10 Rob Wood is the leader of the Bioinspired Robotics Platform.

9

Beneficial Change: The Case for Responsiveness and Robotics in Architecture

TRISTAN D'ESTREE STERK

> At a time when most artefacts, systems and institutions are in an increasingly rapid state of change, the lack of constructive progress in basic problems of enclosure and movement is not merely depressing but also extremely dangerous. It is a cause for total concern when one of the major obstacles to the improvement through change of many activities is primarily hampered by the restriction of their enclosures.
>
> (Cedric Price)[1]

Architects must strive to understand the fundamental problems that exist within society so that they can address them and improve upon them for the benefit of all mankind. The most pressing problems faced by society today stem from the excessive stresses that we collectively impose upon the environmental systems that support us. If we cannot find new ways to increase our understanding of these systems, the chances of our living productive and healthy lives will decrease. I believe that the future of architecture rests in using new building technologies to solve some of these problems. Responsive technologies enable architects to address these problems by producing increasingly lightweight, low-energy structures and buildings.

I believe that architects must systematize their practice to align every process and outcome with new construction and design technologies driven by performance-based automation. Two types of automated systems must be brought together to enable this: automated performance-driven design systems and automated, deployable, performance-driven control systems. I question the current emphasis that architectural technologists place on the

mass customization of ordinary components, and instead will show how building performance can be mass-customized via increased automation.

I started the Office for Robotic Architectural Media & The Bureau for Responsive Architecture (ORAMBRA) as a small technology office that develops new construction systems and components for buildings. We are focused on rethinking construction alongside the emergence of responsive technologies; the office is recognized for developing structural shape change technologies that alter the way that buildings use energy. Some of our projects are described later in this chapter.

Buildings as Dynamic Feedback Systems

Although the development of responsive architecture was first driven by shortfalls within practice, its successes were informed by three forward-thinking ideas: (1) that architects design systems, not just buildings;[2] (2) that feedback could be used as an architectural form generator; and (3) that the profession of architecture must respond to the changes that surrounded its practice.[3] Supported by relatively recent developments within the fields of cybernetics and general system theory, architects were encouraged to think of buildings as dynamic user systems or feedback systems rather than as static objects. This shift enabled architects to rethink the existing modern ideals of form and function within the terms of behavior and fitness for purpose. By employing feedback as a new type of form generator, architects began to conceptualize a new architecture that could tie user needs, wants, and actions directly to architectural form. The realization that the profession of architecture had undergone serious quantitative change added further weight to this shift. Working from observations about the way architects designed, Yona Friedman proposed the model of *participatory architecture*. He introduced the model in the belief that modern architects faced many new types of design problems that were caused by increasing client numbers as well as a significant increase in the degree of impact that single design

decisions had. From here it was a relatively short step for people such as Nicholas Negroponte to recognize that the profession of architecture needed to change and that the systems and cybernetic approach to design offered a tangible model upon which such change could be based.

As someone interested in designing responsive buildings, I would like to frame this discussion differently to support a more detailed understanding of the systems that are required to actually construct a responsive architecture. Even though the participatory and feedback models of architecture are conceptually very similar, one must understand that, at the technological level, both models are actually fundamentally different. They are different because the model of feedback supports arguments of automation while the participatory model proposed by Friedman supports arguments for direct manipulation. Though both models are very useful, I propose a third model that unites each interaction methodology within a single, hybridized, model.

Hybridized models of control are not without their own precedents. Hybridized control techniques are often used within the field of robotics to produce intelligent machines.[4] These types of models support the use of higher-level reasoning and lower-level responsive processes, often scaffolding each together to produce flexible and robust control systems. Though commonly used in robotics, the hybridized model also provides us with insight into the development of new human– computer interaction methodologies that unite direct manipulation and automation within a single interactive process. I have explored the relationship between direct manipulation[5] and automated interaction methodologies and have discussed how each methodology may be woven together to produce useful hybridized control mechanisms for responsive buildings.

Early Models for User-Centered Interaction in Architecture

Architects have long understood that it is possible to change the way that

users interact with the spaces and objects that surround them by integrating logical devices within an environment. Only recently have the devices required been cheap, powerful, and small enough to be economically used within buildings. So, after four decades since it began, responsive architecture has finally become a sensible topic for designers and architects to explore. Two key models were used by architects to design early responsive systems: *adaptive-conditional* architecture was developed by Charles Eastman in 1972 and *participatory* architecture by Yona Friedman.

Eastman's model built upon a lineage of ideas for automation that were first explored in the 1950s by the cyberneticist Norbert Wiener. Wiener's works were well accepted in architectural circles in the 1960s and the 1970s, as well as by computer scientists like Warren Broody who were interested in developing responsive systems, structures, and objects. When applied to buildings, the cybernetic model enabled architects to begin thinking of spaces and users as complete feedback systems. In these systems two-way relationships between users and spaces existed such that a user's influence upon a space did not occur without the user being simultaneously influenced by the space. At that time, applying these types of ideas in designs that could adapt and change was all the rage. For example, in a September 1969 article in *Architectural Design*,[6] Andrew Rabeneck wrote that the basic aim of design is to avoid uncertainty through prediction. He reasoned that in order to design a building that had a longer useful lifespan, architects needed to make predictions about the future needs of a building occupant. He hypothesized that any technological aid that could be used to assist in this process would be very useful to architects. From this position Rabeneck quickly carved a very elegant argument for the application of cybernetic technologies within an automated architecture, noting that both the fields of architecture and cybernetics seek to produce predictive mechanisms that solve real-world problems. Charles Eastman described a slightly different version of this model in 1972, supplementing it with case studies of automation that were already in use.[7] With examples in hand he, like Rabeneck, made the bold proposal that feedback could be used to control an architecture that self-adjusts to fit the needs of users.

Eastman described the application of automated systems and used them to improve the fit between the needs of a building user and the spaces they occupy. He argued that automated systems could control building responses just as thermostats control the temperature of a room. Using this analogy, he described an automated responsive system that consisted of the following components: (1) a series of sensors that would be distributed throughout an environment to monitor its change; (2) a control mechanism or algorithm that would run in conjunction with the sensors, reading their output and comparing it to a predefined instruction; (3) actuators, i.e. devices that do the work to change the environment (by their nature, actuators must be distributed throughout an environment); and (4) a setting for users to enter their preferences. In the thermostat model this device is typically integral to the control mechanism, however, this relationship has been completely overturned in recent years.[8]

Friedman's model of *participatory architecture*[9] introduces direct manipulation methodologies to design. In this model, intelligent systems give users a means of directly controlling the outcomes of design processes without the use of automation. The model depends upon the design process being split in two interconnected halves, those being a hardware and a software system. By networking a hardware system to a software system, Friedman provided a model of architecture that gave users an interface for controlling buildings responsively. He believed this type of system would provide users with a means of adjusting spaces to meet their changing needs. He also believed that these systems would enable buildings to change over the long term on a tenant-by-tenant basis, as well as over the short term on a need-by-need basis. The software components of his system were divided into a repertory or list of spatial configurations that users could select in order to modify a space and a warning system designed to provide feedback to users about the impact that selections from the repertory would have upon the space or building structure. Friedman's building hardware system consisted of a physical building structure, an envelope, and an internal partitioning system. He proposed that these hardware components be as mobile and flexible as possible so that the software selections made by users could be reproduced within the building

itself. The network that Friedman formed between the hardware and software systems was composed of two interconnected feedback loops that converge upon the user. It is worth noting that, unlike Eastman's model of an automated architecture, Friedman's model requires a relatively sophisticated computer interface for users to make their selections. It is also worth noting the communicative nature of Friedman's model and its dependence upon symbolic, mixed initiative, interactions.

Both Eastman's and Friedman's models for interacting with responsive buildings suggest that new relationships between people and space will form when responsive systems are integrated within buildings. Each model enables people to manipulate the environments that they live in through a series of responsive actions. Cybernetic theory describes how these actions work through the principle of dynamic stability.

Hybridized Control

It is clear that both Eastman's and Friedman's models provide different approaches to solving the same problem and that each model has its strengths and weaknesses. Eastman's model for automation provides an example of a machine-led, systems approach to control that is suitable for producing simple logical responses, while Friedman's model for participation provides an example of user-led control. Eastman's model relies upon many hundreds or thousands of low-level distributed devices running in parallel, while Friedman's model relies upon centralized high-level devices that are highly communicative and capable of performing symbol manipulation activities. Eastman's model, with such a weighty dependence upon distributed computing, demands a new type of coordinating control architecture, while Friedman's model, as a communicative system, depends upon mixed initiative interaction methodologies.

Today methodologies from human–computer interaction, artificial intelligence, and robotics provide models that can unite these approaches into

a single model. These methodologies realize that each form of interaction, direct manipulation (deliberative control), and automation (reflexive control) have a useful purpose. Hybridized models combine each to produce a model that is both self-regulatory and participatory.

The hybridized model of control is useful to responsive architecture because it enables both lower-level processes, such as those employed within simple (automated) feedback systems, to be incorporated with higher-level (deliberative) intelligent processes.[10] More importantly the hybridized model can also be used to produce responses that have adjustable response criteria, achieving this by using occupant interactions to build contextual models of the ways in which users occupy and manipulate space.

The hybridized model of control has three major parts: (1) user input, which provides users with the means of controlling or manipulating responses as well as a model of the user and their interactions within an environment; (2) a building structure that has a responsive capability which enables it to respond directly to environmental loads;[11] and (3) spatial responses that are used to control the partitioning and servicing of internal spaces.

The base upon which higher-level systems and occupant interactions are situated is a simple feedback system. One should note that, as within Eastman's model, a typical building would require several hundred lower-level systems to work in parallel and simultaneously. These low-level systems were tied to the environment by sensors calibrated by simple analog devices such as banks of tuning resistors as well as controlled actuators that were designed to do physical work. Both the sensor and the actuator must be positioned within a common environment for the system to work as a self-regulating and dynamically stable feedback device. Upon this lower-level system, two higher-level forms of interaction are now discussed, these are: user interactions, and user models.

When considering the precise relationship between a user and a lower-level system one may conceive of users' interactions as being corrective. For example, a user will typically correct or adjust the behavior of a lower-level system (such as a thermostat) to meet perceived changes within comfort at a

particular time and within a particular context. Corrective actions are instances of direct manipulation that help simpler, automated systems perform well.

A "User-Model" provides the hybridized model of control with yet another level of responsiveness. By watching an occupant interact with a space and by collecting environmental data about a space, a contextual model that describes occupant interactions can be produced. The user model is linked into the larger control system in two ways, first, through a series of sensors that collect information about the environment, and, second, through a series of sensors that collect information about the corrective actions made by a user. By collecting these corrective actions, i.e. "adjustments," and by noting the environmental context that surrounds a corrective action, inductions about individuals and groups can be made. These inductions are important because they help the complete system produce responses that are contextually appropriate.

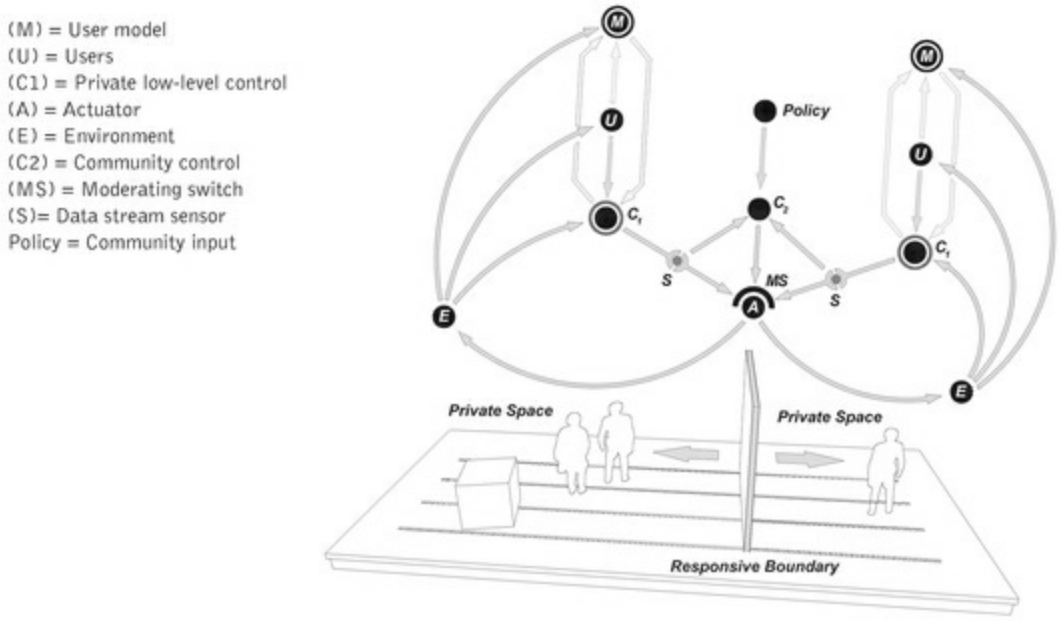
An inference engine performs operations on tables of data that are collected from different types of environment information (i.e., temperature, time, wind speeds, air pressures, internal and external light levels), user information (i.e., non-personalized space use patterns, degrees of activity, locations and time of activities), and data about corrective actions made to lower-level control devices (i.e., any adjustments made to devices such as light switches, thermostats, air conditioners or automated blinds). By collecting all of this information inferences may be made about the context in which users are likely to interact with and adjust their environment. These inferences can be used to produce contextual responses that lower-level systems are incapable of generating by themselves.

Networks of Hybridized Control

Aside from offering a mechanism that controls the responses of a single building, space, or element, the hybridized model also can be extended to

control responses across networks of buildings, or across multiple boundaries that separate spaces within a building. While the extended model of control maintains the structure of the hybridized model, it also supplements it with a second, community-driven, control process. This second tier of control is required to coordinate two unique types of responses that are produced within the network: (1) responses upon coincident boundaries; and (2) responses across adjacent spaces or building elements. In each case different relationships between spaces and the lower-level components embedded within them determine the shape of network.

Coincident boundaries consist of any physical boundary that separates two or more spaces. Responses at coincident boundaries must be coordinated to ensure that boundary responses do not negatively impinge upon any space. For example, consider a moving (shared) partition wall that separates two unique spaces. Note, the actuator or actuators located within the shared wall are accessible to two independent control processes that need to be coordinated to ensure that the most appropriate boundary is maintained. One can conceive of an independent control process that coordinates the boundary as a community process (C2). This process works by building a secondary control loop that monitors actuator use and restricting it when required. One should note that this is essentially the same process for scaffolding simple control devices to produce complex behaviors that Rodney Brookes outlined within his theory of subsumption architecture.



9.1 The networked model of control for coincident private boundaries.

Responses between adjacent spaces and elements differ significantly from the previous case (Figure 9.1) because the division of space no longer results in two control mechanisms sharing a common actuator. The significance of this change is outlined within a new principle. That for links between responsive networks to be made, some form of common element (i.e. a sensor or an actuator) must be present. For example, when two spatial boundaries are coincident, an actuator becomes the common linking element, while when adjacent spaces or elements are present, the common link becomes a sensor that monitors the shared space or element.

When responses are networked across spaces, the shared environment generates a network condition in which at least two new lower-level feedback systems provide the link between networked responsive systems. To better imagine how this system would need to operate, think of a public corridor within a building that must coordinate and maintain several boundary conditions. In this instance, the coordinating control system must ensure that individual boundary responses do not negatively impact upon a common space. To do this, a second tier control device (C2) must moderate each system with sensor data collected from the common environment. This example can

be rethought and applied to many aspects of a building, for example, instead of considering the protection of a common corridor space, one may think of applying this system to a common structural element and the impact that two responsive building envelopes might have upon that structural element. In either case these models enable responsive elements to be controlled such that the integrity of a larger system is maintained.

The precedent model of participatory architecture and the notion that feedback can be used as a form generator for architecture both held significant positions within the discipline during the late 1960s and early 1970s when architects questioned the design methods they used. Although these models did not spawn a new architectural industry for us to build upon, they have provided us with a foundation upon which understandings of responsive architecture may be built and critiques of current architectural design methodologies can be made.

Supporting Responsive Architecture with Digital Tools

Responsive architectures are those that actively change in response to new environmental conditions and patterns of use. But more than being a series of smart systems attached to a dumb building frame, responsive architectures actually consist of intelligent frames, skins, and systems.[12] These buildings change shape and color. They have intelligent systems within them and around them. They track the sun gradually and they adjust their shape to improve shading in the summer or day lighting in the winter. They shake snow from their roof. They even change shape to reduce wind loads or improve the way they ventilate.[13] But, most importantly, responsive architectures provide architects with ways to produce more sustainable buildings.

Unlike the conventional boxes that we live in, these buildings adapt to the natural environment to improve the way that people live. Addressing socio-

environmental and socio-technical issues in significant ways, responsive architectures provide a means to reducing the mass and embedded energy used within buildings without sacrificing robustness. They achieve this by enabling architects to produce a new class of building envelopes that actively adjust and shape themselves in relation to the natural environment, its seasons and weather. Less quantifiable benefits must also be noted. Responsive technologies provide architects with important and very new aesthetic opportunities. Like Modernism, this aesthetic is the product of the way systems are assembled. Reaching beyond this, responsive technologies enable new formal and performance-driven behaviors to become a part of an architect's formal vocabulary, enabling softer, more pliable, and adaptive architectures to emerge.

The systems within responsive architectures operate very differently from conventional architectures. They bring a series of new design strategies, formal tendencies, and grammars to the discipline. The impacts that ultra-lightweight and responsive systems have upon building design are substantial. Yona Friedman reminds us of the impact that such changes have upon our tools when he said that as the tasks of architecture change, so too must its methods.[14]

We are practicing at a time when static and unintelligent building technologies are being superseded by intelligent systems. As architects, we must realize that, for the first time since the rise of Modernism, shifts within the profession are being driven not by the mastery of industrial tools or machines, nor by the challenges of effective computer use, but by the very real need for us to stop harming the natural systems that support our existence. Importantly these new technologies enable architects to reconceptualize building processes and also revisit the older tacit knowledge that architects draw from. The age-old knowledge that the shape of a building is intimately linked to its performance can now be understood, realized, and advanced in very new ways. The impact that these changes will have upon architectural design will be profound. Going back to Friedman, we must realize that this change will result in revisiting the tools and design methods we use to produce buildings. What follows is five fundamental features that

should be built into digital tools aimed at supporting responsive architecture.

1. *Enabling design with variable and controllable rigidity.* The fundamental requirement on which all responsive architectures are based is that of variable and controllable rigidity. Responsive structures, be they frames or skins, alter their shape and structural characteristics most effectively by changing rigidity. Within engineering fields, rigidity is often termed stiffness, referring to the ability of an elastic body to resist deflection or deformation when forces are applied. Stiffness is a property of materials as well as structures. Structures with variable rigidity or stiffness incorporate controlled systems that either compress or induce tensile forces into a system. These forces can be localized or spread across an entire structure. In instances where structures contain many discrete compressive and tensile members, rigidity is controlled most efficiently by pulling different components together. Pushing elements apart is typically not as efficient as pulling elements together because pushing induces additional buckling forces. In other instances, namely within pneumatic structures, the inflation of sealed modules will enable both tensile and compressive forces to be realized.[15] In skins, tensile forces rule and stiffness is often achieved by actuating polymers with an electric current that cause fibers to contract.

2. *Making mathematical and control models available to designers.* Models assist designers in analyzing and testing the systems that they are responsible for. In particular, models help designers rapidly develop and refine processes that control the rigidity of responsive structures. Relevant mathematical models have been developed and they should be integrated into digital design systems. Such models include those that: (a) minimize mass; (b) determine the equilibrium states of structures; (c) locate actuators; (d) determine the energy required to change the shape of a structure; (e) calculate the frequency and location of dampening systems; (f) minimize structural fatigue; (g) calculate load transmission; and (h) calculate thermal loads. Other models that predict the structure's ability to harvest energy are also being produced.[16]

3. *Expanding the quantity and quality of environmental parameters.* A major problem with current parametric processes is the lack of support for expanded environmental models, such as those that include the necessary

spectrum of environmental stimuli to model building responses. A base set of four environmental stimuli is required: (a) light; (b) humidity; (c) temperature; and (d) air pressure. These stimuli support connections between response mechanisms and the environmental factors that surround responsive buildings. They are the minimal needed to produce contextual information about sun location, wind direction, wind speed, precipitation, and temperature. When building responsive structures, designers must place arrays of sensors across the skin of buildings. These arrays enable control systems to build a rough model of an environment that can generate building responses. Digital systems must be able to simulate these processes before they will prove useful tools for the design of responsive buildings.

4. *Enabling designers to construct and test responsive behaviors.* The three previous elements scaffold together to form a rich platform to produce responsive architectures, however, they do not, by themselves, help designers construct and test responsive behaviors. A framework that binds these three design processes into a single, manageable process is required. Two sub-processes are needed. The first sub-process ties structural models to mathematical models used for structural control. This process gives designers a means to hook ideas about control to ideas about structure. Put differently, this frame supports the integration of software (control) onto hardware (the modular building structure). One should note that this process melds the first and second of the five features together. We call this the process of control distribution because it links structural modules to packages of control. The control packages that are distributed within responsive buildings also need to be designed and it is the second sub-process that supports this activity. The challenge of designing these control systems is primarily a challenge of integrating different types of control into a manageable package or module.

Two control processes must be supported within the integration step: these are structural and environmental control sets. I suggest using subsumptive methods similar to those developed by Rodney Brooks for use within robotics.[17] Subsumption works as a method of integration because it enables the foundation of a control model to be governed by continuous structural processes while environmental control processes are overlaid as layers of

intermittent behaviors. This overlay has the effect of hooking the third of our five elements into the first two. By stitching these two sub-processes together we can glimpse a tool that gives architects the ability to design behaviors and distribute them across a building in the simplest possible way.

5. *Tying artifacts to real-world outcomes.* The final step in producing a digital tool that can assist in the development of responsive architectures is to provide a means to collect and embed real-world data into the system so that more accurate design decisions can be made. Only a small conceptual step exists between monitoring the performance of a responsive building that has been constructed and occupied and embedding relevant data collected from that product into a model but the ramifications of this final step are potentially very large.

Architectural practices that follow this method of design will be responsible for collecting environmental and energy consumption data for buildings that they design and maintaining confidential databases of this information. While the data held will be rich and helpful in monitoring buildings, it can also be used as a reflective design tool that improves practice. New architectural analysis and building industries may be born and extend the way in which architects practice and evaluate design outcomes.

Robotic Systems as Dynamic Material Assemblies

Responsive architectures are those that employ sensing, control, and actuation to effect persistent adaptation in buildings. The buildings that result operate as though they are giant robots, programmed by users to respond and adapt to their activities as well as changing environmental conditions. They are buildings that support dynamic relationships, which can morph their shape, color, permeability, and internal workings – mechanical, electrical, and spatial.

Architecture has generally accepted the freezing of the form of a building at

the point of its construction. This acceptance is not shaped by a theoretical ambition but, rather, the practical difficulties of producing more dynamic building methodologies. As a form of material system, robotic media will enable buildings to alter form through time to produce controllable and dynamic architectures. With the richness of parametric systems already informing a good portion of design, robotics will empower those architects who wish to elaborate upon the digital aesthetic but to do so directly in materials that are dynamic, unfrozen, and free of former restrictions.

Responsive architectures are behavioral. They have the power to evoke deliberate change in building fabrics and thus provide architects with opportunities to tie the formal configurations and qualities of a building to social and environmental events. Billowing walls or envelopes can be programmed to reflect a change in season, the passage of the sun or the energy consumption, work, and location of building users. This is the freedom of a responsive architecture that is supported by robotic technologies. But for these responses to be purposeful and meaningful, they cannot be random. Just as with parametric methodologies, where formal relationships are deliberately, purposefully, and explicitly struck between elements, so too sensing, control, and actuation technologies must be purposefully crafted.

The brightness of light, its direction and polarity, humidity, temperature, wind direction, pressure and speed, the location of people, their movements, gestures and voices, the location of inanimate objects and their loads all become potential drivers for this type of architecture. Determined at the discretion of the occupant–architect, each has the opportunity to become an element of a larger functional or aesthetic behavioral choreography. Buildings might re-shape to form spaces that support the desire of users to reduce artificial heating while staying warm in the winter, or alternatively the shape of a space might be formed in a particular way just because a user appreciated that particular spatial quality. And as a pure, or perhaps less than pure form, the configurations programmed by users might drift slowly through time, or if demanded, speed up to provide a new type of balance – a balance that extends the thinking of parametric design directly into the world, its events and ever changing quality. This architecture will constantly vary and be open to

persistent re-design.

The projects that follow each employ responsive and robotic technologies to explore strategies for deploying, interfacing, softening, sheltering, and assembling new forms of architectural systems that are capable of responding to the environments that surround them. More importantly, each project provides a vision for how we might open architectural processes to an increasing array of external influences while not losing – but actually enhancing – the heart and poetry of our core practice.

Shape Change in Responsive Architectural Structures

Shape control within architectural structures is a natural extension to the practice of engineering and architectural design. The knowledge needed for this builds upon the long existing knowledge that building performance and function are intimately connected to the shape of built spaces. The relatively new idea that embedded computational systems may be employed to control devices in useful and beautiful ways provides the method by which this age-old knowledge can be applied to achieve dramatically new and fitting architectures. When combined, each type of knowledge can be used to further architecture and engineering at both the theoretical and methodological levels. Structural shape control is of major interest within architecture because it is the primary ingredient needed to produce building envelopes that change shape. Structural shape control also currently represents a major technological and methodological stumbling block for architects, posing many challenges that have theoretical and practical origins. Theoretically, responsive architectural structures demand a re-evaluation of existing notions of space-making. Practically these systems demand a reevaluation of construction and design methodologies across both engineering and architectural practice. Engineering precedents for the use of adaptive structural systems are varied and include now commonly known systems such as mass dampeners,

piezoelectric structures, actuated tensegrity systems, and deployable structural systems. References for the use of actuated tensegrity systems can be found in aeronautical, marine, space, and civil applications. Other adaptive structures also exist with Chuck Hoberman's *Expanding Spheres* providing one example.[18] These precedents form an important part of the practical knowledge currently available for the development of shape control within architecture.

Architects have always known that the shape of a building is directly related to the way it performs. The way it heats and cools, the way it ventilates, as well as the way loads are transferred are all intimately related to the shape of an envelope and the spaces it encloses. It is clear that shape control within architectural structures possesses enormous potential for producing new classes of buildings that adjust to support user actions while expending the minimum in resources. For example, if a space needs to be heated through a winter night, the height of a ceiling should be reduced to minimize the energy required to maintain a comfortable temperature within the space, while on a sunny winter morning, raising the ceiling and letting it track the movements of the sun should occur to assist direct sunlight in penetrating and warming a space. If spaces need to be ventilated, the same building envelope should change shape to produce high and low pressure zones around the building. These pressure zones can be used to encourage higher ventilation rates though openings, or alternatively if the wind is too strong, the building might reduce its aerodynamic profile to minimize harmful live loads caused by the same wind. It is here where the relationship between user comfort, building envelope, and the natural environment become most obvious. Building envelopes clearly mediate between our needs and the natural environment. Responsive building envelopes have an advantage over traditional building envelopes in that they may actively use several aspects of the natural environment to condition spaces. Responsive building envelopes also transmit loads in ways that traditional buildings cannot. They can help minimize unhelpful or dangerous loads and they can enable spaces to cooperate with air conditioning or other systems that support occupant needs.

Though similar, the methodologies that architects need to produce these

types of buildings are not the same as those used by engineers. Architects require cladding methodologies as well as response methodologies that can adapt to subjective spatial desires as well as to rigid structural criteria. Subjective desires include aesthetic, psychological, and environmental factors such as comfortable ranges of temperature, lighting, and acoustic performance. To construct systems that respond to these desires, control mechanisms that are capable of building partial user models are required.[19] These are contextual models that capture three types of input: (1) environmental data; (2) users' activity data; and (3) data about when users correct the system. Many outstanding challenges exist; to date, methods for constraining subjective shape changes so that safe structural limits are not exceeded have yet to be developed.

The essential characteristics of structural systems used within responsive building envelopes and exoskeleton frameworks are: (1) they must have controllable rigidity; (2) they must be lightweight; and (3) they must be capable of undergoing asymmetrical deformations. These characteristics work together to provide the most robust and flexible outcomes. They form a core set of principles that can be applied in the development of all successful responsive architectures. The following paragraphs explain these principles and methods for achieving each within built structures. Because actuated tensegrity structures are ideal at meeting all of these needs, special attention will be given to their use.

The principle of controlling rigidity within responsive structures is clearly described by Brian Culshaw, who suggests that the key feature to any responsive structure is its ability to alter its stiffness rather than strength.[20] "In most cases the adjustable strength aspects of the structure will involve more material, more weight, and certainly more complexity than the more simple structure designed to operate under the full range of loading condition."[21] By controlling rigidity, load transmissions may be directed very naturally by localizing actuation to particular structural regions that require stiffening or softening. Softening results in the reduction of load transmission, while maintaining rigidity helps it. Likewise by controlling how soft particular parts of the structure are, different shapes will emerge. Within these types of

systems very elegant dialogs between shape, load transmission, and rigidity result.

Actuated tensegrity systems are ideally suited to produce these types of dialogs and do so very naturally when actuators are placed within key structural locations. Actuator placement has two important characteristics. First, actuators must be placed in areas to preserve the purity of a tensegrity structure. Second, they must be placed to ensure that the control systems needed to drive them are distributed in sensible, easy-to-understand, and efficient ways. The ideal location for actuation also varies depending upon the class of tensegrity structure being used.

Lightweight structural solutions are also significant in the development of building envelopes that have the ability to change shape. The overwhelming trend within the engineering of structures has been the increase in our ability to produce lighter and lighter, robust structures. By using fewer materials to transmit loads and by controlling deflection in new ways engineers have managed to completely change construction methodologies. The development of actuated structures has added to this trend. For architecture, lightweight structures are important because they play a crucial role in changing the types of spaces that architects can design. They enable larger spans, more open interiors, and more transparent envelopes. For shape change, lightweight structures are also significant because they enable greater degrees of motion at smaller actuation costs. Tensegrity structures use the minimum amount of mass to transmit loads because they separate tension from compression within distinct members. This enables all tensile forces to be identified and designed as mass efficient cable systems.

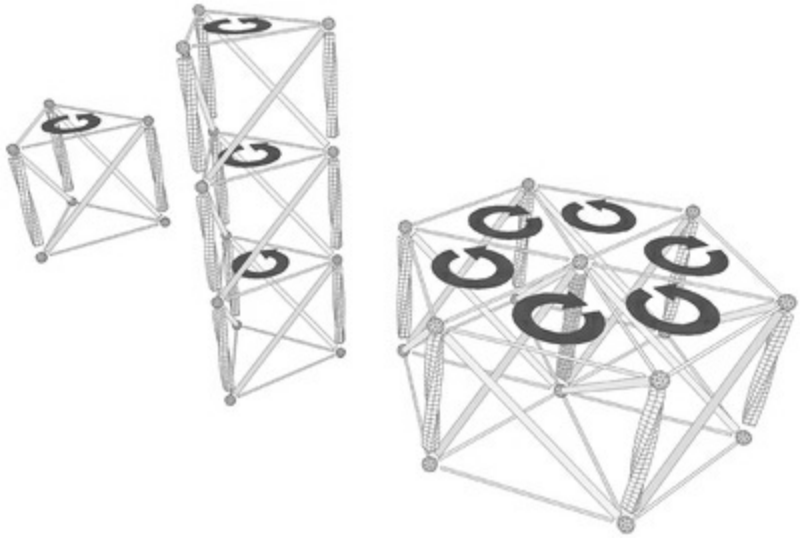
Perhaps the most interesting of the three essential characteristics are those to do with an ability to change shape asymmetrically. Asymmetrical changes are important within architecture for two fundamental reasons. First, because building envelopes are, by the nature of how they sit within an environment, never exposed to the same environmental conditions from one face to the other. Two clear examples of this can be given: those of lighting and ventilation. Light strikes buildings directionally. In natural and built

environments it comes from the direct sun or reflections from adjacent surfaces. As such, lighting conditions are never the same on different sides of a building. Likewise, air pressures also vary across the different sides of a building from windward to protected faces. From these two simple examples it is clear that any building aiming to take advantage of shape to condition its internal spaces must be capable of responding asymmetrically. This point is further compounded. Consider, for example, the potential for adjusting building forms to enable the tracking of sun movements or the dodging of wind. The second reason why building envelope systems and their structures need to enable asymmetrical shape control is to cater to dynamic changes in the way loads are transmitted through a building. Remembering that shape control is closely related to structural rigidity, it becomes obvious that in order to produce efficient structures that monitor their health and respond to external, unpredictable, loading conditions, asymmetrical shape control helps to improve the range of possible responses that structures can make. To put this simply, asymmetry enables loads to be transmitted along several dissimilar paths whereas symmetrical responses do not.

Actuated tensegrity structures form a unique class of structure because they may adopt symmetrical and asymmetrical forms by varying actuator activity. These structures are able to move asymmetrically because their joints are isolated and move in geometrically independent ways. This isolation provides a natural means for limiting the impact that any one actuator will have within the structure, greatly reducing any unwanted propagation of movement. Apart from offering variable rigidity, a light weight, and asymmetry in shape, actuated tensegrity structures are extremely useful in architecture because they can be configured in two fundamentally different ways to produce tube or surface structures. These two configurations are important because they provide the necessary diversity required for applications in large-scale as well as small-scale buildings.

The simplest tensegrity units can be networked together to form more sophisticated structures that are classified according to a method first proposed by Robert E. Skelton and Darrell Williamson in 2001.[22] Williamson and Skelton refer to classes of tensegrity structures as special spatial trusses

that are composed of a stable connection of axially-loaded members. Their definition for classes is described as thus “a class ‘k’ tensegrity structure is one in which at most ‘k’ compressive members are connected to any node.” Class one structures form the simplest tensegrity unit (Figure 9.2a). This class of tensegrity structure is the fundamental building block of most tensegrity systems. They consist of a ring of struts, each of which connects to a cable assembly. It is worth noting that a conventional tensegrity system can be converted into an actuated tensegrity system when any cable within the assembly is replaced by a tensile actuator. Class two tensegrity structures (Figure 9.2b) emerge when two class one units are stacked on top of each other to produce coincident joints between struts. Sandwiched between these joints cables and actuators are stretched to produce actuated tube structures that are capable of changing shape. The degree and nature of shape change will vary depending upon the number of actuators, their location, and the forces they can apply. Similarly to class two structures, class three structures (Figure 9.2c) emerge when several class one elements are connected to each other through horizontal packing processes. Class three structures are defined as tensegrity structures in which three struts meet at a single joint. Skelton refers to class three structures as plates. Once again, as tensile members within these structures are replaced by tensile actuators, the resulting assembly will have the ability to change shape as its rigidity is varied.



9.2a–c From left to right, class one, class two, and class three actuated tensegrity structures. The actuators have been placed vertically and are shown as elastic members. The orientation of each class one unit is shown because in order to build the class three system every other unit must orientate in an opposite direction.

In the field of responsive architecture the way in which buildings change is critical. So while understanding the types of building forms that can be made efficiently with particular classes of structure is important, it is even more important to know the behavioral characteristics of each system and how behavior is tied to actuation and control.

The conceptual model that we can use to describe behaviors within actuated tensegrity structures is built around actuation scope and the impact that changes in scope have upon structural rigidity. Scope is the term used to describe the extent or range of actuation from any particular point within the structure. As such, one can say that larger scopes actuate a larger region of a structure whereas smaller scopes actuate smaller regions. Larger scopes also require that larger numbers of actuators work together, while smaller scopes require fewer. Scope responses should relate to the internal and external forces that a structural system is exposed to, where internal forces are those that come from within the system itself (i.e, the dead load of building materials) and external forces are those that come from beyond the system (i.e., the live loads of wind or bodies moving within a structure). Scope is most easily understood as an actuation limit.

The scope of an actuated response caused by dead loads relates directly to the minimum rigidity required to hold a structure up without it buckling under a load. To give a simple example of how this concept works in practice, let's use our own body to envision how our legs transmit load when rigid. By letting our muscles relax in one leg we cause that leg to be less rigid and also transmit less load. Our legs, because they carry more weight when we stand upright than our torso or arms do, need to be more rigid – a point that certainly becomes apparent when we consider what happens to the rigidity of our arms, torso, and legs when we do a handstand. In this new scenario our

arms become very rigid while they support the weight of our body. At the same time our legs can soften because they transmit much less load. The optimal rigidity for any structural system that carries a dead load to the ground is directly related to the load it carries. Thus, the greater the load, the greater the rigidity required becomes. The maximum rigidity of the system is limited to being less than the maximum compressive and tensile strengths of any member within the assembly. To summarize, one can say that in this framework, actuation scope results in decreasing levels of rigidity, as loads become less. Alternatively one may say that actuated structures can get looser toward their top. This methodology of scope control produces structures that have a minimal degree of rigidity and maximum flexibility.

9.3 A full-scale actuated class three structure built by the author using cast aluminium components, pneumatic air muscles, stainless steel cable, and hardware (2004).

Scope in relation to shape control can also be discussed. In class three prototypes, shape changes that include leaning, extension, collapse, and flattening are all correlated to scope. Scope becomes a tool for enabling

different regions of a structural system to become more or less rigid and affect the shape of the structure. For example, by limiting the scope of actuation to one half of a structure, leaning can be induced, while by enabling a global scope, expansion or contraction result (Figure 9.3). Limiting factors of rigidity still apply to this system. Rigidity limits the impact by restricting the degree of freedom that a structure has to move.

Actuation scope and shape control relate directly to each other but they also are associated with the ways in which structures compensate or respond to live loads. Scope becomes useful in these scenarios because dissimilar building shapes respond differently under the same loading condition. In this paradigm of control, variable scopes are used to control building shapes that help produce minimally loaded structures when loads are composed of live as well as dead loads. It is most beneficial to think of these types of scope actuation as being complementary to those induced by internal forces. For example, one can consider how a building covered in snow might be able to use shape changes to shake the snow from its roof. Alternatively one might envisage a tower that has a wind load exerted upon it might respond by reducing its aerodynamic profile to minimize shear. Buildings might also use shape changes to subtly shift their center of gravity and better position themselves to further reduce shear. Each of these scenarios connects shape control to actuator scope. In class two systems, this can be demonstrated by increasing the rigidity of one string of actuators that run in series up a tube structure. When scope is limited to serial actuation, these structures respond by shifting their center mass through twisting actions (Figure 9.4).

9.4 *Filamentosa, a* prototype, ultra-lightweight tower for Chicago, designed by the author (2004).

The primary goal of any methodology for designing responsive architectural structures that change shape must be to meet the subjective spatial desires of users as well as the safety requirements for correct load transfer. The control methodology required to do this must meld architectural responses to structural ones by placing them within an envelope that guarantees safe maximum and minimum rigidities. The likely result of this process will be the development of a subsumptive architecture for control. Subsumptive control systems[23] are useful to the development of responsive architectures because they enable several simple behaviors to scaffold into larger processes. New design and control methodologies are needed to ensure that architects and engineers can guarantee safety and comfort within these emerging classes of building. The fundamental nature of these problems will ensure that future direction of architectural and engineering practices is driven by how each respond to these common responsibilities.

The Nascent Potential of Responsive Buildings

Responsive technologies let architecture be universal and local at the same time. Robotic technologies provide building assemblies with the means of doing their own analytical work, thus providing a very direct way for buildings to adapt to the environmental conditions of a site. As a result, responsive technologies fundamentally change the nature of design processes, eliminating a great deal of burden from the drafting table by placing it, instead, in programming the building fabric itself.

Like Friedman's programmable architecture, responsive buildings rely upon a mix of hardware and software systems to function in real time. In the prototypes produced by my office, the hardware components of buildings are completely standardized and often consist of very few types of the same, repetitive, component. Projects achieve their flexibility by allowing hardware components, and in particular the structural systems of a building envelope, to move under the power of actuators that are controlled by sensor information. Any number of responses can be produced, depending upon the sensor inputs used. For example, it is possible to control the shape of a building envelope via a geometrical analysis of either strain or distance data collected from the structure.

In principle, our approach uses sensor data to transform standardized assemblies into highly contextual ones – the structures and envelopes that utilize these techniques are able to perform their own analytical work. As a part of this, my office actively exploits the most beautiful qualities of parametric architectures by using programming as a form of architectural media that transposes new modes of customized operation onto standardized building assemblies. Of course, robotic systems form the material conduit of this programming endeavor.

So what are the tangible benefits of this approach? Do responsive buildings that change shape or color actually result in improved levels of environmental performance or a new aesthetic? They do.

Recently my office has been working on a residential project sited in Illinois. The project, called *Prairie House* (Figures 9.5a and b), is for a small residence that uses active systems to improve the performance of the house and reduce carbon emissions to 40 percent of those made by a typical home.

Although a combination of systems is used to produce these savings, the house derives most of its success via shape-changing structural systems.

Mathematical simulations[24] indicate that general returns for skins that can change color, for example, by shifting from black to white via thermo or photo-chromatic inks, typically provide a combined annual saving of 0.45 percent in the Mid-West climate zone. To maximize savings the interior membrane must become lighter on warmer days while turning darker on colder days. For a building with a naturally ventilated rain-screen, the color of an exterior rain-screen has a negligible impact on the thermal performance of a building, leaving the exterior screen to adapt more freely than its interior. Further savings are provided when combining color with permeability. When building rain-screens that can open or close, combined annual savings of 2.48 percent result. These savings are achieved when the exterior screen opens to let warming sunlight hit the dark interior on cold days while closing to shade the interior during hot days. Levels of insulation can also be controlled. By varying insulation levels seasonally, from 2" to 12", a larger combined annual saving of 8.01 percent savings is obtained in the Mid-West climate zone. The saving is provided when the thickness of insulation is reduced to shed heat in the summer, while insulation is increased in thickness during colder periods.

Though productive, each of these savings is dwarfed by those provided by structural systems that can change shape and volume. Shape-changing systems provide combined annual savings of 23.72 percent in the Mid-West climate zone. To achieve these savings buildings should expand to reduce the impact of internal heat loads on hot days, and shrink to reduce heating requirements on cold days. These results have informed our practice's focus on building structural systems that change shape while also bringing some of the oldest architectural knowledge into a new light. That the shape of a building or space is intimately tied to its performance has been known since people started to build, what has not been known is that we can use this principle to drive a fundamentally different type of architecture that can actively vary through time in a continuously evolving choreography with nature and user.

9.5a and b *Prairie House,* a small residence that uses active responsive systems to improve its performance.

Opportunity Knocks: Buildings are Giant Robots

As a young architect who has developed a practice around a robotic future, it is clear that the profession of architecture is ripe for change. We are at a point in history where deep questions about our collective future are being asked – and answered – with, or without, our input. Some architects have spoken about this future and positioned the idea of robotics on the sidelines of what has become conventional digital practice. These practitioners wrap robotics within the guise of CNC machines and, worse still, the Hollywood prop factory.[25] They see robotics as a means to legitimize custom fabrication and justify the continuance of static architectural form. They miss seeing the real opportunity of robotic systems as being integral to a changing architecture.

Buildings are giant robots that embody analytical and persistent computational processes in built assemblies that can change shape, color, configuration, and character. These buildings tie their responses to changing user actions and environmental conditions. Furthermore, they alter the nature of design, and its relationship to industry, by enabling architects to produce highly contextualized assemblies from very limited numbers of standardized parts. These new architectures achieve their highly customized or contextual configurations via their ability to respond to the world in real time.

Finally, robotic systems enable a fundamental shift to take place within architecture. This shift has its own logic, a logic that extends persistent or parametric design into the material world via behavioral systems that provide architects with the ability to develop sustained and newly poetic relationships between buildings, people, and nature. These are the opportunities of responsive and robotic systems in architecture.

Notes

1 Price, Cedric, *Cedric Price Works II* (London: Architectural Association, 1984) p. 56.

2 Pask, Gordon, "Architectural Relevance of Cybernetics," *Architectural Design*, Sept. (1969): 494–

496.

3 Friedman, Yona, *Towards a Scientific Architecture* (Cambridge, MA: MIT Press, 1975), pp. 1–4.

4 Coste-Maniè, E. and Simmons, R., "Architecture: The Backbone of Robotic Systems," in *Proceedings of the 2000 IEEE International Conference on Robotics & Automation* (San Francisco, CA: IEEE, 2000), pp. 67–72.

5 "Direct Manipulation vs Interface Agents", excerpts from the Ben Shneiderman and Pattie Maes debates at the Intelligent User Interfaces Conference, January 6–9, 1997, and at CHI 97 in Atlanta, March 22–27, 1997; reprinted by The Association for Computing Machinery.

6 Rabeneck, A., "Cybermation: A Useful Dream," *Architectural Design*, Sept. (1969): 497–500.

7 Eastman, C., "Adaptive-Conditional Architecture," in *Design Participation: Proceedings of the Design Research Society's Conference*, Manchester, Sept. 1971 (London: Academy Editions, 1972), pp. 51–57.

8 Once integral, control settings are now often removed from the control mechanisms that they interface with to control mechanisms. Today we can often provide preferential settings remotely, for example, via telephones and or TC/IP connections.

9 Friedman, Y., "Information Processes for Participatory Design," in *Design Participation: Proceedings of the Design Research Society's Conference*, Manchester, Sept. 1971 (London: Academy Editions, 1972), pp. 45–50.

10 Coste-Maniè and Simmons, op. cit.

11 Sterk, T., "Using Actuated Tensegrity Structures to Produce a Responsive Architecture," in *Proceedings of the 2003 ACADIA Conference* (Indianapolis, IN, 2003), pp. 85–93.

12 See works by this author: available at: www.oframbfra.com/earlyPrototypes/index.html.

13 See recent articles:

(1) www.wired.com/news/technology/0,71680-0.html;

(2) edition.cnn.com/2006/TECH/science/09/08/smart.buildings/;

(3) www.economist.com/science/displaystory.cfm?story_id=E1_RPTNNDD;

(4) http://newcityskyline.com/ResponsiveArchitecture.html.

14 Friedman (1972), op. cit., and Friedman (1975), op. cit.

15 Pneumatic structures can push and pull by two variations of the same pressurization processes. Pushing is easily pictured via balloon-like models: as a balloon inflates, it can exert compressive forces on neighboring pneumatic members. Pulling is less easily pictured but it can be accomplished by pressurizing a device called a pneumatic muscle. As air flows into a pneumatic muscle, the muscle contracts, causing tension forces to be exerted on neighboring members. See: www.shadowrobot.com/airmuscles/overview.shtml.

16 This work is being done by Robert Skelton, partner at The Office For Robotic Architectural Media & Bureau For Responsive Architecture. See: www.oframBFRA.com.

17 Brooks, R., "A Robust Layered Control System for Mobile Robots," *IEEE Journal of Robotics and Automation*, (1986): 14–23.

18 See Chapter 8 by Chuck Hoberman in this book.

19 Sterk, T., "Responsive Architecture: User-centered Interactions within the Hybridized Model of Control," in *On Computer Games, Advanced Geometries, and Digital Technologies: Proceedings of the Game Set and Match II Conference* (Amsterdam: Episode Publishers, 2006), pp. 494–501.

20 Culshaw, B., *Smart Structures and Materials* (Boston, MA: Artech House Inc., 1996).

21 Ibid, p. 20.

22 Williamson, D., and Skelton, R., "A General Class of Tensegrity Systems: Geometric Definition," in *Proceedings of the ASCE Conference Engineering Mechanics for the 21st Century* (La Jolla, CA, May 1998), pp. 164–169.

23 Brooks, op. cit.

24 All simulations were conducted in Ecotect Analysis 2011, using weather data for Chicago, supplied by the US Department of Energy. Further results are available from the author upon request; see: www.orambra.com.

25 Lynn, G., *Greg Lynn Form* (New York: Rizzoli, 2008), pp. 250–277.

10
Self-Assembly and Programmable Materials

SKYLAR TIBBITS

Over the past decade it has become clear that recent developments in computation have dramatically changed design by introducing capabilities for massive iteration, geometric complexity, evolutionary solvers, multi-variable optimization, and various other tools. Many solutions can be pulled out for simulation and analyzed structurally, environmentally or against various other metrics. Computation has fundamentally changed what we can design and how we design. Computational tools and methods allow designers to go far beyond what they could conceive independently. CAM tools and digital fabrication have also radically altered our processes of making. Code has now become the language of design, the language of analysis as well as the language to communicate with machines for fabrication and manufacturing. Digital tools allow for a streamlined process from idea to computational design to machine code.

Unfortunately, that remains the end of the story. Once fabrication culminates, computation is often finished, and we have become far too comfortable to delegate construction processes to puzzle-like assembly done by massive teams of students or construction crews. At the moment, when fabrication finishes, all of the information that had been embedded in the machine and the design process is thrown out, and it's left to the construction crew to discover sequences, material tolerances, and other brute-force techniques.

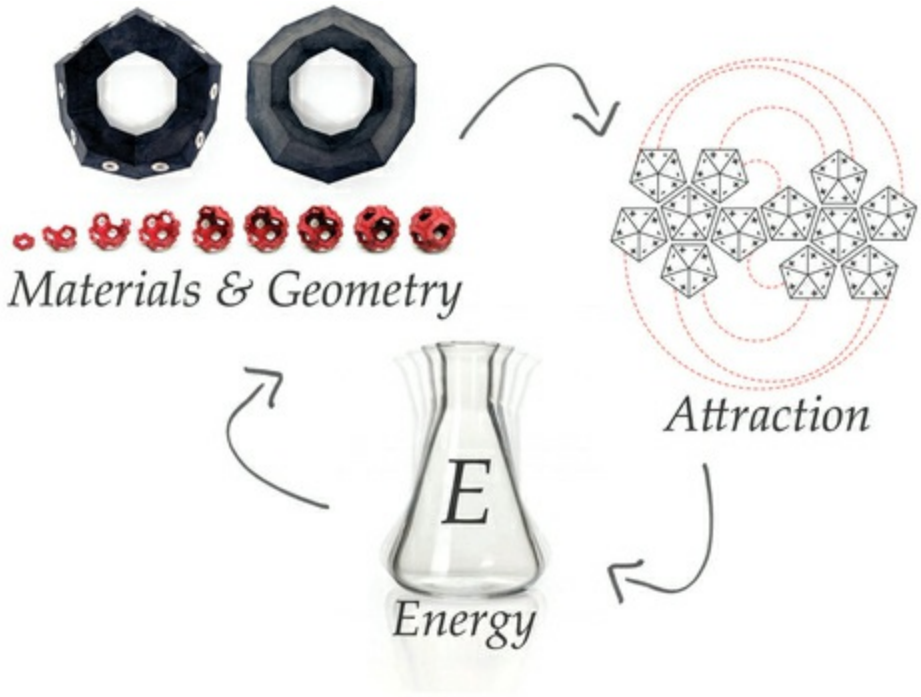
There is an extremely ripe opportunity to reimagine the types of information used in construction; how we assemble things, how we

communicate, and how we collaborate with materials. Similarly, at another scale, in nanotechnology, synthetic biology and material science, there is an unprecedented revolution happening. One can now take materials, biological or synthetic, and program them to change shape or properties, and even compute. For example, a new field called "DNA origami" demonstrates the emergence of design tools in synthetic biology.[1] The first design software, caDNAno, was introduced by Sean Douglas and George Church at the Wyss Institute in collaboration with Autodesk Inc.[2] A designer can build 2D and 3D shapes similar to any other modeling tool and then the design can be broken down into DNA base pairs, ACTG. A file of base pair sequences can then be synthesized. Test tubes of the custom DNA sequence will be delivered shortly after. The DNA is then heated and cooled in a thermo-cycler and, finally, the DNA assembles itself into the three-dimensional designs and highly functional parts. The Wyss Institute demonstrated a functional nanorobot drug delivery mechanism that self-assembled entirely out of single strands of programmed DNA.[3] The nanorobots are capsules that only open under certain conditions and then release drugs or other elements. Increasingly, scientists are designing, and then self-assembling, nano-scale structures which have the construction information embedded in the materials. There is no other construction process at this scale; there are no nano-screwdrivers, DNA-sledgehammers, or any of our human-scale tools. The information for assembly *is* the material for assembly.

These nano-scale developments are a paradigm shift in the way we think about code, construction, and assembly. We need to rethink our human-scale processes of the built environment from construction to manufacturing and infrastructure to take advantage of these new capabilities. There are emerging opportunities to rethink the ways that we collaborate with materials and the way that we assemble components. In construction and manufacturing, there are huge inefficiencies, brute-force human labor, errors, and massive energy consumption. In infrastructure, one of the major concerns in recent decades is the lack of resilience and lack of adaptation with respect to how things fluctuate; either demand fluctuates or the environment fluctuates.

The worlds of nano-scale self-assembly and the human-scale built

environment can now collide to reimagine manufacturing and construction processes. However, this fusion does not necessarily require automation, as is the current dogma for industrial manufacturing. Rather, it requires embedding information directly into materials. This process is called self-assembly and is the fundamental focus of the Self-Assembly Lab at MIT. Self-assembly is defined as a process by which disordered parts build and ordered structure through only local interaction. If this is possible, then all the information for assembly, all the information for interaction, and all the information for decision-making can be embedded in the materials themselves.



10.1 Ingredients for self-assembly and programmable materials.

The Self-Assembly Lab has identified a number of ingredients for self-assembly and programmable materials including: (1) materials and geometry; (2) interactions; and (3) energy (Figure 10.1).[4] Materials and geometry are the fundamental properties of the built environment and the key components to any physical system. But if they become highly coupled with the activation energy and a particular length-scale, they can become highly active. Either the components are autonomous parts that need to come together on their own or

they are pre-connected parts that need to go from one state to another. This physical interaction can be designed to incorporate error-correction, shape change, and other smart dynamics. After designing a system with these key ingredients, self-assembly can be utilized across scales, domains, and energy sources.

It is particularly important to be sensitive to the forces and scale of implementation. The forces and the materials that may be available at the nanoscale will likely not work at much larger scales, and vice versa. Rather, the materials and energy sources need to be highly coupled and dialed into the scale of application in order to take advantage of programmable dynamics. The Self-Assembly Lab has developed a number of projects to demonstrate these principles across length-scales, geometric configurations, and 1D, 2D, 3D, and even 4D systems.

BioMolecular Self-Assembly was one of the first projects developed at the Self-Assembly Lab that focused on pure self-assembly from a biomolecular point of view. *BioMolecular Self-Assembly* was a collaboration with molecular biologist Arthur Olson

10.2 *BioMolecular Self-Assembly* project showing a number of components that can self-assemble when shaken randomly.

10.3 500 glass flasks were produced with different biomolecular structures that can self-assemble through random agitation.

10.4 The *Chiral Self-Assembly* project demonstrating two types of units that can error-correct and self-assemble into two distinct structures when shaken randomly.

from the Scripps Research Institute and Autodesk Inc. (Figure 10.2).[5] The exhibit consisted of 500 glass flasks, each containing different molecular structures inside including: a polio virus, a tobacco plant virus, and different

enzymes (Figure 10.3). Each of the structures demonstrated a different number of components and geometric configurations. Some of them had 12 parts, 8 parts or 4 parts and that resulted in drastically different final configurations. The goal was to demonstrate that self-assembly is possible with very different component shapes and sizes. The colors of the units helped demonstrate different probabilities of assembly and the stochastic nature of the process. The final structure never assembled in exactly the same way, even though the final geometric shape appeared to be the same.

People would pick up one of the glass beakers, for example, the polio virus. They would shake it vigorously and the parts would separate, and then when shaken slightly more softly, yet randomly, the parts would come back together. This project demonstrates that random energy can produce non-random structures. It is not in the energy that was input, like a robot arm, and it is not in the user's assembly instructions that allows the parts to assembly, rather, it is the noisy, ambient energy and the smartly design components that are guided through error-correction into the final, precise, shape.

Similarly, the *Chiral Self-Assembly* project emphasizes biological chirality, or the self-sorting nature of a right-handed and left-handed structure (Figure 10.4).[6] A number of black and yellow parts can be placed inside a container, then, when shaken randomly, the separate parts will always form one completely black and one completely yellow structure. This project emphasizes the "interactions" component of the self-assembly ingredients because the geometry, the energy, and the material properties remain the same. Each of the units has a number of weak magnets, designed in a specific pattern; the yellow units having the opposite of the black unit's attraction pattern. In the demonstration of this project, when a black and a yellow unit met, which happened very frequently, they would connect upside down. However, a third unit could never assemble between those two and thus the connection would remain weak and eventually break off. When two like-colored units assembled, a third unit would connect between the two and

10.5 An irregular, yet stable, assembly that emerged (left) as compared to the expected assembly (right).

10.6 The *Autonomous Mass-Assembly* project that demonstrated many components in a continuous process of assembly and disassembly.

10.7 A number of partially formed dodecahedron structures that emerged throughout the *Autonomous Mass-Assembly* project.

make the structure increasingly stronger. In this way, error-correction can be built into the physical system and ensure that accurate and self-sorted structures emerge from random energy input.

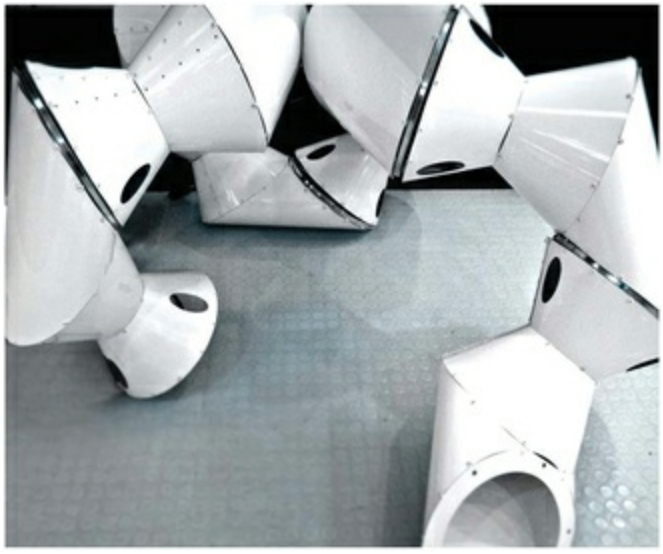
An interesting behavior emerged during this project. While shaking the flask, a unique structure appeared that resembled a ring. All of the units were incorporated into the ring and thus it was not a momentary error, rather a secondary comfortable state that the components could form (Figure 10.5). This structure, though it appeared only once, points towards a possibility of non-deterministic structures as opposed to purely deterministic structures. One possibility is to utilize hierarchical orders of structure through stochastic interaction to potentially arrive at a design tool that could propose geometric solutions, if given a set of interactions and the external environment. This is drastically different from the previous examples where individual components came together to always form the same structure, as non-deterministic

assembly points more towards a self-optimizing material design tool.

The Lab has also recently continued these investigations by studying large quantities of parts. These experiments consisted of many parts assembling at the same time, in the same container. The *Autonomous Mass-Assembly* project tried to emphasize the speed with which the structures can sort themselves into separate colors and spontaneously begin forming closed structures (Figures 10.6 and 10.7). This installation consisted of a rotating table that could be dialed up and down to control the input energy. In this way, structures could assemble and disassemble continuously through the exhibit. One interesting point that emerged is the study of yield, quantity of energy, and time of assembly. It appears that the amount of time needed for assembly can be decoupled from the amount of energy input. For example, the container does not know if there are 12 parts or 144 parts and thus the same amount of energy can produce many structures in parallel. If an endless stock of material is fed into the system and successful structures are weeded out continuously, then the assembly process should produce an average yield that is far more efficient in time as compared to a human or robotic assembler, given the massive parallelization. Similarly, the cost for assembly should be dramatically reduced, given the inexpensive random energy as compared to labor wages or highly specialized industrial robotics.

10.8 The *Self-Assembly Line* project that demonstrated large-scale self-assembled furniture in a rotating chamber.

The *Self-Assembly Line* project attempted to demonstrate scalability in self-assembly processes (Figure 10.8). The aim of this project was to produce an installation that produces installations, thereby creating a machine to produce furniture pieces for the outdoor plaza at TED2012. As people engaged with the installation, they would spin the chamber faster or slower, essentially becoming the input energy for the system. In this case, users were not the information or the decision-making; rather, they were providing the energy for self-assembly to take place. This was in opposition to the traditional assembly line where humans (or robots) are usually the assembly instructions, decision-making processes, and skilled craft of assembly. The *Self-Assembly Line* flipped this model and embedded the instructions into the materials directly.

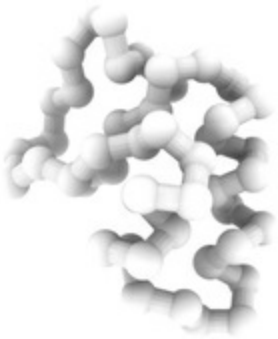


10.9 The *Decibot*, a reconfigurable robot developed that can transform from any 1D, 2D or 3D structure.

The second major element of research at the Self-Assembly Lab is programmable materials. I began focusing on this area as a graduate student at MIT while doing research for Neil Gershenfeld's lab, the Center for Bits and Atoms, under a DARPA grant for Programmable Matter. Programmable Matter is the science, engineering, and design of physical matter that has the ability to change form and/or function (shape, density, moduli, conductivity, color, etc.) in an intentional, programmable fashion.[7] This is the vision of the Star Trek replicator that can produce any materials and geometries instantly from a single machine. At the time, most of the research in this area was looking at robotics at increasingly smaller scales. We instead started to develop large-scale reconfigurable robots called the *Macrobot* and *Decibot* (Figure 10.9).[8] One was 8 feet long and the other was 12 feet long, each with a number of identical connected units. Each unit was self-similar and linkable along the strand. The units could rotate into three different positions, 0, 120, and negative 120, to lock into space-filling geometries. Information could be sent to discover the sequence of units, the neighboring units, and angle orientations. The *Macrobot* and *Decibot* became a platform to reconfigure structures from one-dimensional, two-dimensional, and three-dimensional shapes. This research fits within a field of reconfigurable robotics with the ultimate vision of mechanical proteins, a universally programmable system for construction and shape-change.

However, in order to achieve scalability, in terms of either very large structures or many, many parts, it is important to focus on robustness, resilience, easier fabrication, cheaper materials, and less failure-prone systems. Thus, it became clear that robotics was likely not the best way forward. For this reason, after *Macrobot* and *Decibot*, my research has been focused on completely passive systems while maintaining fully dynamic and programmable capabilities.

10.10 A series of photographs demonstrating the self-reconfiguring strand that transforms from a 1D strand to the 3D structure of the Crambin protein.



10.11 A rendering of a 3D model of the Crambin protein.

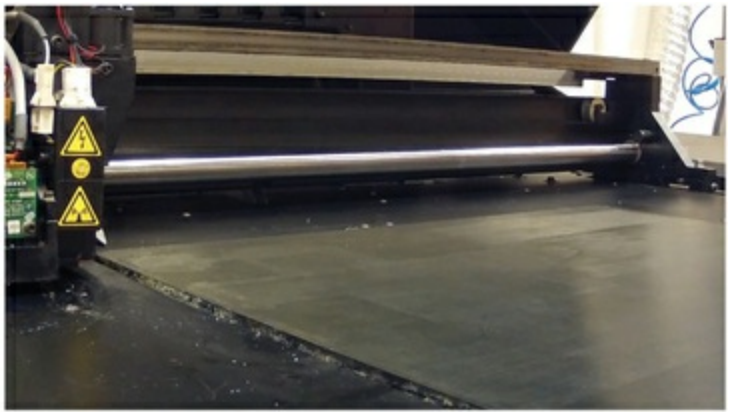
One of the first passive self-reconfiguring projects was a collaboration with molecular biologist Arthur Olson, looking at how protein folding can transform from one-dimensional strands into fairly complex three-dimensional structures (Figure 10.10). A three-dimensional model of the

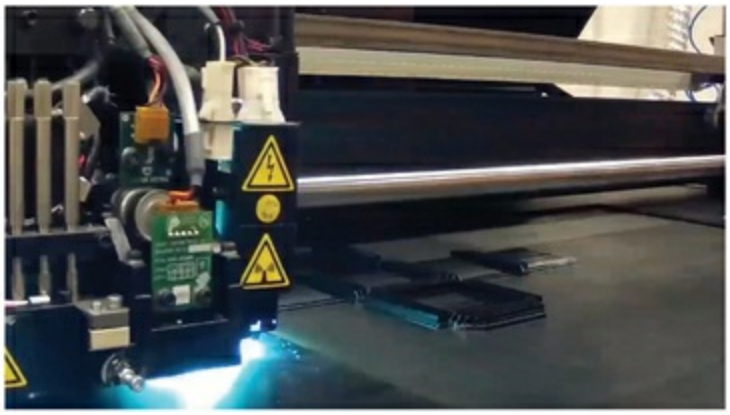
protein was downloaded from the Protein-Data-Bank and then was broken down with a series of codes into a sequence of parts (Figure 10.11). The parts were then printed on an Objet Connex 3D printer and embedded with an elastic strand. The elastic strand that ran through the protein embedded a form of potential energy to fold from one state to another. When the protein was thrown into air, it spontaneously folded from a straight line into the precise three-dimensional structure of the protein (see Figure 10.10). This demonstrated that we have embedded the folding instructions as well as the potential energy directly into the material.

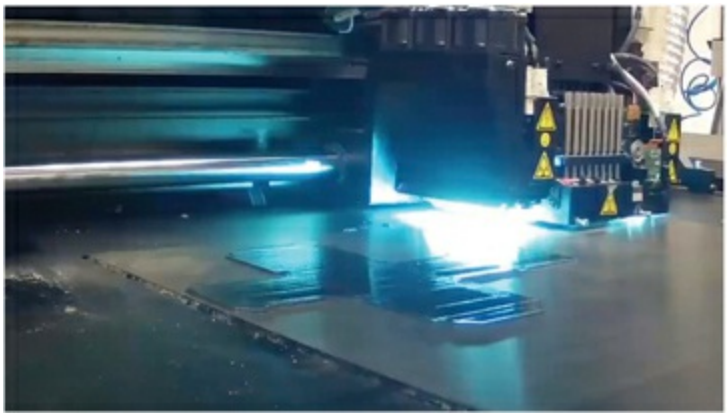
10.12 A self-reconfiguring sheet that transforms from a flat surface into an approximation of a hyperbolic paraboloid.

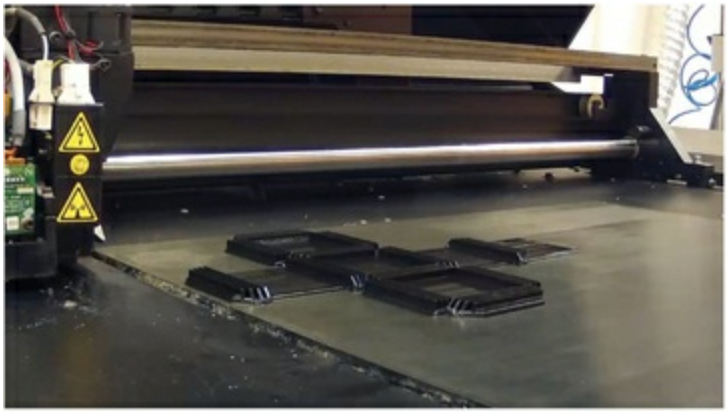
The self-folding protein project was then translated into a two-dimensional structure that can self-fold from a flat sheet into a rigid three-dimensional surface (Figure 10.12). The challenge we were addressing was how to build smart surfaces, self-folding origami or self-folding construction sheets in the future that could have the potential energy and geometric information to transform from a flat state into a fully functional 3D structure. A number of further prototypes were developed to prove this concept. One of them demonstrated a flat sheet transforming into an approximation of a hyperbolic parabola simply through printed components and elastic strands as activation energy.

The Lab's most recent work is focused on programmable materials and is a collaboration with Stratasys Ltd and Autodesk Inc, called *4D Printing*.[9] This project emerged out of the frustration created by the continually increasing difficulty of fabricating "smart" components. Since the aim was to produce self-assembling and programmable materials, we decided that we needed a more efficient and streamlined production method, rather than hand-assembly with lots of components. The question became: How could we embed information and potential energy directly into the prints so that they can transform from the moment they are taken off the print bed? Thus, 4D Printing emerged. This technique utilizes Stratasys' Connex multi-material printers to deposit two materials in precise quantities and configurations to enable self-transformation (Figure 10.13). One of the materials is static rigid material that provides the geometric code, much like braille; the black material is the information and structure with all of the constraints for precise angles. The second material is an active material that swells 150 percent when it encounters water.









10.13 A series of photographs showing the process of building a 4D-printed part on the Connex Multi-Material printer.

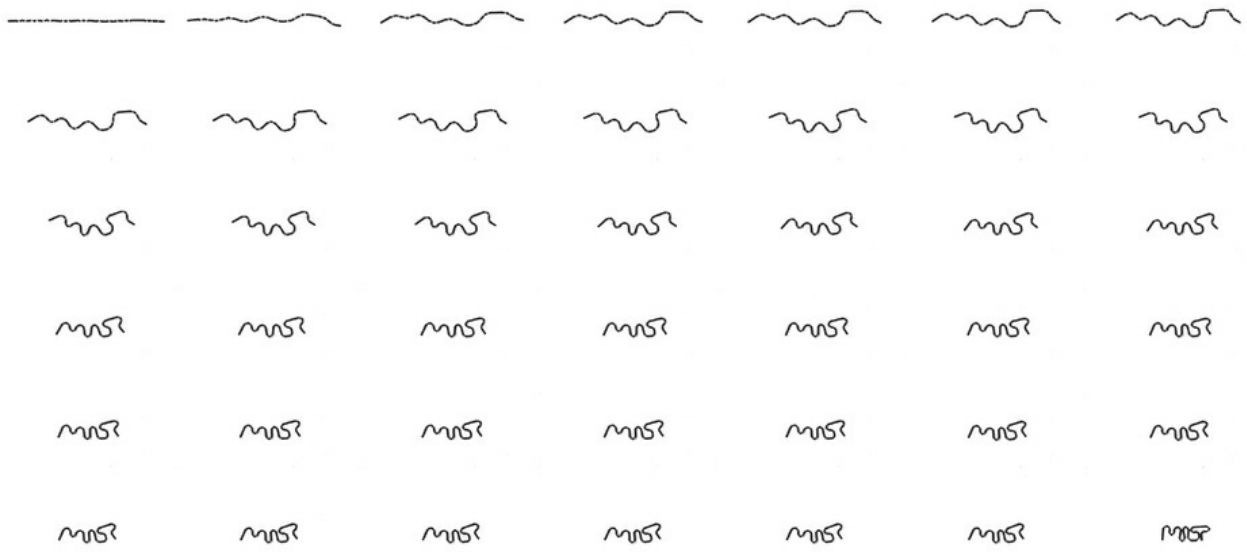
These two materials provide the information and the potential energy for self-transformation. 4D printing essentially provides smart materials that can easily be produced and printed directly into the part. Thus, we are not limited to the properties of traditional, off-the-shelf, smart materials, rather, we can design the amount of material, where to deposit it, the initial state and which secondary state the smart materials should contain. Throughout this project we have been working with Autodesk Inc. on a new software they are developing called *Project Cyborg* that allows us to stimulate and optimize these folding structures. Most importantly, this allows us to cross disciplines while utilizing the same principles. We can use the same software to develop DNA origami, self-assembly principles as well as much larger applications like 4D printing.

The first demonstration we produced was a single strand with multiple black and white portions throughout the strand. When dipped in water, the strand folds into the letters "MIT" (Figures 10.14 and 10.15). This emphasizes that no additional steps or components are required to embed the information for assembly; rather the material becomes active by reacting to the surrounding environment. This technique points towards new ways to create products that respond to the user's changing demands and to the fluctuations of the environment.

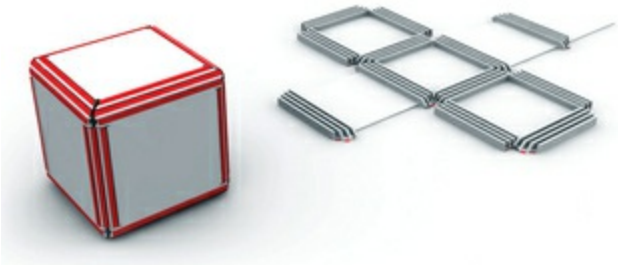
After producing the first linear strand prototypes, we moved to surface structures. We used an unrolled surface cube and then set it in a bath of hot

water.

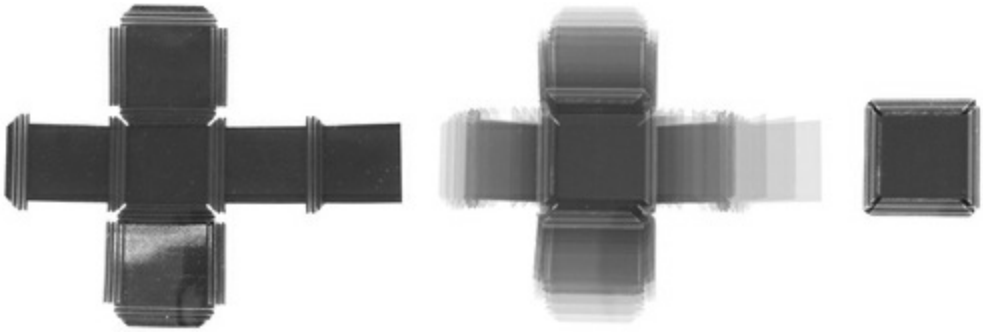
10.14 A 4D-printed single strand that self-transforms into the letters “MIT.”



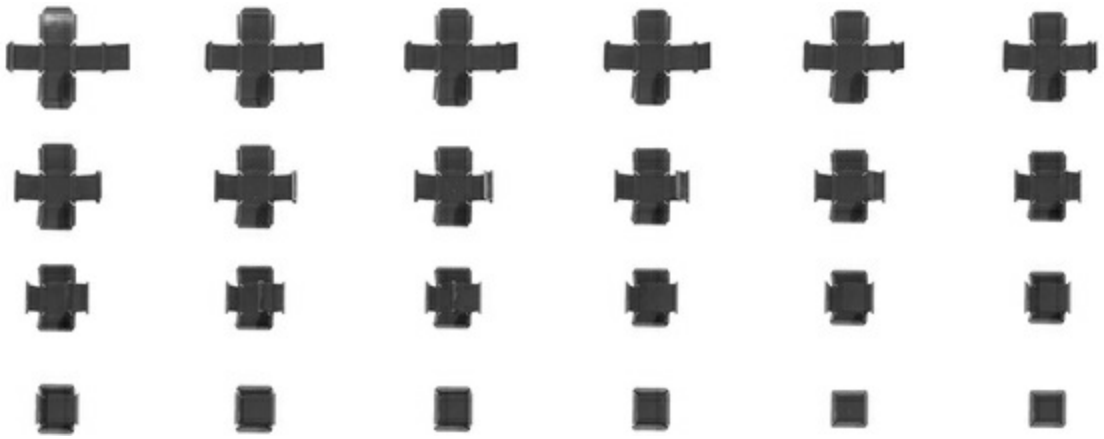
10.15 A series of photographs showing the self-transformation of a single strand turning into the letters “MIT.”



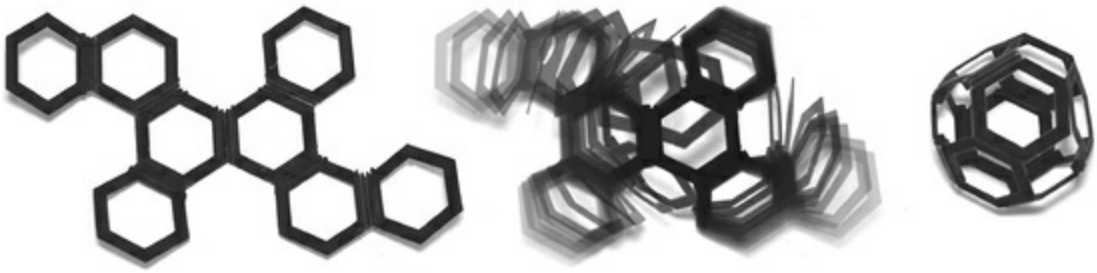
10.16 A rendering of a 4D-printed surface that can self-transform into a closed surface cube.



10.17 A 4D-printed flat surface self-transforming into a 3D surface cube.



10.18 A series of photographs showing the self-transformation of a 4D-printed flat surface into a 3D surface cube.



10.19 A 4D-printed flat surface self-transforming into a truncated octahedron.

The water activated the surface transformation, and the surface started to self-fold into the closed and precise cube (Figures 10.16, 10.17, and 10.18). Similarly, we unrolled and 4D printed a truncated octahedron structure,

demonstrating custom angle transformations (Figure 10.19). These prototypes emphasize the completely customizable capabilities of 4D printing. We can design the materials and configurations to produce many different geometric transformations as well as changes in property or appearance. Further, we are investigating a wider pallet of activation energies that go beyond water, such as heat and light, as well as single-direction and bi-direction materials for a variety of applications.

Today's world of construction and manufacturing consist of extremely complex products, built with complex parts, put together in complex ways, and operated in complex environments. Ultimately, we should aim to change this mentality and find applications that utilize smart materials, products, and assembly processes for a more elegant, scalable, and adaptive built environment. Initially we need to focus on scenarios where our traditional construction mechanisms and manufacturing techniques are insufficient/ineffective. For example, in extreme environments which are expensive, dangerous or difficult to reach, there is an opportunity to reinvent our material components and processes for smart construction. Similarly, sectors that have remained outdated and static call for a new model of highly resilient and adaptive material constructions. Infrastructure today needs smarter systems to accommodate challenging environmental requirements, extreme weather, and fluctuating peak demands. We are looking at new models for wiring, water pipes, and other infrastructure where systems can expand or contract on demand. These systems will transform with abundant passive energy and become a scalable material actuator and sensor.

Our physical products and material constructs are ready for change. It has been traditionally difficult to create smart systems due to the tendency to use robotic systems, whose components are often expensive, difficult to assemble, and prone to failure. We need to take advantage of the programmable material revolution that lies ahead of us. This is a revolution that argues for smart materiality, novel ways to interact with physical products and dynamically responsive systems for our highly energetic environment.

It is now possible to design material parts with enough information and decision-making so that they can assemble themselves and adapt

independently to internal or external demands.

Acknowledgments

This work has been made possible by the entire Self-Assembly Lab team and the great collaborations with Arthur Olson, the Scripps Research Institute, Stratasys Ltd., and Autodesk Inc.

Notes

1 Rothemund, P.W.K., "Folding DNA to Create Nanoscale Shapes and Patterns," *Nature*, 440 (2006): 297–302.

2 Douglas, S.M., *et al.*, "Rapid Prototyping of 3D DNA-Origami Shapes with CaDNAno," *Nucleic Acids Research*, 37(15) (2009): 5001–5006.

3 Douglas, S.M., Bachelet, I., and Church, G.M., "A Logic-Gated Nanorobot for Targeted Transport of Molecular Payloads," *Science*, 335(6070) (2012): 831–834.

4 Tibbits, S., "Design to Self-Assembly," *Architectural Design*, 216 (2012).

5 Olson, A.J. and Keinan, E., "Chemical Mimicry of Viral Capsid Self-Assembly," *PNAS*, 104(52) (2007): 20731-20736.

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7 Hawkes, E., An, B., Benbernou, N.M., Tanaka, H., Kim, S., Demaine, E.D., Rus, D., and Wood, R., "Programmable Matter by Folding," *Proceedings of the National Academy of Sciences of the United States of America*, 107(28) (2010): 12441–12445.

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11
Bio-Robotic Architecture

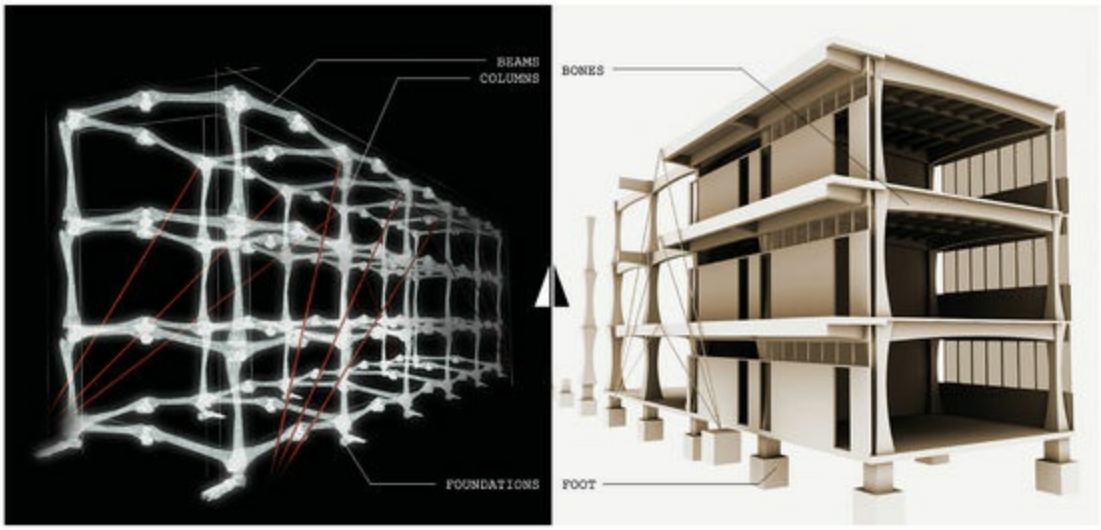
MICHAEL FOX

11.1 *Breathing Skin* of the KfW Tower in Frankfurt, Germany, designed by Sauerbruch Hutton (2010).

Bio-robotic architecture defines an architecture that goes beyond the mere capacity to interact; it defines a world that repositions the role of the designer as a catalyst of design that can adapt and evolve with the world around it. It lies at the intersection of biology and robotics; it hinges on a unique area of naturally inspired and robotically augmented design. As the term adaptive has increasingly fostered a shift from the paradigm of the mechanical to the biological, it has left a gap in the area of control. Robotics helps to fill this gap in the strictly biomimetic approach to architectural design. This chapter

explains the unfolding combinatorial worlds of biomimetics and robotics and guides us through a variety of scales with an emphasis on control.

Let's begin with a clarification in terminology. A cybernetic system is an inclusive one, encompassing organism, machine, organization, and the environment. Cybernetics was defined by Norbert Wiener back in 1948 as "the scientific study of control and communication in the animal and the machine."[1] As a secondary matter of clarification, biomimetics was started by Otto H. Schmitt in 1969 as a scientific approach that studies systems, processes, and models in nature, and then imitates them to solve human problems.[2] Biocybernetics then is a relatively new term for an abstract science focused on the application of cybernetics to biological science. Lastly, it seems necessary to define robotics, which I will do so here as that of a mechanical agent guided by a program. The point of clarifying such definitions lies in focusing this exploration on how robotics can serve as a means of augmented control for natural biomimetic adaptation.



11.2a and b *Special Moment Resisting Frame* (SMRF) is a bone-inspired building frame by Tectonica.

The Mechanical Paradigm of Biomimetics

In the recent past, we have seen a wealth of explorations in biomimetics applied to architecture. The architecture profession has been rapidly embracing digital design technologies developed and applied in the framework of biologically inspired processes. Yoseph Bar-Cohen sums it up well: "Nature has 'experimented' with various solutions and over billions of years it has improved the successful ones."[3] He adds: "Adapting mechanisms and capabilities from nature and using scientific approaches led to effective materials, structures, tools, mechanisms, processes, algorithms, methods, systems and many other benefits."[4] Specifically in terms of the development of robots, he states that "the multidisciplinary issues involved include actuators, sensors, structures, functionality, control, intelligence, and autonomy."[5] Put simply, nature is the largest laboratory that ever existed and ever will. In addressing its challenges through evolution, nature tested every field of science and engineering, leading to inventions that work well and last.

A good example of a biomimetic approach to architecture based on mechanical paradigm is *Breathing Skin*, designed by the German firm Sauerbruch Hutton, as a responsive building envelope system that, as its name suggests, breathes like the skin of some organisms, adapting to its immediate environment to act more efficiently. Applied to the KfW Tower in Frankfurt (2010) (Figure 11.1), the sensor-controlled ventilators on the outer skin open and close throughout the day in response to temperature, wind direction and speed, throwing a ring of positive pressure around the building. That air is drawn into offices through floor vents and windows along an inner façade that workers control; it is then exhausted into the building core. The result is a system of natural ventilation that eliminates the need for air conditioning and heating in the fall and spring. In extreme weather, when you need an artificial bump, the pressure balance will not interfere with the heating and cooling systems.

Another example is the *Special Moment Resisting Frame* (SMRF) by Tectonica, a custom building frame modeled on the human femur bone (Figures 11.2a and b). Like the bones in the human skeleton, each column and beam is designed precisely according to its specific load condition and its own bending moment diagram.

11.3a and b *HygroScope* by Steffen Reichert and Achim Menges at the University of Stuttgart, Germany.

A Biological Paradigm

Technological advances in manufacturing and fabrication, in particular with respect to materials, have continued to expand the parameters of what is possible in the area of natural adaptation, and influence the scale by which we

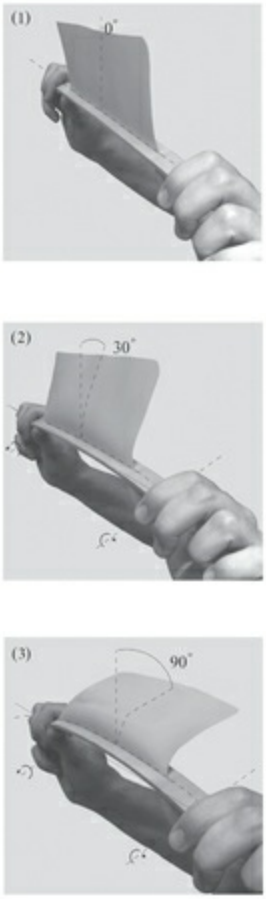
understand and construct our world, resulting in a reinterpretation of the above mechanical paradigm of adaptation. Such advances have fostered an understanding of adaptation that is much more holistic, and operates on a very small internal scale.

A biological paradigm requires more than just understanding pragmatic and performance-based technologies; aesthetic, conceptual, and philosophical issues relating to humans and the global environment must also be taken into consideration. A number of architects and philosophers are beginning to formulate the basis for a physically dynamic architecture that is supported by an improved understanding of biological systems and scale in particular. Arnim von Gleich *et al.* have identified three main strands of developments in biomimetics: (1) functional morphology (form and function); (2) biocybernetics; and (3) sensor technology and robotics and nanobiomimetics.[6] The point is that the organic paradigm reinterprets the scale at which designers work and view the world at both ends of the spectrum. In the recent past we have seen innovations in related fields deriving from electronic systems, but now we are beginning to experience an explosion of innovation in manufacturing and fabrication that is heavily influenced by both biology and scale.

Scale and Materiality

Until recently, we have seen robots getting smaller and smaller yet still relying on the tiniest of conventional mechanical parts. The possibilities from the vantage point of a materiality make the mechanical paradigm seem dated, ironically before it ever had a chance to fully manifest itself. As Michael Weinstock poetically states, "Material is no longer subservient to a form imposed upon it but is instead the very genesis of the form itself."[7] Achim Menges has created a number of non-mechanical interactive projects that are actuated based on the material's natural properties and prompted by atmospheric conditions. He articulates the point in stating that material has

the capacity to compute: “Long before the much discussed appearance of truly biotic architecture will actually be realized, the conjoining of machine and material computation potentially has significant and unprecedented consequences for design and the future of our built environment.”[8]



11.4a and b The *Flectofin* Façade System developed by Simon Schleicher at the University of Stuttgart, Germany.

The *HygroScope* project (Figures 11.3a and b) by Steffen Reichert and Achim Menges at the University of Stuttgart, Germany, explores a novel mode of responsive architecture based on the combination of material inherent behavior and computational morphogenesis. The dimensional instability of wood in relation to moisture content is employed to construct a climate-responsive architectural morphology. Suspended within a humidity-controlled glass case, the model opens and closes in response to climate changes with no need for any technical equipment or energy. Mere fluctuations in relative humidity trigger the silent changes of material-innate movement. The material structure itself is the machine.

Decker Yeadon, a studio out of New York City, has devised a beautiful contemporary double-skin glass façade system that includes mechanisms modeled on muscles, enabling the system to automatically regulate heat loss and heat gain. The system advances double-skin technologies by taking advantage of the unique flexibility and low power consumption of dielectric elastomers. The façade regulates a building's climate by automatically responding to environmental conditions. Because the surface material is also the motor, it essentially offers localized control along any segment of the

façade. The actuator is an artificial muscle, consisting of a dielectric elastomer wrapped over a flexible polymer core.

The *Flectofin Façade System*, developed by Simon Schleicher at the University of Stuttgart's Institute of Building Structures and Structural Design (ITKE) (Figures 11.4a and b), uses a hingeless mechanical system that reduces the amount of maintenance commonly associated with interactive façade systems. The *Flectofin* system is capable of shifting its fin 90 degrees by inducing bending stresses in the spine caused by displacement of a support or change of temperature in the lamina.

Developments in architecture have always been intrinsically tied to developments in new materials. As Toshiko Mori points out: "We can theoretically produce materials to meet specific performative criteria; this transformation often takes place at the molecular level, where materiality is rendered invisible."[9] Intelligent materials and smart materials are general terms for materials that have one or more properties that can be altered. Blaine Brownell describes transformational materials as those materials that undergo a physical metamorphosis triggered by an environmental stimuli; such change may be either based on the inherent properties of the material or user-driven.[10] Michelle Addington and Daniel Schodek divide smart materials and systems into two classes. The first are materials that undergo changes in one or more of their properties (chemical, electrical, magnetic, mechanical, or thermal) in direct response to a change in external stimuli in the surrounding environment. The second are smart materials that transform energy from one form to another. This class involves materials with the following types of behavior: photovoltaic, thermoelectric, piezoelectric, photoluminescent, and electrostrictive.[11]

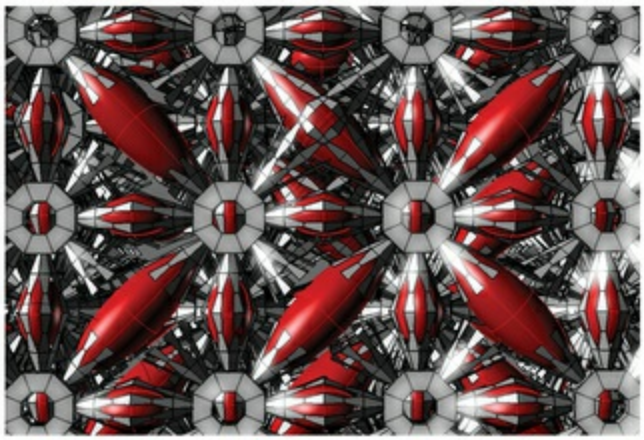
Although not common in architectural scenarios, in many other industries we can already see how smart materials can be used as sensors, detectors, transducers, and actuators. As piezoelectric material is deformed, it gives off a small but measurable electrical discharge. An example of a piezoelectric material is the airbag sensor in your car. The material senses the force of an impact on the car and sends an electric charge to deploy the airbag. John

Fernandez points out that such embedded sensors, self-healing composites, and nanoscale and responsive materials are perfectly poised for many architectural applications to counteract loads and reduce material, to change shape to block sunlight, to allow for active ventilation and insulation, and to prevent their own degradation.[12]

Smart materials are inherently tied to a function of scale. Nanotechnology is a new area of research based on the control of matter on a scale smaller than one micrometer, as well as the fabrication of devices on this same scale. Nanocomposite materials are being developed that are self-sensing and self-actuating to improve strength, reliability, and performance. Perhaps even more relevant to the discussion here is the area of bionanotechnology (as opposed to nanobiotechnology, which is nanotechnology used to further the goals of biotechnology). This area is the logical integration of biological functions and nanoscale precision. Nano bio-sensors are currently being fabricated and commercialized. Such technology based on the principles and chemical pathways of living organisms, ranging from genetically engineered microbes to custom-made organic molecules, provide the basis for the development of nanomachinery, which might be guided by studying the structure and function of the natural nanomachines found in living cells. Mavroidis and Yarmush use the term molecular machines to describe such nanomachines, as devices that can produce useful work through the interaction of individual molecules at the molecular scale of length.[13] Sean Hanna of University College London has been working on the idea of responsive materials that could be inherently intelligent and respond to external forces in the environment, like the cells living in an organism. Although research on the nano scale is the eventual goal of these efforts, he has started a millimeter level project through Subtle Technologies of the University of Toronto.

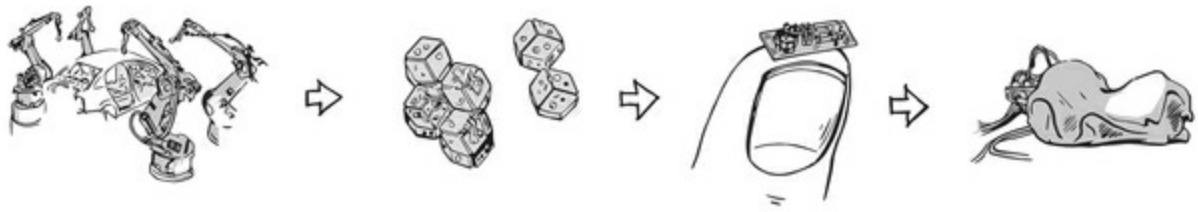
Growth and Development

Diving a bit deeper requires an understanding of the process by which organisms grow and develop. This area of study is called developmental biology and includes growth, differentiation, and morphogenesis. In terms of adaptation, the area of morphogenesis, which is concerned with the processes that control the organized spatial distribution of cells, is particularly relevant. In simple terms there is a genetic "program" that can be modified by environmental factors. A useful definition relies on a framework of recognizing the larger *systems* in which all design resides. Biomimicry then at this level is intrinsically tied to such performative aspects of the operational scale and the inherent behavior of materials, as well as the role that innovative materials may play in designing and building environments that address changing needs. According to Gary Brown, "Organic theory emerges from nature, an environment that … has a base code and an inherent program where information is strategically interrelated to produce forms of growth and strategies of behavior, optimizing each particular pattern to the contextual situation."[14]



11.5a–c Mimicking the process of bone rebuilding.

My students have done a number of projects in which scenarios of growth and development have been applied to systems that make up architectural space. One of the projects uses the process of bone remodeling as applied to an architectural building skin (Figures 11.5a–c). In particular, the cells will rebuild the structure to adapt to the load it carries; a bone can change its physical shape after a fracture that heals out of position, so that the load is adequately supported. The pattern is essentially inherited like overall body shape whereby living cells in bone are constantly breaking the bone down in little areas and rebuilding it. Such a process of continuous turnover dynamically ensures the mechanical integrity of the skeleton over time.



11.6a–d Evolution of robotics: this module used a male–female latching strategy and two separate complementary modules.

The Changing Face of Robotics

In general, we are interested in the following evolution of robotics applied to architecture (Figures 11.6a–d): (1) standard pick-and-place, which has been applied to numerous architectural systems and façade systems in particular; (2) modular robotics; (3) micro and nano-scale robotics; and (4) soft robotics.

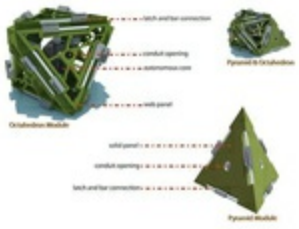
The landscape of projects that makes up the field of robotics is also seeing a shift in the way that we both design robots and understand robots. Here, too, the overriding influence is that of scale. Current advances in metamorphic, evolutionary, and self-assembling robots, specifically dealing with the scale of the building block and the amount of intelligent responsiveness that can be embedded in these modules, are setting new standards for the construction of robotics. Ironically, advances in robotics are viewed as a transitional area where scale is also heavily influenced by the same developments in material science and biomimetics mentioned in the previous sections. In general, researchers are moving away from looking at robotic locomotion through "legged" robots and are instead developing robots made up of modular parts that work as a system to interpret and act upon information.[15] Almost all modular systems in existence today are limited in how small they could be produced because of the technology that was available at the time of production.

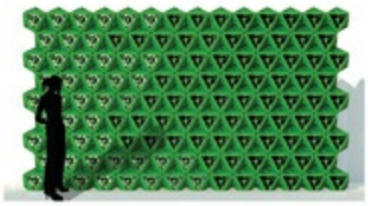
My students have done a number of projects with modular robotics, applying them to dynamic situational activities and building them into

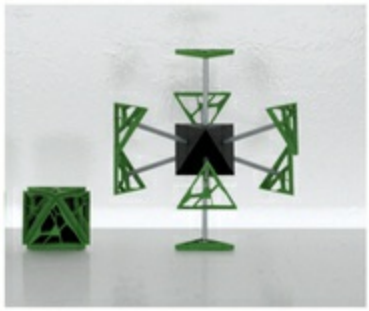
systems that make up architectural space. Individual modules were created as modular autonomous robotic components and applied to scenarios of space making at various scales (Figures 11.7a–d, 11.8a–d, 11.9a–d). Physical models demonstrated actual robotics, structure, and materials. Several strategies for decentralized control were explored, dictating how individual parts of a system should behave and how local interactions between individual modules can lead to the emergence of global behavior. The projects successfully demonstrate various strategies for mechanical design, locomotion, and control.

The area of "redesigning the brick," or creating a new vocabulary of basic architectural building blocks with modular robotics, appears to be somewhat of a transitional step, however, in the evolution of robotics. As digital manufacturing technology advances, it will be possible to produce smaller parts and future 3D printing machines will be able to physically print out electrical circuits, microcontrollers, actuators, and servos in one seamless final product.

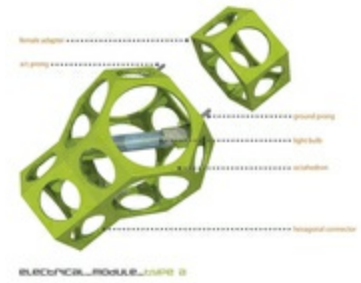
Perhaps the most relevant research lies in the area of soft robotics which is the science and engineering of soft and deformable structures in the robotic systems. From a robotics standpoint, soft and deformable structures are crucial in the systems that deal with uncertain and dynamic task-environments, locomotion in rough terrains, and physical contact with living cells and human bodies. Further, soft materials are also necessary for the more visionary research topics mentioned above such as self-repairing, growing, and self-replication.

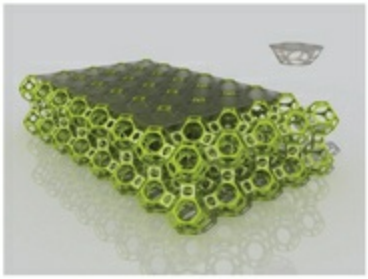






11.7a–d *Modular Autonomous Robotic Module Components*: this module used a panelized design with linear actuators for motion built around a dodecahedron hub.





11.8a–d *Modular Autonomous Robotic Module Components*: this module used a male– female latching strategy and two separate complementary modules.

11.9a–d *Modular Autonomous Robotic Module Components*: this module used a six-pointed star with linear actuators on extending arms for motion and latching and a strategy for injection infill.

A Question of Control

Early use of pick-and-place robotics has primarily used a system of top-down control when applied to architectural scenarios. Modular robotics, on the other hand, relies on decentralized control and although there may be no centralized control structure dictating how individual parts of a system should behave, local interactions between individual modules can lead to the

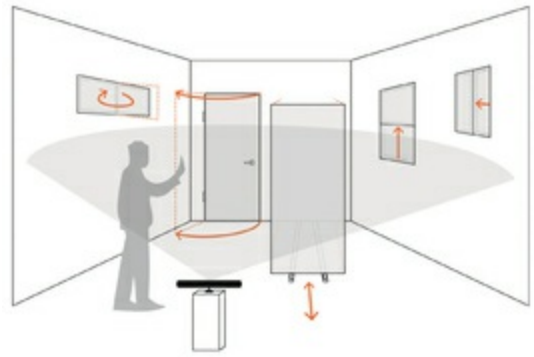
emergence of global behavior. Most architectural applications are neither self-organizing nor do they have higher-level intelligence functions of heuristic and symbolic decision-making abilities. Most applications do, however, exhibit a behavior based on low-level intelligence functions of automatic response and communication. The beauty of such distributed control is that when it is applied to a large system, there is the potential for emergent behavior. An emergent behavior can occur when a number of simple systems operate in an environment that forms more complex behaviors as a collective.

In terms of a resolution with respect to the sensing of human factors, recent developments in the area of interface design will eventually play a major role. Interface design is heavily tied to sensor innovation and manufacturing, which has signaled the availability of previously unimaginable means of gathering data and information and non-tangible forms of interaction, such as gesture and even brain-wave recognition. It may soon be commonplace to embed architecture with interfaces to allow users to interact with their environments, and we believe that gestural language (Figure 11.10) is the most powerful means of control through enabling real physical interactions. Advances in multi-touch hardware technology is significant for architecture because in many cases the gestures used to control an interface are the most similar to gestures that would be used to replicate these activities in real space with tangible objects. The manipulation of physical building components and physical space itself is more suited to gestural physical manipulation by its users instead of control via devices, speech, cognition, or other processes.

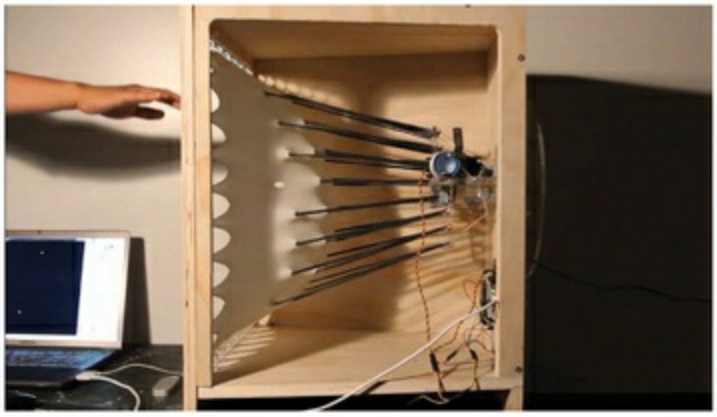
11.10 Diagram of the origins of intuitive gestural languages.

As architectural scenarios move beyond direct sensing and response conditions, we are confronted by the need for more natural and direct means of control. Many in the architectural profession have begun to study and learn from interactive media precedents and usurp the technologies employed to control interactive digital environments. Technologies that allow users new means to control and interact with digital information can be broken down into three general categories: (1) touch and multi-touch; (2) gesture; and (3) cognitive control. To date, there are many touch and multi-touch interfaces; gesture interfaces are still in their infancy with regard to architectural applications, and direct cognitive controls rest on the developmental horizon but show fascinating promise.

In the following project we defined a catalog of architectural gestures; the research was intended to further define the notion of "intuition" as related to the creation of gestural languages. The project used a Kinect sensor and a series of mechanically driven typical architectural fenestrations to discover the most referenced categories of relative intuition among test subjects prompted to "invent" gestures for specific architectural tasks (Figures 11.11a–c). The issue is not just how to create a system that is capable of changing but also researching the quality of change as well as defining the stimulus for adaptation.



11.11a–c A vocabulary for gestural control in architecture: the project used a Kinect sensor and a series of mechanically driven typical architectural fenestrations to discover the most referenced categories of relative intuition among test subjects.



11.12a and b Complex gestural interactions: student designs utilizing the Leap motion sensor to integrate complex gestural input to control mechanically driven façade designs.

Taking the sensor a step further in terms of resolution with respect to architectural gestures, a study was carried out using the Leap sensor rather than the Kinect in order to gather a high degree of gestural complexity (Figures 11.12a and b). The Leap sensor was used to understand complex gestures such as drawing a circle in the air with a point in the middle as a means of triggering action in the physical world.

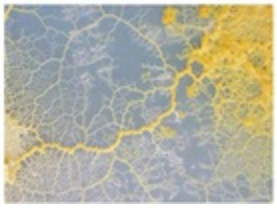
Behnaz Farahi has taken the direct interaction via gestures a step further in her project *Alloplastic Architecture* (Figures 11.13a–c). The main focus is on the relationship between materials, form, and interactive systems of control.[16] Central to interactivity between a user body motion and the environment is the notion that for this process to happen effectively, there should be a common logic of behavior shared by both the user and the environment. If both the body of the user and the structure of the environment itself are governed by a similar logic of behavior, then the modeling of the behavior of one on the other will be all the easier to engender. Moreover, states Farahi:

> As we shift from a mechanical to a biological approach, the properties of actual materials are likely to play an increasingly important role in the transformations of physical spaces so that a material might be able to move continuously in relationship to its users and their environment. In the *Alloplastic Architecture project*, Shape Memory Alloy [SMA] springs operate as "muscles" or active members, aluminum tubes as "bones" and textile fabric as "fascia" or passive members.[17]

Robotically Augmented Biomimetics

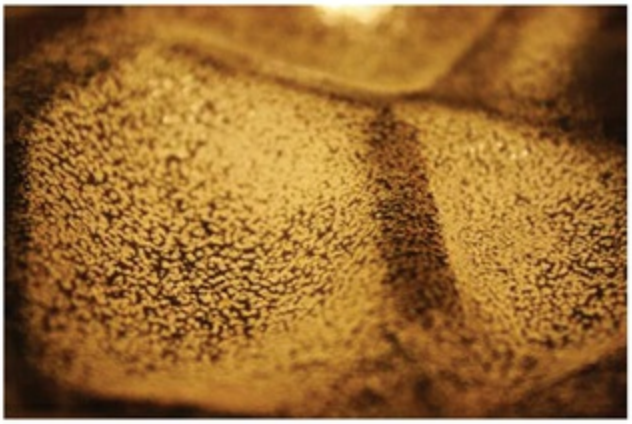
We also explored how robotics can serve as a means of augmented control for natural biomimetic adaptation. As mentioned previously, I defined a robot as "mechanical agent guided by a program." And while what has been already mentioned, in terms of scale and materiality, shows fantastic promise, there is a current need for control at the architectural scale in particular when adaptation must mediate the needs of building users and the environment. The utilization of novel materials has altered the course of architecture. Today we have a compressed technology transfer of modes of production and design methodologies tied to form-making that bring innovations in materials to architectural reality faster than ever. What has been outlined so far are advancements in both robotics and new materials whereby the adaptation becomes much more holistic, and operates on a very small internal scale. In the following series of student projects focused on façade designs, biomimetic systems were augmented with a secondary means of robotic control.

11.13a–c *Alloplastic Architecture*: performance artist dances with the structure that reacts to her presence without any actual physical contact.



11.14a–e *Augmented Slime Mold Bio-Façade.*

In *Augmented Slime Mold Bio-Façade* (Figures 11.14a–e), the goal is to use materials with specific characteristics in order to minimize energy use and mechanical complexity. Slime mold possesses a natural ability to provide varying levels of transparency as it passes through multiple phases of growth. The growth cycle, and consequently the esthetic effects and patterns, are controlled through the robotic manipulation of depositing and retrieving a regulated texture of growth medium, and food quantity, to specific locations.

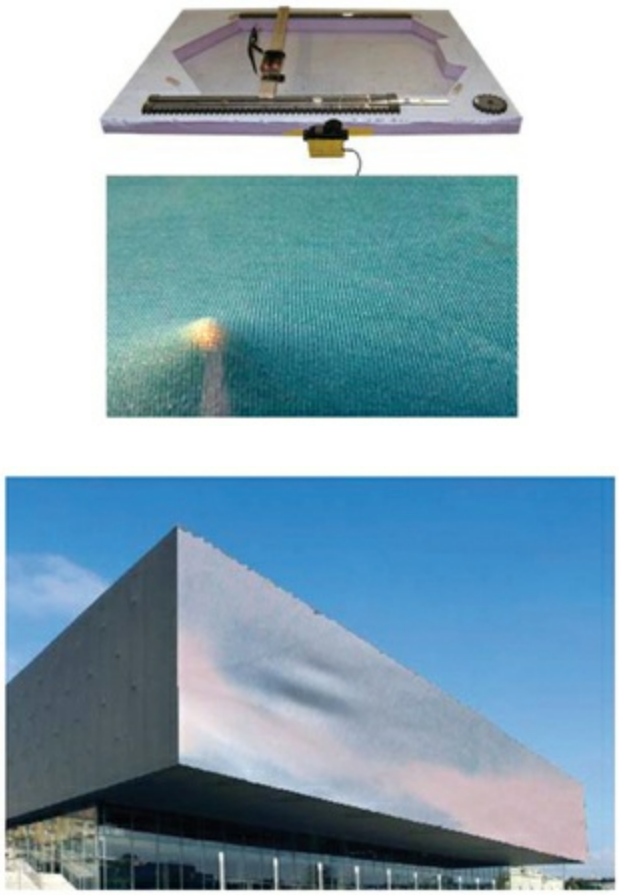


11.15a and b *Augmented Electro-Magnetic Façade* (*The Sisyphus Façade*).

The *Sisyphus Façade* system (*Augmented Electro-Magnetic Façade*) relies on the specific control of an electromagnetic array on the acrylic skin (Figures 11.15a and b). Through control of the grid, tiny metallic balls that are constantly falling down the skin are allowed to congregate on the surface. The effect has a sense of generalized robotic control that is influenced by the natural random effects of the system creating a slightly different pattern every time with the same controlled effect.

The Augmented Thermochromic Façade (Figures 11.16a and b) uses robotic control to paint on the thermochromic fabric by means of a heated brush that regulates the color change configuration. The traditional sensor-driven robotic mechanism augments the natural response of the material to induce specific non-mechanical change at any location in the area. The material itself has a natural delay before returning to the original color.

It is important to note that the need for augmented control for natural biomimetic adaptation is seen as a transitional phase. There have already been some explorations which successfully demonstrate the global scale of the material controlled at a specific local scale. Recently developed prototypes of thin film electropolymeric display systems for glazing based on research at NVMG and CASE have designed working examples of a new technology for façade applications that enable instantaneously switchable patterns to be embedded within the surfaces of Insulated Glazing Units (IGU).[18]



11.16a and b *Augmented Thermochromic Façade.*

Catalyst Design

The important thing here is that such systems that are controlled but yet control themselves on another level have the potential to reposition the role of the designer. As Behnaz puts it: "The architect no longer designs the final form but rather creates an initial state, introduces a set of controlled constraints and then allows the structure to be activated to find its form in real time."[19] What results is the emergence of unexpected shapes rather than an architecture that literally interprets and responds to human and environmental desires; the architecture is allowed to take a bottom-up role in configuring itself in a malleable way. As Gordon Pask states in his Foreword

to John Frazer's book, *An Evolutionary Architecture*: "The role of the architect here, I think, is not so much to design a building or city as to catalyze them: to act that they may evolve."[20] Architects should be informed of developments in biomimetics to understand what is possible to extrapolate from these ideas and technologies in the creation of a vision to direct the future of their profession. While such ideas have been around for quite some time in the architectural world in terms of scripting, generative design, evolutionary design, etc., the possibilities seem very different – they have the potential to affect the architecture itself after it is built. Such an extrapolation of advancements in both robotics and new materials demonstrates an architectural future whereby adaptation becomes much more holistic and operates on a very small internal scale.

Notes

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16 Video of the performance is available at https://vimeo.com/55514649.

17 Bouzanjani, B., Leach, N., Huang, A., and Fox, M., "Alloplastic Architecture: The Design of an Interactive Tensegrity Structure," in Beesley, P., Khan, O., and Stacey, M. (eds.), *Adaptive Architecture: Proceedings of the 2013 ACADIA Conference* (Cambridge, ON: ACADIA, 2013).

18 See http://smartgeometry.org/index.php?option=com_content&view=article&id=141:bioresponsive-buildingenvelope&catid=44.

19 Bouzanjani, *et al.*, op. cit.

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12
Material as Mechanism in Agile Spaces

VERA PARLAC

Behavior, adaptation, and responsiveness are characteristics of live organisms; architecture, on the other hand, is structurally, materially, and functionally constructed. Natural systems use adaptation to adjust to and compensate for the constantly changing environment that surrounds them. There is a constant exchange of matter, energy, and information through their productive relationship with the environment. Adaptation and responsiveness of the constructed environment, however, are not easily achieved. The challenge stems in part from the way we build and the hierarchical, top-down nature of the design process. Nevertheless, we increasingly expect buildings not only to house and facilitate various modes of human activity but also to adapt to, behave, respond, and accommodate the flow of energy and information.

Many concepts and ideas have emerged over the past decades that propose adaptation of spaces, structures, or systems, including their configuration and behavior. Buckminster Fuller's work paved the way towards a deeper understanding of the relationship between form and geometry. Frei Otto's form-finding experiments highlighted the inseparable relationship of form and material in nature. Concepts and projects developed in the late 1960s and early 1970s, such as Cedric Price's *Fun Palace*, Nicholas Negroponte's *Soft Architecture Machines*,[1] and Chuck Eastman's "adaptive-conditional architecture",[2] began to explore "intelligence" and the programmability of architecture's processes and spaces in order to form a two-way relationship between spaces and users and to accommodate environment, human use, or climate. Today, the increasing complexity of the constructed environment – and its energy exchanges – are bringing the adaptive capacity of buildings into focus. The latest advances in distributed computation, embedded

computing, material innovation, and digital architectural design are enabling the development of integration strategies that facilitate the further exploration of adaptive systems in buildings. An increasing number of projects are envisioning buildings as productive participants within the larger ecology by emphasizing their adaptability and responsiveness.

Arduino, Mems, and Alive Buildings

In 2005, an inexpensive open source microcontroller board called *Arduino* (Figure 12.1) was released in Italy. It could receive input from a variety of sensors, detecting light, motion, touch, sound, temperature, etc. and it could affect its environment by controlling lights, motors, pumps or other devices and actuators. The platform came with a simple development environment for writing software that could interpret the received input values from the sensors and produce output instructions that would control the operation of the actuators. Since its release, hundreds of thousands of these inexpensive electronics boards have been sold worldwide, enabling enthusiasts to create all sorts of interactive objects and environments. *Arduino* boards also found their way into the schools of architecture worldwide, sparking the imagination of students and reigniting the vision of dynamic built environments that could alter their shape, position, or orientation. Buildings could thus become more sensitive to what was happening in and around them and respond by altering their spatial configuration or the environmental conditions. The dynamically changing structures, imagined in science fiction novels from the 1960s and 1970s,[3] started to emerge as a not-so-distant technological possibility… Ruiz-Geli's *Media-TIC* building in Barcelona features a number of control systems based on over a hundred networked Arduino boards that can sense various changes in the environment and then produce a corresponding reaction not only in shading but also how the building is lit.[4]

While Arduino boards require wires to supply them with electricity and connect them with sensors and actuators, another interesting, emerging

thread of technological development is Micro-Electro-Mechanical Systems (MEMS), tiny electromechanical devices made of miniaturized structures, sensors, actuators, and microelectronics. Due to their scale these micro machines could be embedded in other materials. For example, Siemens has created microsensors for heat changes that could be embedded in glass to measure solar heat gain and trigger the appropriate action, such as darkening the glass by applying electricity to its coating. Of particular interest are wireless microsensors, which could sense changes in air temperatures, humidity, CO_2 levels, and other inputs and transmit that information to the building's management system. The size of only several millimeters, they could eventually be "sprinkled" on building surfaces in thousands; such "dense network sensing" holds the promise of turning building envelopes into actual "skins." A building skin will no longer be a poor biological metaphor, but increasingly a layer that can sense and react.

12.1 *Arduino* microcontroller board.

The concept of programmable matter reflected in the work of the Harvard Microrobotics Lab and the collaborative research by Carnegie Mellon and Intel go a step further in redefining the relationship between an object/surface and its materiality. For example, recent research by Harvard Microrobotics Lab and MIT proposes a preprogrammed sheet material that can fold itself into a boat or an airplane origami shape. The thin resin-fiberglass composite sheet, divided into triangular segments, has heat-sensitive connections that fold into a particular shape depending on the program used.[5] This concept could one day produce objects or surfaces that can shift shape or transform

into a number of useful objects. Similar work at Carnegie Mellon is looking at developing small computers that can work together to form shapes.[6] These particle-sized machines are conceptually the same as modular robots but work on a smaller scale – each particle is less than a millimeter in diameter.[7] The *Claytronics* project integrates the physical and the computational with a concept of "fungability" that enables many computers to talk to each other and allows them to separate into sections without losing overall computing power.[8]

Another direction that holds promise for changing the way buildings participate in their environment is the research done in the field of synthetic biology, which is concerned with constructing biological devices and systems. In synthetically produced biological materials, "intelligence" is embedded in the matter itself. In 1974, Waclaw Szybalski suggested that synthetic biology "would be a field with an unlimited expansion potential and hardly any limitations to building 'new better control circuits' or ... finally other 'synthetic' organisms."[9] In an article published in 2010, Rachel Armstrong discusses a new class of materials, developed with technologies derived from synthetic biology, which are capable of "decision making" by relying on the chemical computational power of their molecules.[10] They are "programmed/designed" to make decisions about their environment and respond to it in complex ways that involve a change in their form, function, or appearance. The responsiveness of these materials lies in their capacity for chemical computation. Without the need to rely on traditional computing methods and actuation devices these materials offer a very different way of imagining an operational capacity of matter.[11]

Material-Based Actuation: Embedded Low-Energy Responsiveness

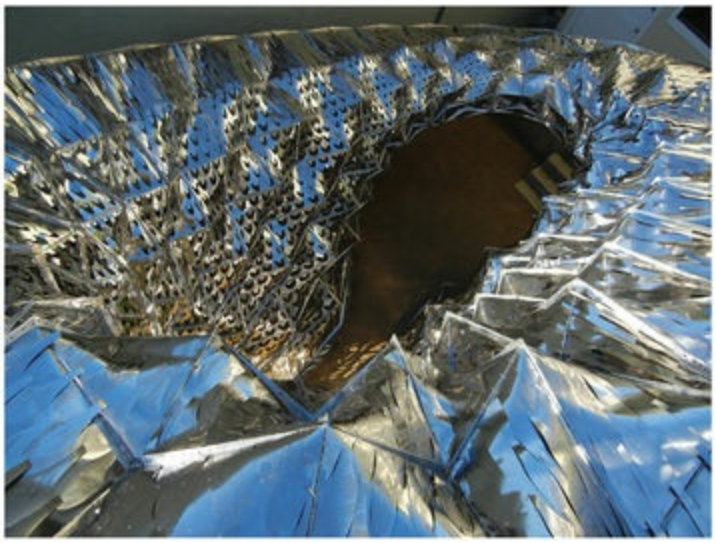
The dynamic control of energy flows (manifested as light and heat) is at the

center of innovation in adaptive building envelopes, facilitated by new materials and the latest advances in sensing, control, and actuation systems. Most of the automated adaptive façade systems that have been deployed to date rely on motor-based, i.e. mechanical actuation. Recently, we have seen increasing use of pneumatic actuation, primarily with the use of ETFE-based systems. There are, however, ongoing experiments in material-based actuation, which offer the promise of "zero energy" dynamic building envelopes.

12.2 *HygroScope* by Achim Menges and his ICD research group at the University of Stuttgart, Germany.

Researchers are also exploring biological paradigms of kinetic adaptation, which relies on material instead of mechanical actuation. Much of that work shares John Frazer's observation from his *Evolutionary Architecture* book, published in 1995, that "natural ecosystems have complex biological structures: they recycle their materials, permit change and adaptation, and make efficient use of ambient energy."[12] For example, Achim Menges has recently designed *HygroScope* (Figure 12.2), a prototype that relies on the intrinsic properties of material to produce an actuated response. As described on his website, "The dimensional instability of wood in relation to moisture content is employed to construct a climate responsive architectural morphology … Mere fluctuations in relative humidity trigger the silent

changes of material-innate movement."[13] As Menges notes, "The material structure itself is the machine."[14] Joanna Aizenberg at the Wyss Institute at Harvard University is also experimenting with adaptive building materials, such as superhydrophic surface materials that can collect rainwater efficiently by switching from hydrophobic (non-wetting) to hydrophilic (wetting) state. Other adaptive materials explored by Aizenberg are light-sensitive materials that can change transparency and harness energy from the environment.



12.3 Doris Sung's *Bloom* canopy in Los Angeles is made from thousands of bimetallic components.

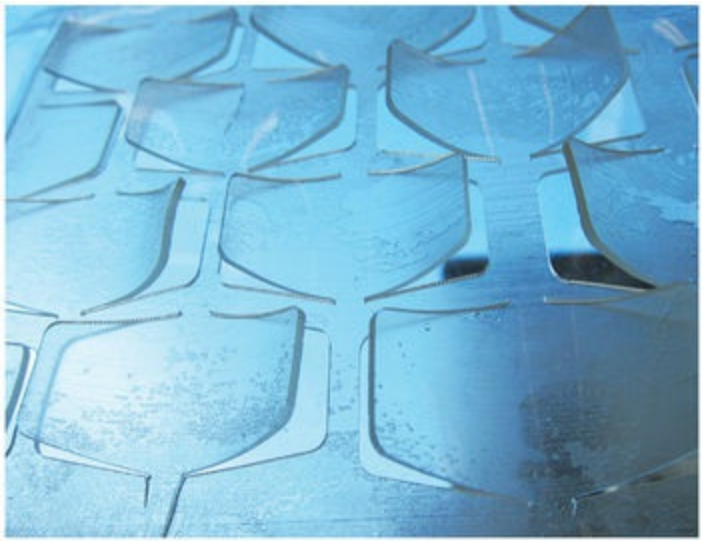
Another trajectory in material-based activation is to work with two (or more) materials that react to environmental changes at dimensionally different rates. For example, Doris Sung is experimenting with bimetallic panels in which two laminated sheets of metal expand and contract at different rates when exposed to heat, i.e. direct sunlight. If one end of the laminated sheets is fixed, the different rates of thermal expansion or contraction result in deflection, which can be then exploited in different ways, depending on the intended performance of such material assemblies. This method of material activation is rather old: the thermally induced bending of bimetallic strips has been used in thermostats for decades to produce an "automatic" electronic contact. What is novel in Sung's work is the scale of application, which has shifted tenfold from millimeters in thermostats to

centimeters in the canopy project called *Bloom* she designed, produced, and installed in 2012 in Los Angeles (Figure 12.3). The canopy consists of tens of thousands of lasercut bimetallic components assembled into over 400 hypar-shaped panels that create a self-supporting structure when assembled. When exposed to sunrays, the panels start to open in the morning as the temperature rises and then begin to close in the afternoon as the sun sets, i.e., as the temperature drops. The bimetal assembly used by Sung in the *Bloom* relies on the molecular bond between two different manganese-based alloys (i.e., there is no adhesive). The bimetallic panels are thermally very sensitive, with almost real-time deflection when exposed to solar heat. They could lead potentially to the development of dynamic, "zero-energy" building envelopes in which bimetallic-based components could open up vents for the hot air to escape or could move other elements into the proper position to shade the spaces from direct sunlight.

12.4 *Living Glass* prototype by David Benjamin and Soo-in Yang (The Living).

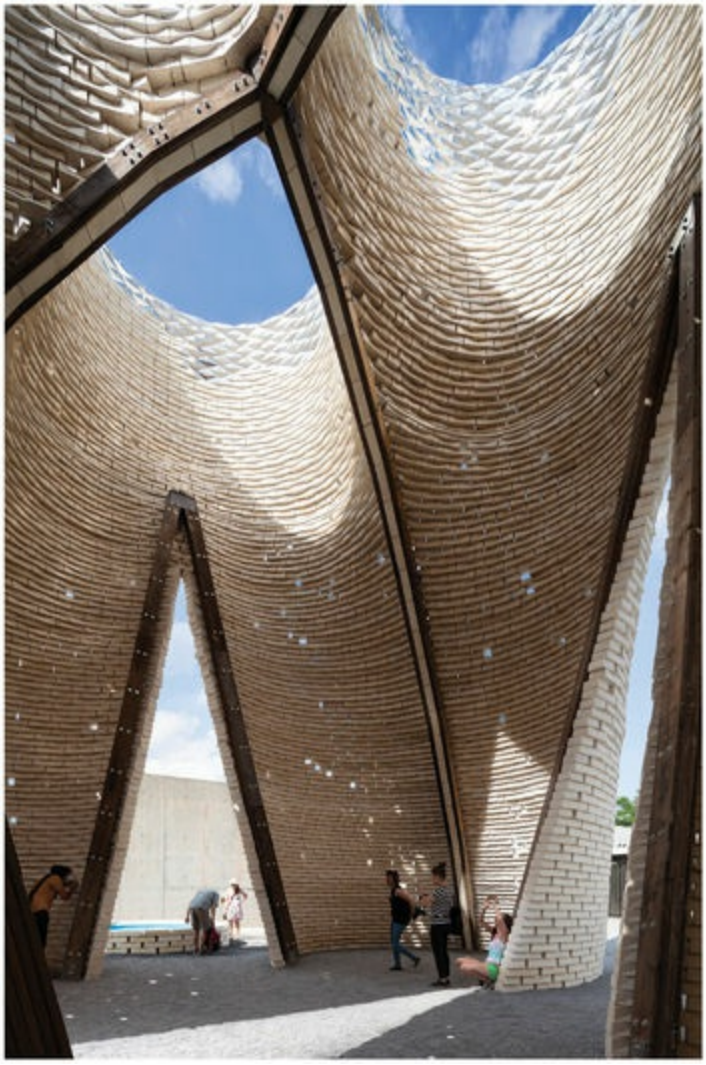
Other researchers are working with shape-memory materials, in which deformation can be induced (and recovered from) through temperature changes. David Benjamin has experimented early on with shape-memory alloys (SMA) and Nick Puckett has used various shape-memory polymers to create material-actuated prototypes of building façades. In the *Living Glass*

prototype (Figure 12.4), David Benjamin and Soo-in Yang (whose firm is called "The Living") created a cast silicone membrane in which slits were lined with Flexinol, a shape-memory alloy (SMA) wire manufactured by Dynalloy, which shrinks when an electrical current is applied to it – and then returns to its original shape when the current is cut off (i.e., it "remembers" its shape). *Living Glass* registers the concentration of CO_2 in the air and when the acceptable level is exceeded, the Flexinol wire is activated to open the silicone "gills," allowing a fresh supply of air. Nick Puckett experimented with strips cut into a sheet made from shape memory polymers that bend when exposed to sunlight, thus creating apertures in the surface; the strips return to their original position when not exposed to sunlight, closing the openings in the polymer surface (Figure 12.5).



12.5 Nick Puckett's dynamic skin prototype made using heat-activated shape-memory polymer.

The so-called smart or designed materials that can change their shape based on external stimuli are of increasing interest to researchers in the building industry. Besides shape-memory alloys and polymers that change shape based on temperature, there are magnetic shape alloys, in which magnetization affects shape, then photomechanical materials, in which light affects shape, electroactive polymers, pH-sensitive polymers, etc.

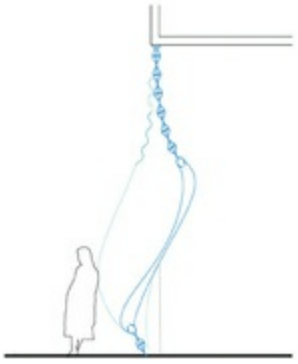


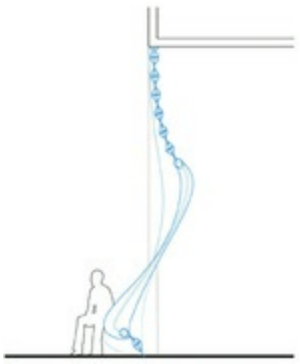
12.6 *Hy-Fi Tower* at MoMA PS1 in New York, designed by David Benjamin (The Living) was built using fungi-produced bricks.

None of these examples requires sophisticated sensory, control, and actuation systems to produce a dynamic response to changing environmental conditions; instead, they cleverly exploit the embedded, intrinsic properties of the materials. Challenges, however, do exist before systems that rely on material-based actuation are fully developed. Most of the prototypes that make use of the designed materials are small-scale; in fact, *scale* remains a principal challenge in developing such smart material-based systems, for the simple reason that materials behave differently, i.e., in a non-linear manner, at different scales. So, what works at the 1-meter scale will not work at the 10-

meter scale. It is highly likely that most adaptive systems (at the scale of building) that rely on shape or volume changes in smart materials will be based on some kind of hybrid actuation, such as mechanic amplification of material-based actuation. For example, in the *Hylozoic Ground* installation, Phillip Beesley used mechanical levers to amplify contractions in the "muscle" wire (i.e. shape-memory alloy) used in the assembly that produce real-time dynamic behavior. Such hybrid actuation, combined with proximity sensors and controlled through a network of *Arduino* microcontrollers, produced what looks like a living, breathing forest of acrylic fronds that change shape as people move through the installation.[15]

Other researchers are exploring the possible use of bio-reactive material systems. Arup's engineers developed a photo-bio-reactive façade prototype called *SolarLeaf* that features a layer of microalgae (sandwiched between two sheets of glass) that generates biomass and heat as renewable energy resources.[16] The four-story *BIQ House* (2013) in Hamburg has over a hundred of these bioreactor panels installed on its façades, with a total surface area of approximately 200m^2. Solar thermal heat and algae are harvested in a closed loop system, in which they are stored and then fermented to generate hot water. *Silk Leaf* by Julian Melchiorri consists of chloroplasts suspended in a matrix made out of silk protein.[17] The synthetic biological leaf absorbs water and carbon dioxide to produce oxygen; it is living and breathing as a leaf. It is very light, with low energy consumption – and biological. Its possible application could be as part of the façade ventilation system. David Benjamin used fungi-produced bricks for The Living's *Hy-Fi* "mushroom" tower (Figure 12.6) built in the courtyard of MoMA's PS1 in New York. Organic, biodegradable bricks are grown in brick-shaped molds using a production technique developed by Ecovative, a manufacturing company that uses mycelium fungus that binds itself to a food source – corn stalks in this case, i.e. farm waste – to create a strong, resilient material in any shape desired. Ecovative was using mycelium fungi to produce packaging for Dell computers and has worked with The Living on a new bio-degradable material for the building industry.





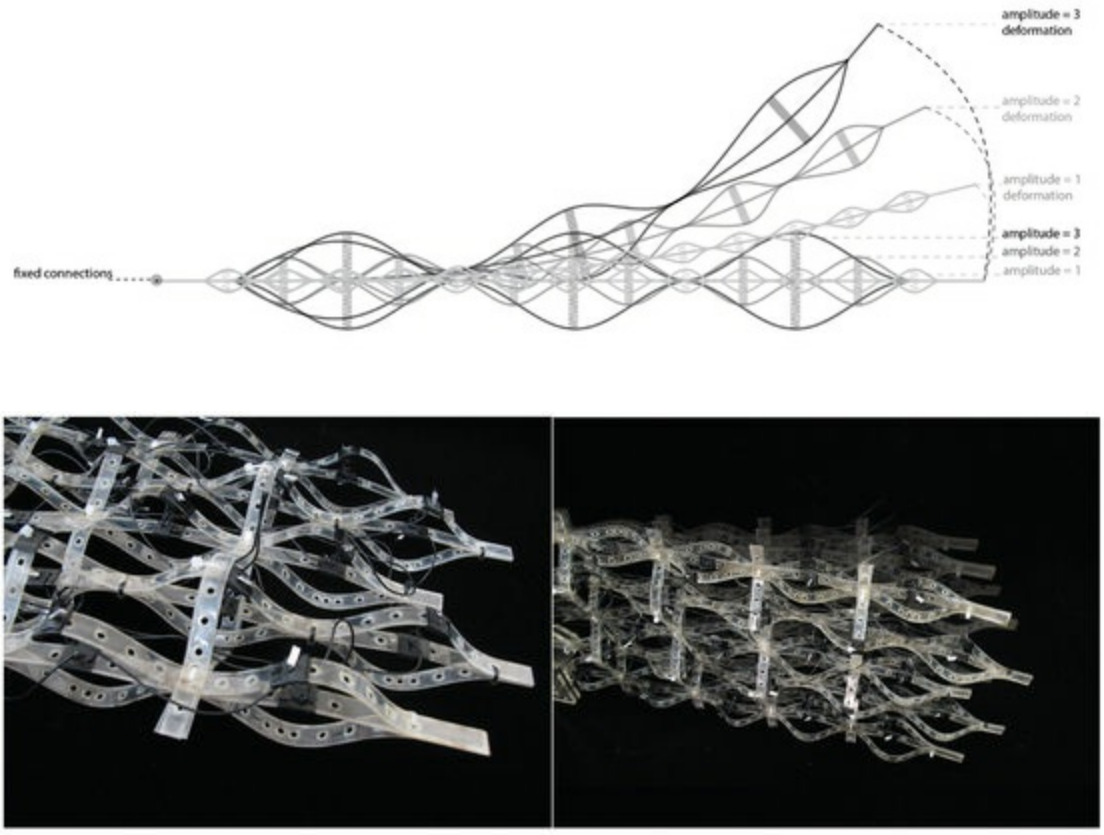
12.7a–c *Agile Space* provides small occupiable spaces that interact with the environment and people.

Agile Spaces

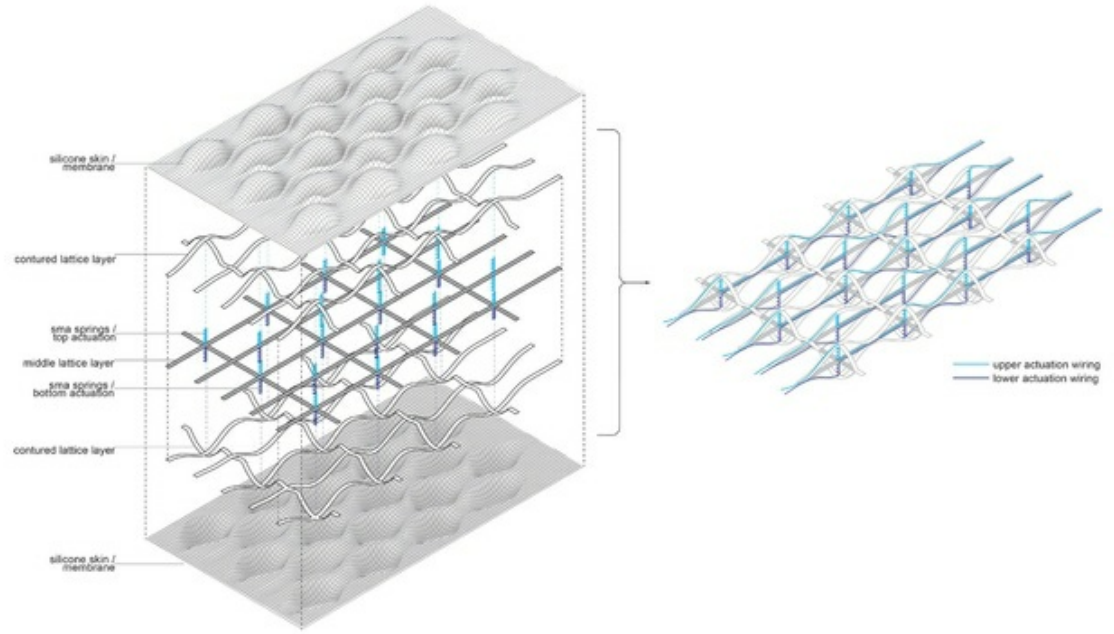
In his seminal book, *An Evolutionary Architecture*, John Frazer suggests a new form of designed artifact, one that is interacting and evolving in harmony with natural forces, including those of society.[18] To achieve this, architecture depends on information transfer. The relationship between information and the physical response of an adaptive structure is supported by the application of sensors and actuators as well as mechanisms that control and activate the intelligence of physical environment. These concepts are explored in a series of *Agile Space* prototype projects, which I have developed iteratively over the past few years.

The *Agile Space* prototypes rely on non-mechanical material-based actuation using shape-memory alloy (SMA) wires that are integrated into the structural lattice of the surfaces. The movement resulting from the material-based actuation is augmented by an inflatable soft-robot surface, while the network of sensors distributed throughout the surface serves to enable information exchange between the surface, environment, and people. The *Agile Space* project proposes an adaptable and responsive material system capable of sensing its environment and responding to it by changing its shape or revealing small occupiable spaces to passers-by. These spaces can provide

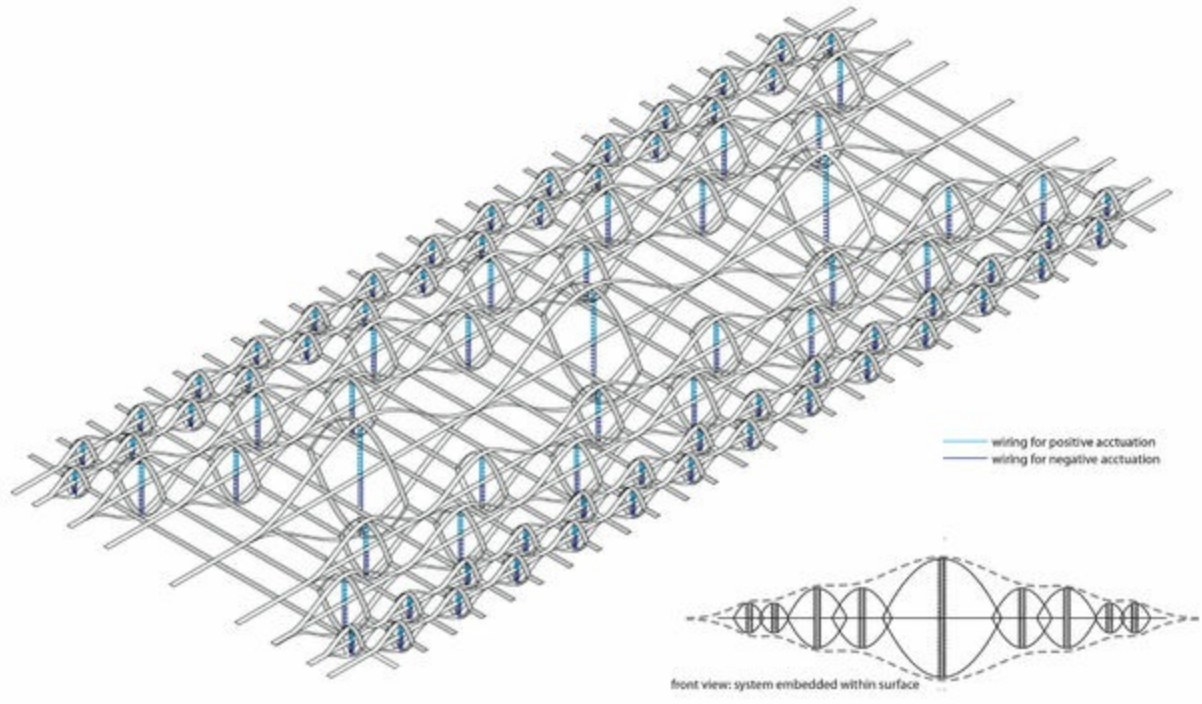
shelter or mediate the temperature of the environment, making public spaces in harsh, cold climates more vibrant. The "intelligence" of the surface's physical environment is capable of incorporating climate and human-related conditions into its working. By sensing the environmental temperature, the surface can mediate between the internal and external environments and provide localized heated regions. These regions can then act as attractors that draw people towards the surface (Figures 12.7a–c). The heat generation of the surface is closely related to its movement and change of shape since embedded shape memory alloy wires generate heat when activated. This heat is captured, stored, and moved through the surface; it can "follow" movement and activity of people.



12.8a-c Prototype of the lattice structure made of SMA springs: amplitude of bending and cell deformation after SMA spring actuation.



12.9 Lattice assembly and the actuation logic.



12.10 Differential cell size lattice assembly and the actuation logic.

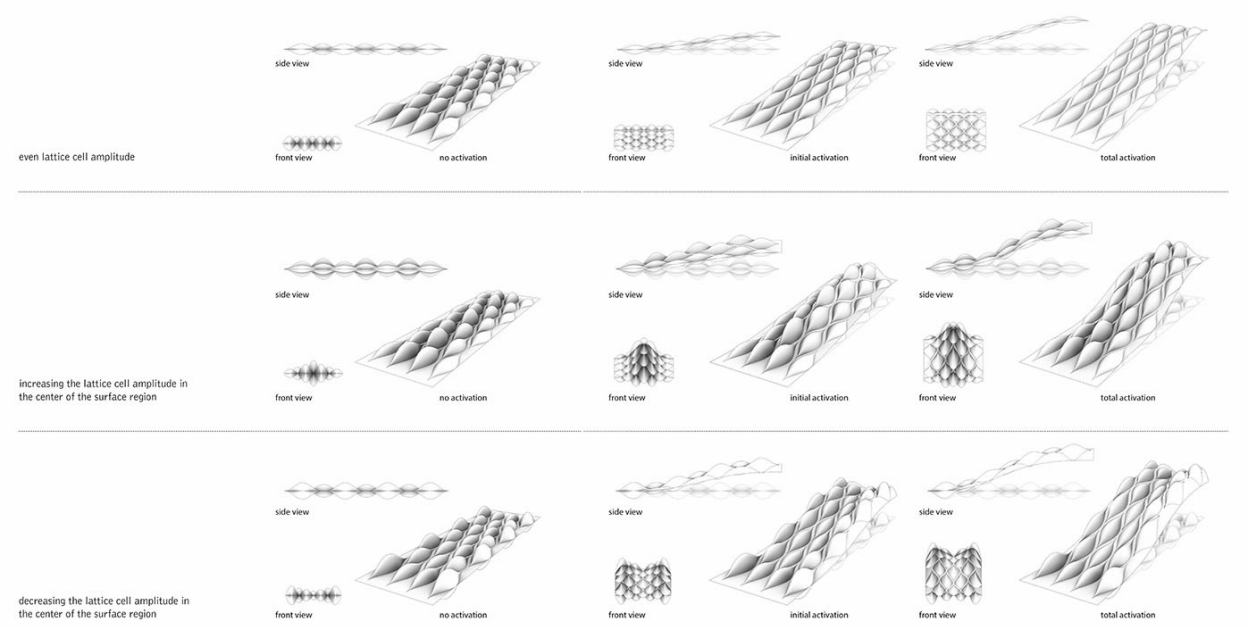
The backbone of this project is a kinetic material system actuated by SMA

springs. The system's lattice structure and its structural behavior are key to its operation; it relies on the elastic deformation of the constituent members. The system becomes kinetic when the SMA spring actuators are activated, which introduces tension into the lattice members and causes a change in the geometry of the lattice cells. The result is the elastic deformation of the surface; the lattice structure amplifies the bending by distributing the bending forces over a wider region of the surface (Figures 12.8a–c).

The lattice assembly and the actuation logic allow for bending in two directions. Depending on the zone of actuation the lattice deforms and moves upwards or downwards. Strategic placement of the actuators across the lattice produces an accumulated bending effect and deforms the entire surface. The structure consists of lamellas of thermoplastic material (which were previously contoured) of high tensile strength and low stiffness (Figure 12.9). The material is oriented in a particular way to allow for bending and reversed elasticity.

The lattice cells could also vary in size. This variation affords the change of amplitude and produces differentiated movement. Components of variable size are joined in a lattice surface. This variable cell size produces variable thickness (in cross-section) of the system's structure (Figure 12.10) and therefore, when activated, a variable curvature of the lattice.

The thicker regions have a larger deformation amplitude and "structure" the space by forming the "pockets" that with adequate scale of the surface could be occupied when activated. The behavior of the larger lattice structure can be designed by strategically placing larger and smaller cells across the lattice, which could be then actuated into "ridges" and "valleys" within the surface (Figure 12.11).



12.11 Choreographing the surface movement by changing the lattice cell size/amplitude.

The key features of the proposed variable lattice structure are its controllable rigidity, light weight, and asymmetrical shape change. The movement of the proposed structure could be symmetrical or asymmetrical depending on the actuator activity, i.e. which area of the lattice is activated. Tristan Sterk writes about asymmetrical deformations of the surface and emphasizes two important reasons why asymmetrical deformation is needed: (1) to respond to sun or wind movement and take advantage of its shape to condition the internal spaces; and (2) to cater to dynamic changes of load transmission through a structure.[19] As shape control is closely related to structural rigidity, an asymmetrical shape would enable the structure itself to respond to unpredictable loading conditions and by doing so improve the range of structural responses. Brian Culshaw suggests that the structure's ability to alter its stiffness rather than its strength is a key feature of any responsive structure.[20] Structure capable of dynamic response to its loads would require less weight, less material, and most likely less complexity. Tensegrity structures are an example of such dynamic responsiveness.[21] According to engineer Guy Nordenson, if a building was designed like a body, with a system of bones, muscles, and tendons and an ability to change its posture,

tighten its muscles, and brace itself against wind, its structural mass could be cut in half.[22] As Sterk states, "Asymmetry enables loads to be transmitted along several dissimilar paths whereas symmetrical responses do not."[23] An asymmetrical shape control would enable the structure itself to respond to unpredictable loading conditions, and by doing so improve the range of structural responses.

In naturally constructed materials, information travels through integrated material layers – functional needs inform the material and structural distribution. This is facilitated by the lack of discrimination between material and structure as well as between structural and functional materials. Such a logic of integration was important in the development of the physical prototypes of the lattice, in which the shape memory alloy is used to integrate the actuator and the building material of the surface into a single system that works in unison.

The *Agile Space* and its occupiable spaces are envisioned as interacting with the environment and people, i.e., they would not just react. Kas Oosterhuis points out that a two-way relationship between the user and the structure is extremely important to avoid the notion of simple interactiveness.[24] The key to achieving this is to exchange information in both directions and engage not only the control and actuation of the motion of the physical structure but also to include human behavior input.[25] Cohen de Lara and Hubers use game software to organize the dynamic relations between the input received by the sensors and the output from the behavior of the structure itself.[26] With this dynamic feedback, their *Muscle Body* interactive architecture project becomes constantly aware of the movement of the occupant's body. At the same time the occupant perceives that the body movement is shaping the behavior of the space. When this is achieved, an adaptive structure/space could have a transformative effect on participants and on the environment itself.

As John Frazer argues, architecture should be a living, evolving thing.[27] A truly responsive environment would enter into a "conversation" with its users and allow them to become participants. In other words, such an environment should not only sense and respond but also perceive and act.[28] Design of

spaces that actively engage with their users goes beyond form and space delineation and requires the design of complex behavioral and informational systems.

To engage people, the structural lattice of the *Agile Space* is extended by the inflatable soft robot surface that augments and amplifies the movement, as described earlier. This soft surface addresses the issues of human comfort and through its gentle movements reacts to the human body. The surface is activated by registering personal mobile devices and the duration of their presence in its proximity. When activated, the structure gently moves, offering a shelter, privacy, or passage. Sensors are distributed throughout the surface. They are grouped into several networks, for internal surface control, external sensory input, and internal sensory input feedback. The behavior of the surface is programmed through the integration of the three networks. The networks exchange information, and control and activate the "intelligence" of the surface. Internal surface control enables the surface to collect physical information from the environment (temperature around the surface), to process this information, and to regulate the heating by activating motion within the surface. Movement of the surface produces and captures the heat generated by the SMA embedded in it. That movement is directly related to the physical inputs and outputs and does not involve any human behavior input. The movements initiated by the internal surface control are relatively uniform across the surface and do not produce significant deformation. External sensory input is generated by registering the presence of mobile devices. That input responds to the number and proximity of people; the surface responds to this input with more dramatic deformations, revealing and forming spaces. The user information feedback is correlated to the behavior of the system through an adaptation algorithm defined by the physical behavior of the kinetic system.

The constantly changing information creates and recreates the physical behavior of the structure, its form, and its temperature in response to the physical conditions of the environment. In this context, the surface is not limited to its traditional role of property demarcation, delineation of prescribed program, or limitation of movement. Its new functionality as a

"thick" surface and its capacity to produce heat enable it to act as an attractor for people and activities. Through a dialog with its surroundings, the surfaces determine the movement of energy and shifting of phenomena, creating an environment that does not have to be enclosed to provide a comfortable place for activity. Like Banham's campfire,[29] the regions of the surface mediate the external environment by generating heat. The only boundary is the perceived extent of the field of radiated heat. This environment is in constant flux, its size determined by the interplay of the released energy and the air temperature. This is not a stable environment; to be in this thermally modulated space one has to accept its fluctuating thresholds. This reflects a broader commitment to suspending a notion of finding a non-permeable and clearly defined boundary between inside and outside in exchange for a surface that fosters a constant flow of information, matter, and energy.

Conclusion

One of the most interesting challenges of this project was constructing an architectural assembly that integrates and fully utilizes the capacities and properties of smart materials. One of its main objectives was that the functional qualities of smart materials and the technologies that transfer energy and/or information would have to achieve a full overlap and integration with the structural functions of a material system necessary for architectural applications. That way, the change of scale, currently one of the greatest challenges in the projects of this kind, could be more effectively addressed. Given the relatively small size of SMA materials that are currently available on a commercial scale – and their relatively high cost per unit of material – the project's focus was experimentation with the accumulated effects of discrete movements of the system's components to produce a larger global effect on the entire system, i.e., its surface.

The agile spaces would do many things. They could change their functionality, perform several functions at the same time, change form and

physical location, harvest and distribute energy. As Tristan Sterk suggests, employing feedback as a new way of form generation affords architects a way to conceptualize a new kind of architecture that ties users' needs and actions directly to architectural form.[30]

Shifting situations and changing needs are evident not only in the dynamics of natural world but also in those of contemporary society. Adaptation as a transformation through time can address these indeterminate changes. To do so, however, this "constructed" adaptation should operate through responsive and flexible systems whose organization is based on resilience and feedback. Designing with responsiveness and flexibility as a basic principle could be, on one hand, an effective overall design strategy to integrate a project into the "life" of its larger ecology; on the other hand, such an approach could be employed in designing receptive and "intelligent" systems that can accommodate physical and material change and behavior and can be integrated into non-adaptive models.

Notes

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2 Eastman, Charles, "Adaptive-Conditional Architecture," in Cross, N. (ed.), *Design Participation: Proceedings of the Design Research Society Conference* (London: Academy Editions, 1972), pp. 51–57.

3 See Chapter 1 by Branko Kolarevic in this book.

4 See Chapter 18 by Enric Ruiz-Geli in this book for a detailed description of the *Media-TIC* building.

5 Matson, John, "Shifty Science: Programmable Matter Takes Shape with Self-Folding Origami Sheets," *Scientific American*, June 28, 2010. Also available at: www.scientificamerican.com/article.cfm?id=computational-origami-robot.

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7 See also Chapter 10 by Skylar Tibbits in this book.

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10 Armstrong, Rachel, "Systems Architecture: A New Model for Sustainability and the Built Environment using Nanotechnology, Biotechnology, Information Technology, and Cognitive Science with Living Technology", *Artificial Life*, 16(1) (2010): 73–87.

11 Ibid.

12 Frazer, John, *Evolutionary Architecture* (London: Architectural Association, 1995).

13 www.achimmenges.net.

14 Ibid.

15 See Chapter 14 by Philip Beesley in this book.

16 The project was developed collaboratively by Arup, SSC Ltd., and Colt International.

17 The project was developed as part of the Royal College of Art's Innovation Design Engineering course in collaboration with Tufts University Silk Lab.

18 Frazer, op.cit.

19 Sterk, Tristan, "Shape Control in Responsive Architecture Structures," in *Proceedings of 4th World Conference on Structural Control and Monitoring* (4WCSCM) (San Diego, CA, 2006).

20 Culshaw, Brian, *Smart Structures and Materials* (Boston, MA: Artech House, 1996).

21 See Chapter 9 by Tristan Sterk in this book.

22 Davidson, Cynthia, "Three Engineers [Sitting around Talking]," in Davidson, C. (ed.), *ANY: Architecture New York*, no. 10 (New York, Anyone Corporation, 1995).

23 Sterk, op. cit.

24 Oosterhuis, Kas, "Introduction/Editorial," in Oosterhuis, K. and Xia, X. (eds.), *iA1 – Interactive Architecture* (Rotterdam, the Netherlands: Episode Publishers, 2007).

25 See also Chapter 17 by Kas Oosterhuis and Ilona Lénárd in this book.

26 Cohen de Lara, M. and Hubers, H., "Muscle Body Interactive Architecture," in Oosterhuis, K. and

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28 Fox, Michael, and Kemp, Miles, *Interactive Architecture* (New York: Princeton Architectural Press, 2009).

29 Banham, Reyner, "A Home Is Not a House," *Art in America*, 2(2), 1965.

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13
Exploring Responsiveness in Architecture

VERA PARLAC

An increased interest in exploring the capacity of built spaces to respond dynamically and adapt to changes in the external and internal environments is technologically and socially motivated. Advances in embedded computation, material design, and kinetics on the technological side, and increasing concerns about sustainability, social and urban changes on the cultural side, provide the background for the adaptive architectural solutions that have started to emerge.

Thanks to current technological advances, a broadening of scientific knowledge, and an understanding of the underlying processes that govern the metabolisms of the natural world, we are able to see deep connections between the made and the natural worlds. The confluence of various technologies and their assimilation are altering the way we perform our activities. Technological and scientific progress is re-calibrating architecture's engagement with temporality and change. It seems that now we can expect more from architecture. We can expect buildings not only to house and facilitate various modes of human activity but also to adapt, behave, respond, and accommodate the flows of energy and information. Blaine Brownell calls for an architecture imbued with foresight; for him, "Foresight shapes architecture that, like life itself, produces as well as consumes, reincorporates all of its waste, and maintains an ecological footprint in balance with the requirements of its context."[1] According to John Frazer, architecture should be a "living, evolving thing."[2] For them and others who share similar views, building and consuming architecture should be seen and practiced as life-

sustaining metabolic processes. This view of architecture as a responsive and productive participant in a larger ecology is fueled, on the one hand, by "material shifts occurring in the domains of energy, resources, and technology"[3] and, on the other, by grasping a deeper connection between biological and cultural systems.

Architecture, Time, and Environment

In a recent essay on responsive environments, Chris Perry examines the origins of architecture's involvement with temporality.[4] According to Perry, these were grounded historically (over centuries) in new developments in technology and science and a mindset these changes brought forward. Dividing the last hundred years into three machine ages, Perry lists technologies that progressively shifted a view of architecture from representation to instrumentality. First, machine age architecture borrowed from the dynamism of large-scale machines and factories – it captured the representation of the temporality.[5] According to Perry, the work of Antonio Sant'Elia, a member of the Italian Futurist movement, and his *La Città Nuova* responded to the temporal phenomena by integrating architecture into the mechanical and circulation networks of the city and did so on a spatial level; architecture itself, however, remained static. For Perry, second machine age architecture, as manifested in Cedric Price's *Fun Palace*, Archigram's speculative imagery, and Reyner Banham's writing, was an environment populated by electronics, communication technology, and audio/visual media. While *La Città Nuova* addressed movement and change by orienting architecture towards flows and interaction, Cedric Price's *Fun Palace* instrumentalizes a programmatic change by allowing movement and change of architectural elements.[6] At the same time, Reyner Banham's arguments for the inclusion of environmental phenomena and their variability in a design process began to orient architecture towards adaptive environments. Perry then describes the third machine age architecture as influenced by software,

information, multi-media technology, robotics, and material science.[7] All those technological advances enabled explorations of dynamic qualities and their effects on architecture, offering an opportunity to position architecture towards a more productive integration within larger ecologies.

Michael Weinstock discusses the growing interest in the dynamics of fluidity through the concept of nature as a source of interrelated dynamic processes.[8] His studies of metabolisms are aimed at the development of metabolic morphologies for buildings and cities whose organizations and systems are correlated to those of the natural world. Weinstock's work extends the arguments put forward previously by John Frazer in his seminal book, *Evolutionary Architecture*, in which he suggests a new form of designed artifact, one that is interacting and evolving in harmony with natural forces, including those of society.[9] The metabolic morphologies that "relate pattern and process, form and behavior with spatial and cultural parameters"[10] would support a symbiotic relationship of architecture with the natural world.

The idea of coupling the responsive technologies with the emergence of constructed metabolic morphologies opens the possibility of an intelligent, environmentally sensitive built environment that is connected to metabolic networks. Recent explorations in materiality and material processes (as seen, for example, in the work of Achim Menges, Neri Oxman, and Rachel Armstrong), architectural assembly and its construction (as shown in Skylar Tibbits' projects),[11] as well as localized control of the interior environment (as argued for by Michelle Addington)[12] further this idea by projecting fundamentally different attitudes towards materialization, form, performance, and construction of the built environment. New content for architecture is being formulated that relies on the integration of change and dynamics into architecture – dynamics that not only address kinetic movement but also include flows of energies, material, and information. Buildings that could sense and interact with its environment can operate more synergistically within larger ecologies and therefore can move closer to more sustainable participation within the global environment. The responsive architectural systems could act as ecologies in themselves, allowing architecture as a discipline to recalibrate its role in the larger socio-economic context by

becoming a more intelligent and operative participant – a participant imbued with foresight.

Information, Energy, and Material

As mentioned earlier in this chapter, John Frazer proposes a new form of a designed artifact, one that is interacting and evolving in harmony with natural forces, including those of society.[13] To achieve that, architectural systems, components, or surfaces should have not only a level of kinetic capacity but also capacity to support information transfer, energy transfer, and material transformation similar to biological systems.

The relationship between information and the physical response of an adaptive structure is supported by the application of sensors and actuators as well as mechanisms that control and activate the intelligence of the physical environment. Gordon Pask emphasizes architecture's "operational" capacity (and its "intimate relationship" to cybernetics) by pointing out that "architects are first and foremost system designers."[14] From the organizational and operational aspects, the focus on architectural systems supports the idea of the flow of information. Several concepts developed in the late 1960s and early 1970s, such as Cedric Price's *Fun Palace*, Nicholas Negroponte's *Soft Architecture Machines*, and Chuck Eastman's concept of "adaptive-conditional architecture",[15] began to explore "intelligence" and the programmability of architecture's processes and spaces in order to form a two-way relationship between spaces and users. When a two-way relationship between the user and the structure is achieved, an adaptive structure/space could have a transformative effect on participants and on the environment itself. A truly responsive environment would enter into a "conversation" with its users and allow them to become participants. In other words, such an environment not only should sense and respond but also perceive and act.[16] The design of spaces that actively engage with their users goes beyond form and space

delineation and requires the design of complex behavioral and informational systems.

On the one hand, energy transfer relates to the capacity of the built environment to sustain itself through energy harvesting. Such functions, as material system morphologies are developed, could be integrated into materials and the skins of buildings. On the other hand, energy transfer relates to the capacity of the built environment (its surfaces and regions) to facilitate movement and the concentration of some forms of energy (heat, light) in order to form the phenomenological, non-physical boundaries of spaces. By forming micro-climatic regions, spaces could densify and generate nodes of activity and gathering.[17] This presents the challenge of finding a non-permeable and clearly defined boundary between inside and outside in exchange for a surface that fosters the constant flow of information and energy.

Rayner Banham reminds us that there are two basic ways of controlling the environment: by hiding under the tree/tent/roof (in other words, by building a shelter) or by mediating the local environment by a campfire.[18] He points out that "a campfire has many unique qualities which architecture cannot hope to equal, above all, its freedom and variability."[19] The most recent attitudes to environmental control – where conditions are mediated locally and not globally and in relation to a body and not space – are a testament to this. This is achieved through material that does not need thermal mass but regulates the heat exchange inside a thin zone of a few millimeters.[20] But a "campfire" as a source of heat and light is localized and specific to its placement within the space. If we think about it beyond its traditional form – and in relation to energy exchange – we can imagine it as a distributed system that can be activated locally and "intelligently," and only where needed. Viewed in the context of flow and exchange, a "campfire" can become an intelligent surface that can thermally modulate the environment and through that facilitate the circulation and gathering of people.

Current technological achievements as well as the expansion of our understanding of the underlying processes in nature have brought about a

new generation of materials that are capable of "decision-making" beyond simple reflexivity.[21] These materials, products of synthetic chemistry and biosciences, are capable of material or chemical "computing." A material transformation is triggered by the molecules' ability to make decisions about their environment and respond to it by changing their form, function, or appearance. The availability of such materials offers an opportunity to design material behaviors as opposed to choosing materials on their properties. This would certainly alter the way we design: it would require that we begin to relinquish control of the design process (understood in a traditional way) and find ways to channel the material transformations to produce equally rigorous and reliable architecture, but only more aligned with its own materiality and larger ecologies.

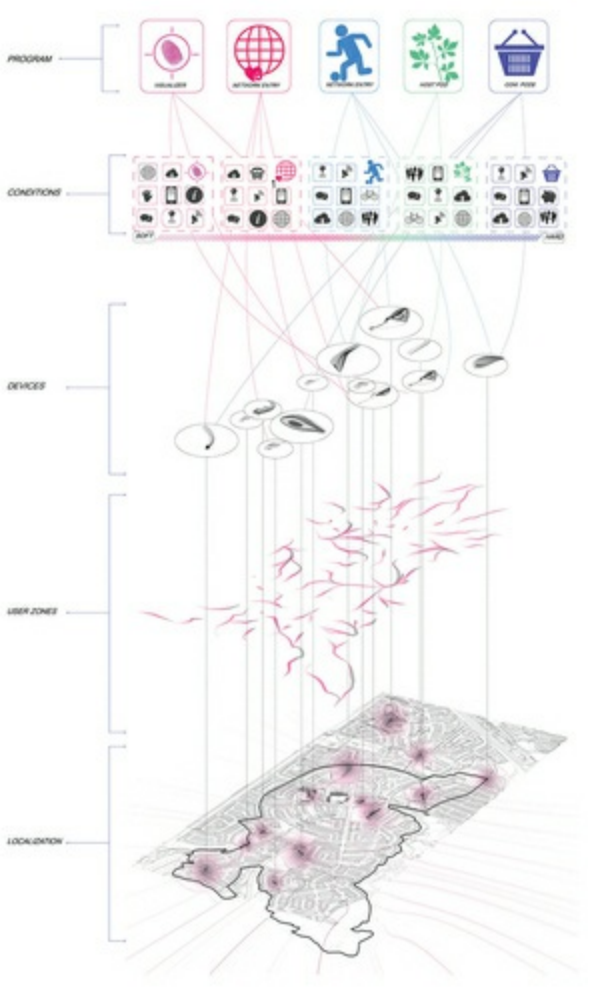
Designing Responsiveness

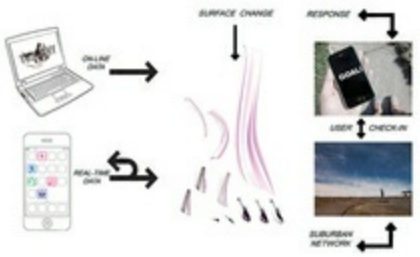
Responsiveness can be achieved at different scales, from the city and buildings down to a single space or surface. But how would omnipresent responsive environments change architecture's role in the cultural fabric of the society? They would certainly give rise to new social dimensions, enabling new forms of social communication that would emerge from new opportunities of operating within a humanized, technologically augmented space that is dynamic, sensing, and more "alive" than ever before. How would we live in spaces that like very comfortable clothes (or not) respond to our movements? Can we leave the orbit of "fixed", static architecture and interface fluidly with kinetic and changing environments?

The process of designing responsive environments relies on flows and dynamic behavioral patterns. It is inherently open to new and oftentimes emergent configurations. Cities populated with "intelligent" buildings that communicate among themselves, capable of altering and changing patterns of use, would generate a constant information feedback. "Intelligent and sensitive" streets, walkways, and public spaces could, by varying

environmental phenomena such as light, heat, or coldness, create microclimatic zones that attract and encourage particular human activities. Metabolisms behind those changes could create densities of activities that relate to constantly changing networks of information that redirect patterns of movement. This new "intimacy" between the built environment and human movement and the occupation of space can extend into new relationships between the built environment and the larger ecology, through energy, resource, and material exchange.

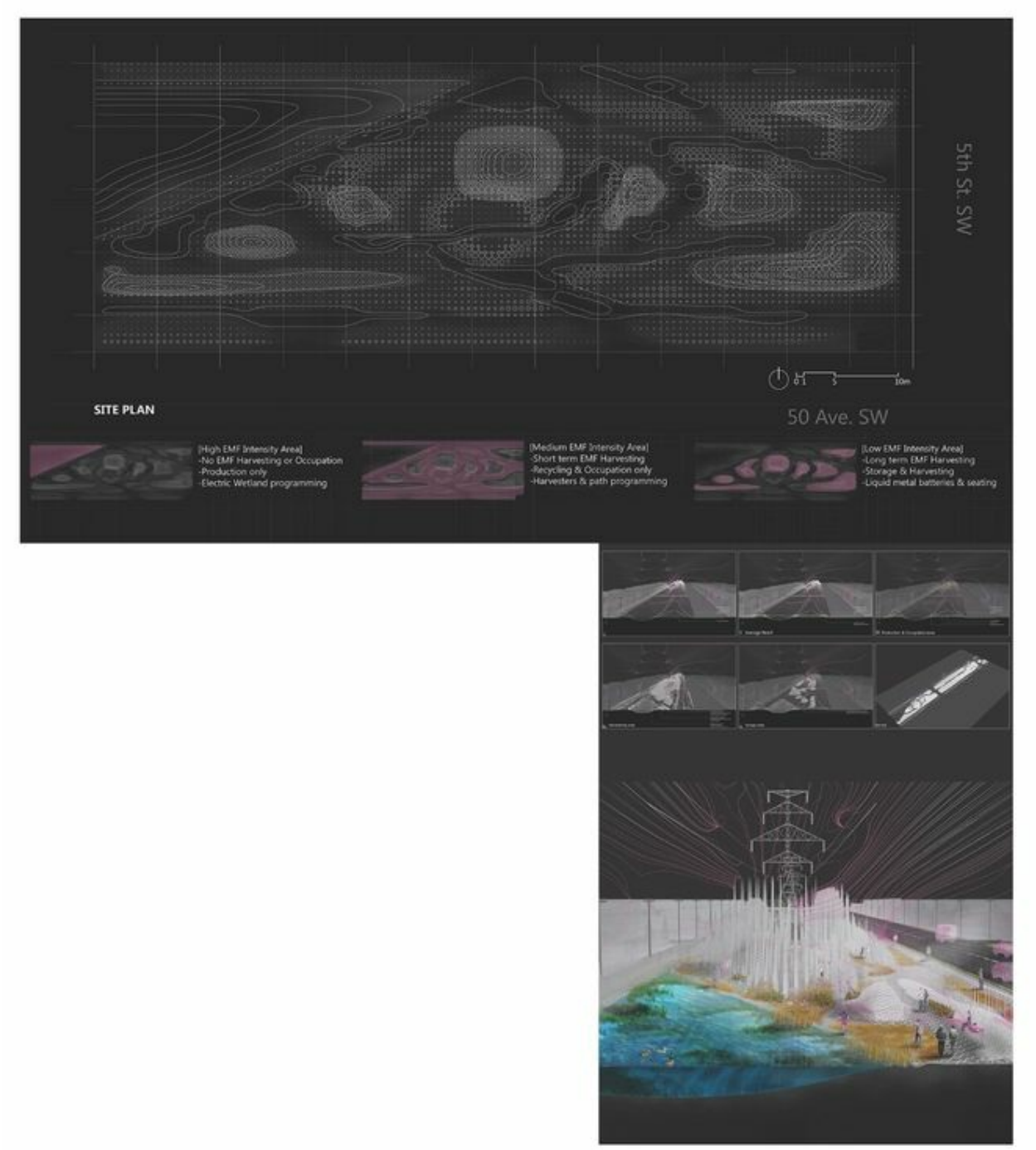
The student projects that follow explore responsiveness in a variety of ways and at very different scales. The goal of each project was to develop strategies and attitudes to engage natural or manufactured processes directly in a design process; to work and design with these processes in order to form a productive relationships between an intervention, its users, and its environment; and to deploy technologies through the projects in order to speculate on future architectures and organizations that would emerge as a product of the fusion between architecture and technology.


PROGRAM
CONDITIONS
DEVICES
USER ZONES
LOCALIZATION


SURFACE CHANGE
RESPONSE
USER CHECK-IN
SUBURBAN NETWORK

13.1a–c *Suburban Remediation* by Andrea Patry.

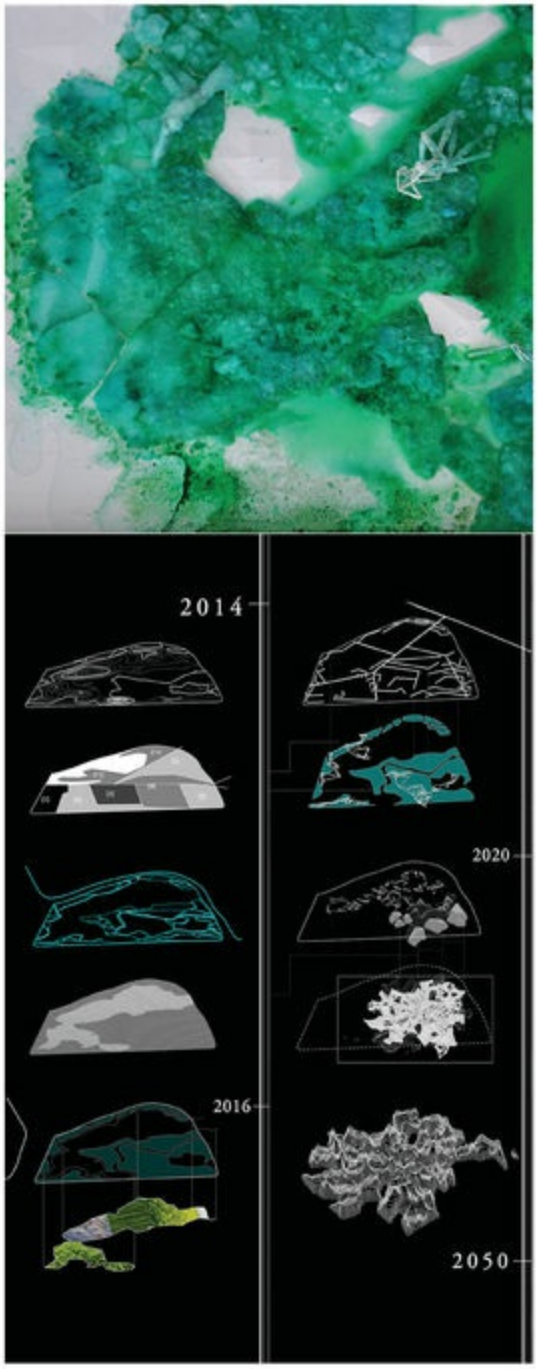
Suburban Remediation project (Figures 13.1a–c), by Andrea Patry, proposes a networked territory based on programmatic hybridization and spatial dispersal of a community center. This new form of community center promotes momentary intimacy by integrating virtual social networks and physical space through a personal device, such as an iPhone. A new typology of architectural devices emerges in places where repeated patterns of use and circulation generate a programmatic opportunity. This crowd-sourced landscape of activities overlaps with the physical space. It fragments the existing network of pathways and public spaces to form a new fluid networked spatial infrastructure that is related in real time to the intentions and desires of its inhabitants. The new infrastructure enables users to understand at a glance trending information according to distance and time – by marking the traces of use through the community. These devices range from items that visualize the levels of activity present in the community to those that actually attempt to remediate the lack of activity and interaction in these areas. Entering the network induces a desire to wander and to claim the space of the other, enabling the users to take control of the dynamics of the public realm.



13.2a–c *Charged Landscapes* by Jose Trinidad.

Charged Landscapes (Figures 13.2a–c), by Jose Trinidad, takes advantage of under-utilized sites that intersect with high-voltage transmission routes passing through the city of Calgary. The project charts the network of electromagnetic energy and attempts to overlay new morphologies and

metabolisms upon existing single-purpose energy infrastructures. Diagraming the form and flux of the electromagnetic boundaries around high voltage transmission lines reveals patterns of consumption, the potential of harvesting wasted residuals, and its hazards to health and the environment. Through this process, zones of energy production, storage, recycling, and human occupation are established. Together, these zones synthesize into productive, connective, and charged landscapes. The project attracts public interaction and participation by creating regions for human occupation that mediate the external environment by generating heat. Spaces delineated in this way are in constant flux; their sizes are determined by the interplay of released energy and air temperature. This is not a stable environment; to be in such a "thermally modulated space,"[22] one has to accept its fluctuating thresholds.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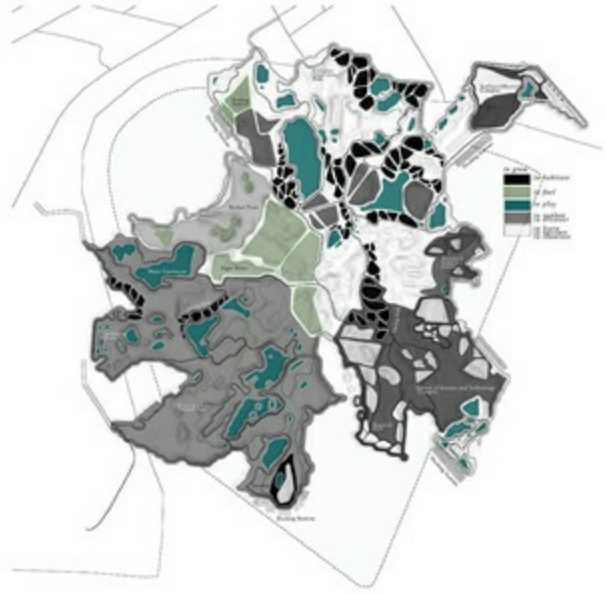
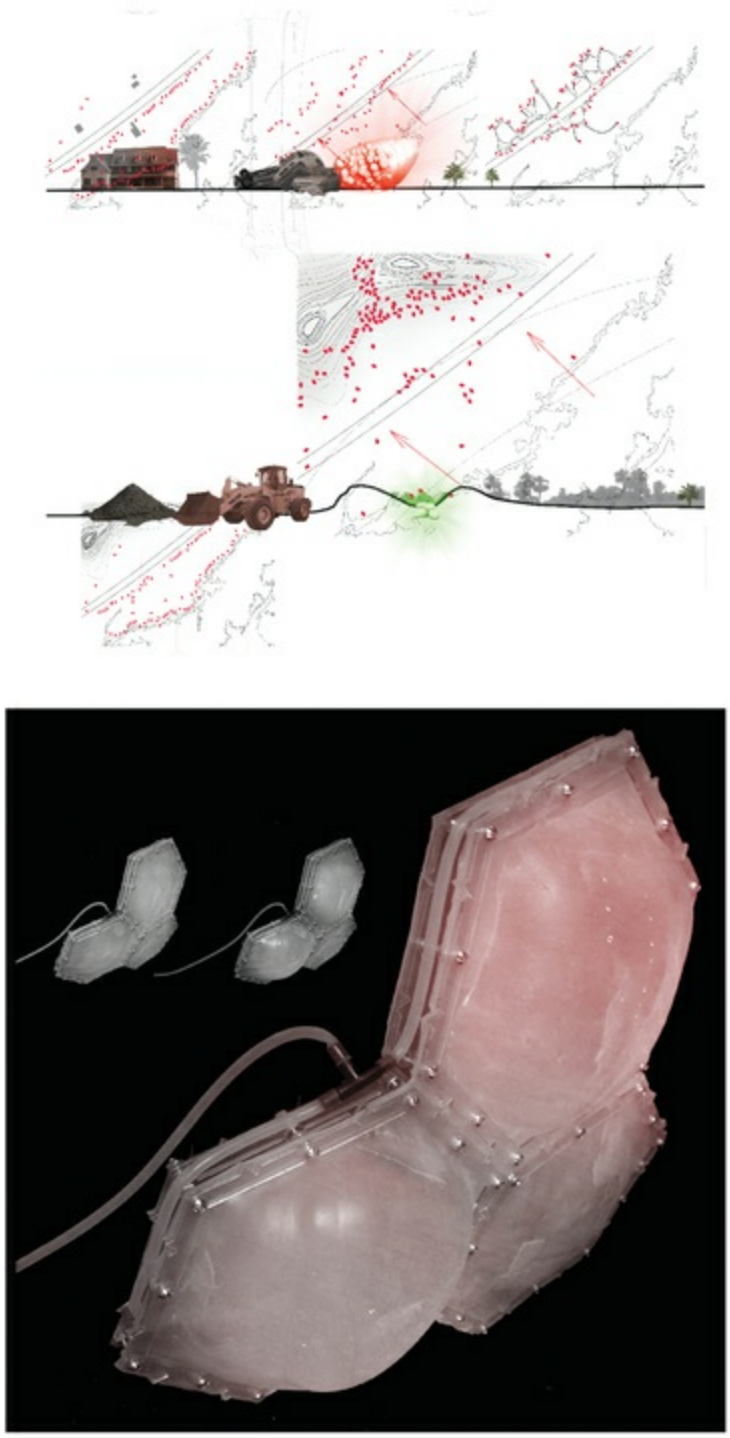


13.3a–c *Urban Reef* project by Caitlyn Browning.

The *Urban Reef* project (Figures 13.3a–c), by Caitlyn Browning, is conceived as a remediation of a heavily polluted industrial area in Detroit. It relies on synthetically produced protocells that use pollutants to produce matter that provides a new ground and building material for the site. The project is supported by current research in synthetic biology and a capability to produce synthetic "organisms" that could be programmed to consume and gravitate towards specific substances or conditions. The protocells are distributed throughout the polluted terrain by following the topography and the level of pollution. The density and the distribution of the growth are further channeled through an infrastructure that supports its hardening and is integrated into the topography of the site. The emerging landscape is a product of all those forces as they work across the site. The infrastructure distribution is related to the projected program that evolves over a long time period. Nothing in this project is entirely predictable. An emphasis is placed not on the design of the landscape but on facilitating processes that will generate the new ground. The program alters, based on the shifting activities and the densities of the activities that form and disappear as the ground changes. The infrastructure mediates and forms the terrain so that at different

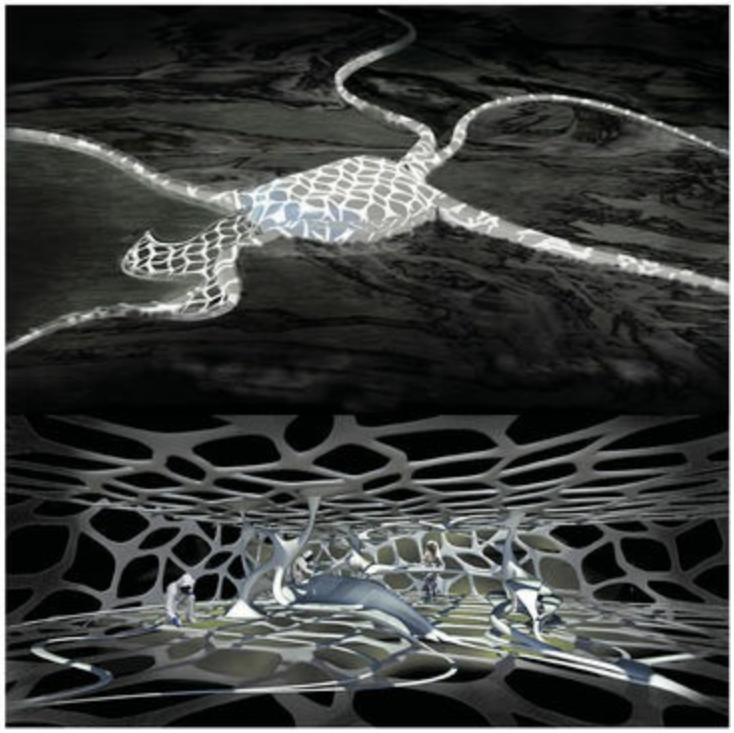
phases of its formation it could support specific activities related to recreation and research.

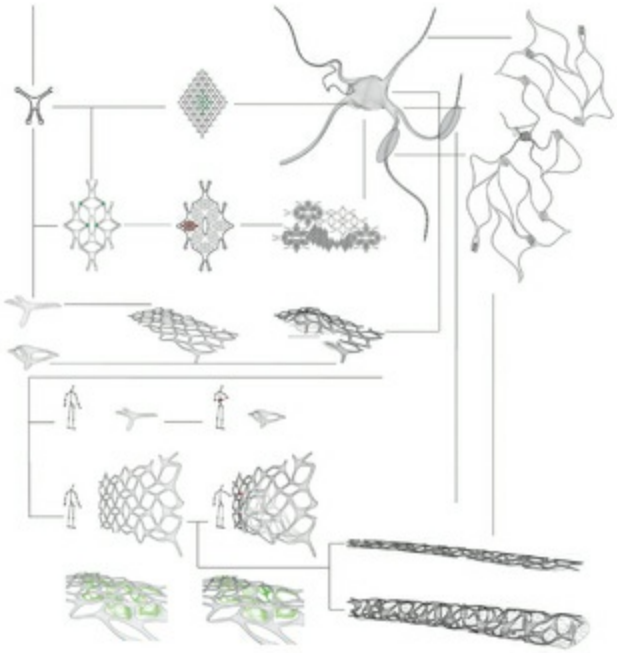


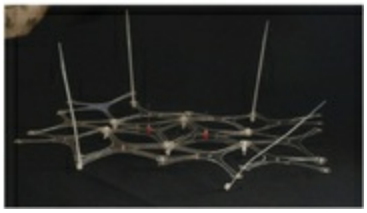
13.4a–e *The Imminent Emergency Defense System* (IEDS) by Kevin Spaans.

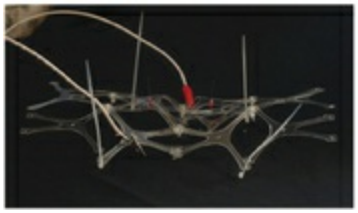
The Imminent Emergency Defense System (IEDS) (Figures 13.4a–e), by Kevin Spaans, is a living pod that endeavors to reverse the accepted inevitability of architectural destruction in regions prone to major meteorological

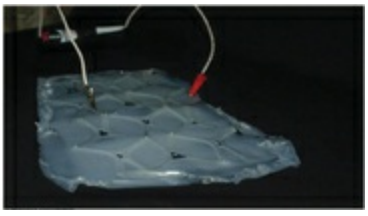
catastrophes. The IEDS living pod supports a system of exterior and interior panels that inflate to cushion and protect the pod against flying debris and during relocation. The panels are connected to a series of internal air pumps that respond to changes in the natural environment and are activated to provide the appropriate level of defense. While the exterior inflates to accommodate the influences of Mother Nature, the interior may be inflated or deflated to accommodate different human spatial demands. Without rigid foundations, IEDS living pods migrate to follow the influence of meteorological catastrophes, thus creating urban landscapes with a true connection to their immediate environment.





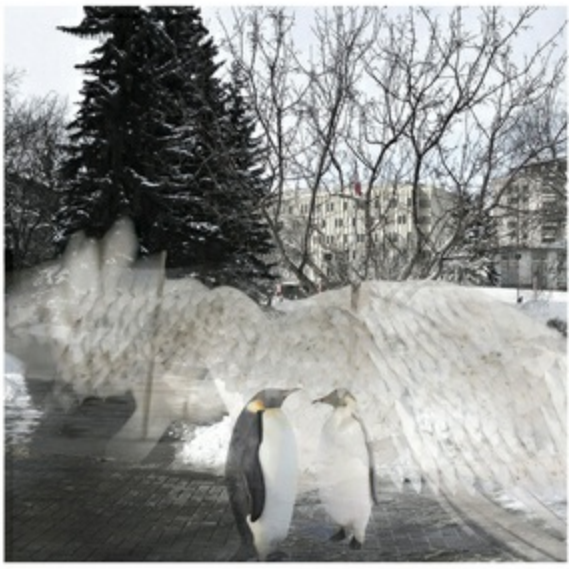






13.5a–d *Remedia[c]tion* by Matt Parker.

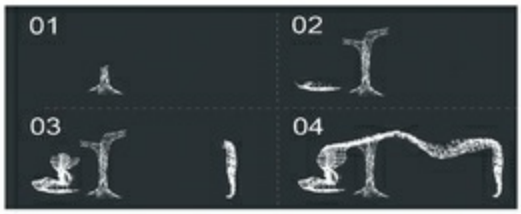
Remedia[c]tion (Figures 13.5a–d), by Matt Parker, is a transportable aquatic disaster relief laboratory and dwelling for deep water oil spill remediation. It consists of a network of flexible pods that can be deployed to help stabilize and clean polluted marine ecosystems. The project explores what it means for architecture to be fully integrated through a responsive system capable of sensing and productively adapting to environmental inputs and inhabitant occupation. The responsiveness of the system is reflected in its capacity to sense the level of pollution and to grow, cultivate, and release algae in response to it. The production of the algae is located in the pod's "tentacles" and certain regions of its surface. The interior area of the pods is a flexible environment capable of adjusting to suit the immediate needs of its inhabitants by sensing human movement and adapting from areas specific to work/ laboratory processes to those of living and relaxing.

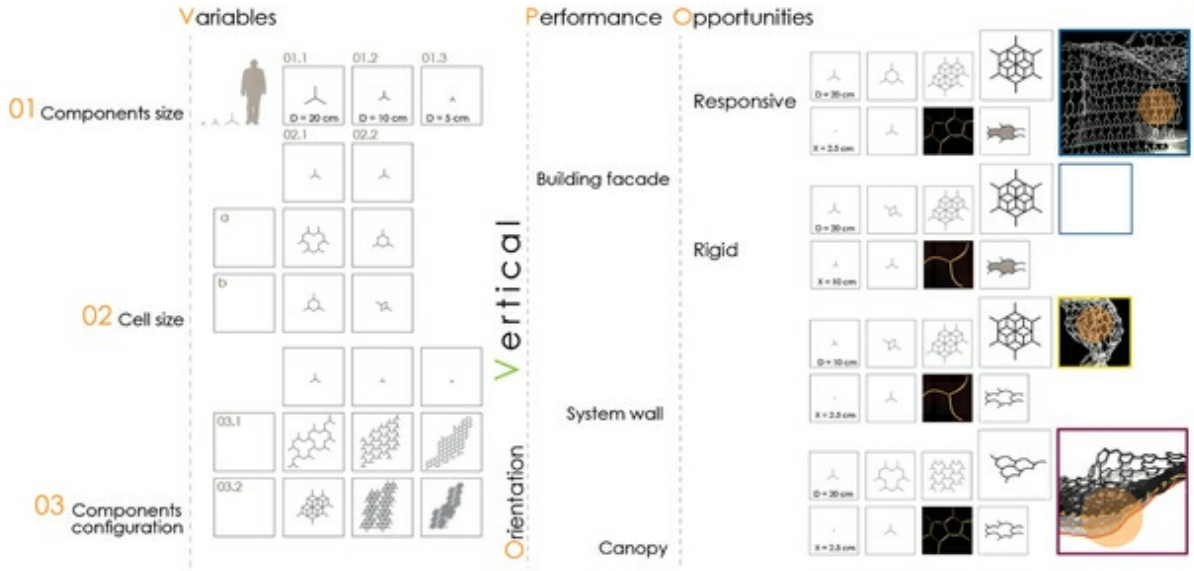


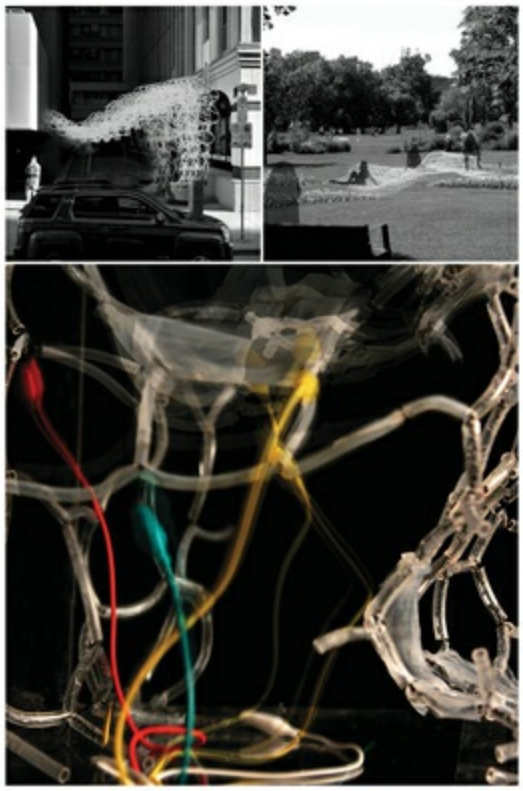
13.6a–d *Huddle Response* by Lindsay Farr.

Huddle Response (Figures 13.6a–d), by Lindsay Farr, is inspired by the adaptability of the emperor penguin to harsh climatic conditions; it proposes a climate-responsive surface/architecture that is implemented in public spaces. An important component of the emperor penguin's survival during the coldest

months of the winter is self-organization, understood through the patterns of movement of the penguin huddle. The penguins move and self-organize in response to the dropping temperature and the increase in wind force, resulting in the formation of a denser huddle. The proposed design is based on an idea that a system of adaptive surfaces that respond to climate and passers-by by tightening or relaxing the surfaces could be distributed in public spaces. They would form a protective layer or sheltered space that would enable outdoor public gatherings and intensify the vibrancy of urban public spaces in the cold climate cities. The material system of the surface is made up of "feather" components that operate in a similar manner to the feather system of the emperor penguin. The outer material layer opens and closes in response to the temperature and wind, allowing air to enter the system and act as an insulation layer. The inner layer acts as a muscle, expanding and contracting in response to the climate and supporting the outer layer to reconfigure itself and adapt to the changing conditions.

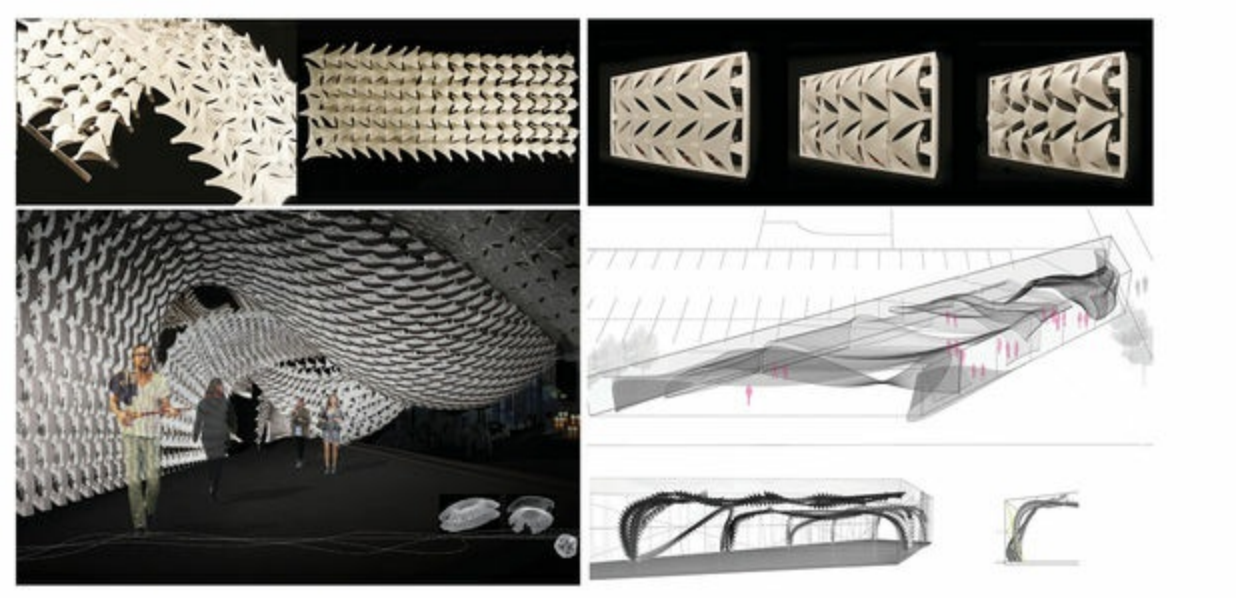




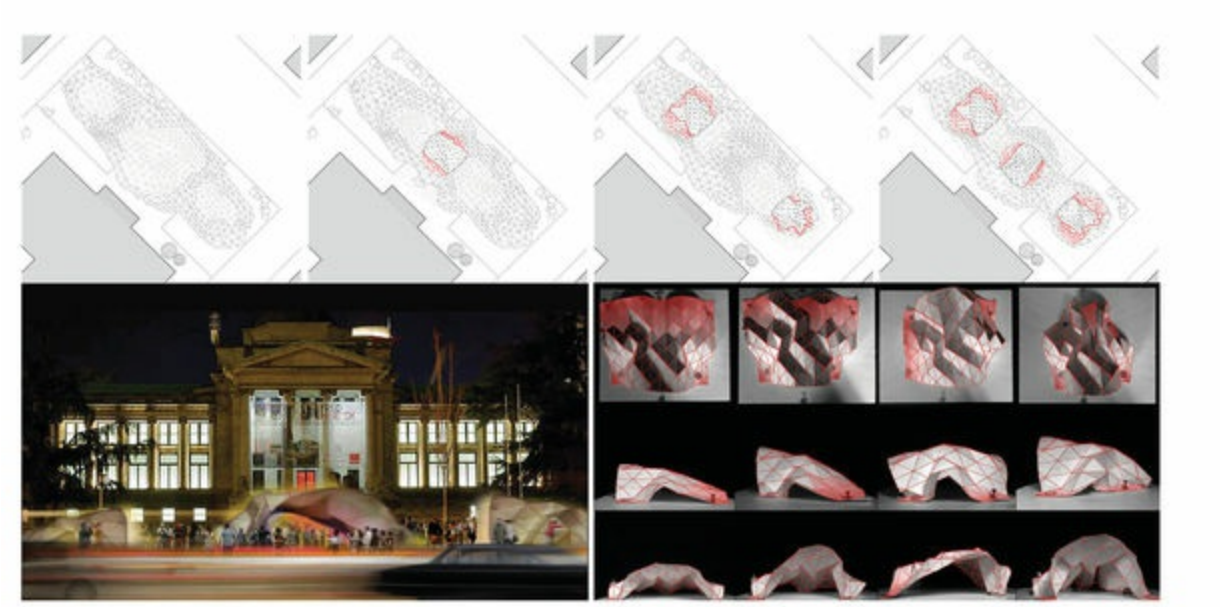


13.7a–e *The Augmentum* by Faria Hamidzadeh.

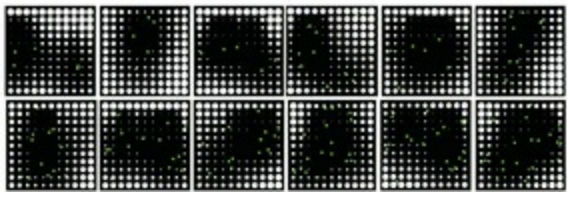
The Augmentum (Figures 13.7a–e), by Faria Hamidzadeh, is an adaptive material system capable of adjusting to a wide variety of spatial conditions. It can be constructed within any public space and serve as a transition between sheltered and open environments. It is easily erected out of a large number of self-similar components designed to enable the "growth" of the system, regardless of the spatial boundaries. By combining the components in a particular way, the system can vary from "soft" to "hard" to provide soft surface conditions as well as hard structural regions. *The Augmentum* can shift between parasitic and self-supporting structure and be constructed in a variety of urban void conditions. The cells of the structure have active or inactive infill. Active infill enables an energy-harvesting capacity that can power regions of the structure. Inactive cell infill provides a seating surface or shading. The project celebrates urban voids by highlighting and capturing human activity – it can be "grown" into a light sculpture, a landscape piece, an active façade, a shelter or a seat.



13.8a–d *Emiliania* by Erin Chartrand.



13.9a–c The *Re-configurable Morphing Surface* project by Julia Baker.



13.10a–c *Swarm Space* project by Bin Tian.

Emiliania (Figures 13.8a–d), by Erin Chartrand, is a transformable space and surface inspired by the study of *coccolithophores*, single-celled algae found in the euphotic zone of the ocean. Referencing the structural accumulation of the *Emiliania huxleyi coccolithes* as well as the bloom patterns of this phytoplankton, the architecture flows through motion as a breathing

mechanism locally within each surface component and globally through the strands of these components that make up the responsive spatial condition. The surfaces respond to occupancy and, depending on the needs, can alter the size and number of spaces allowing for a variety of activities to unfold within the space. The surfaces also enter into a dialog with their occupants by registering and amplifying movement through space.

The *Re-configurable Morphing Surface* project (Figures 13.9a–c), by Julia Baker, explores the capacity of the kinetic triangulated surface to accommodate changing needs and channel activities within a public space. The key premise of the project is that a transformable surface is desirable for several reasons: it enables the use of a public space in all weather conditions, it accommodates specific/ prescribed activities by dramatically transforming space, and it allows a public space to be a dynamic and changeable environment. The main focus of the project was to understand how the surface could be "controlled" and reliably transformed between four different configurations that relate to the program of the space. The study focused on physical modeling and exploration of a material system in order to determine elements of the geometry, structure, and materiality that would enable the desired choreography of space. In this process, the triangulation of the surface was hybridized, the hinging system was altered, and the ground track system proposed to achieve the spatial transitions necessary for the suggested program. The proposed surface would accommodate a varying number of people and provide a shelter for very small or large gatherings. In its inactive form the surface would serve as a traversable topography within the public space. The surface would have active and inactive regions, enabling a variety of spatial and surface transformations.

Swarm intelligence is at the core of the *Swarm Space* project (Figures 13.10a–c), by Bin Tian. The variable boundary adjusts to the collective movement of people and realigns the space to allow for adequate size and the passage of people, producing a dynamic responsive environment.

The changing environments explored in these projects redefine architecture by undermining its claims on stability and stasis. They redefine social

interactions, the flow of activities, and stability at large. Through them, the students have attempted to answer the following questions: If everything can be reconnected, re-grown or redirected, who or what is triggering the change? What is the stimulus and catalyst of this "metabolic process"? How is the role of an architect changing? Is the architect becoming a facilitator or a catalyst of an evolving design?

Conclusion

One can only imagine the scope of social and ecological changes that responsive built environments will introduce over time. Rem Koolhaas reminds us that we are seduced by the neatness of architecture and its capacity to define, exclude, and limit.[23] The level of control within which architecture has operated so far might not be possible or feasible within the responsiveness model. Given that changes in position, use, shape, phenomena, or boundary require transformations of the environment, it might be necessary to begin to think about zones of transition as opposed to instances of control. If we accept change as a fundamental contextual condition, architecture could then begin to truly mediate between the built environment, the people who occupy it, and the larger context. As Ed van Hinte notes, "Instead of being merely the producer of a unique three-dimensional product, architects should see themselves as programmers of a process of spatial change." Thus, the principal task for architects is to create "a field of change and modification" that would generate possibilities instead of fixed conditions.[24]

Notes

1 Brownell, Blaine, "Material Ecologies in Architecture," in Tilder L. and Blostein B. (eds.), *Design Ecologies: Essays on the Nature of Design* (New York: Princeton Architectural Press, 2008), pp.

221–237.

2 Frazer, John, *An Evolutionary Architecture* (London: Architectural Association, 1995).

3 Brownell, op. cit.

4 Perry, Chris, "anOther Architecture: The Responsive Environment," in Lorenzo-Eiroa, P. and Sprecher, A. (eds.), *Architecture in Formation: On the Nature of Information in Digital Architecture* (New York: Routledge, 2013), pp. 181–185.

5 Ibid.

6 Ibid.

7 Ibid.

8 Weinstock, Michael, "Metabolism and Morphology," *Architectural Design,* March/April (2008): 26–33.

9 Frazer, op. cit.

10 Weinstock, op. cit.

11 See Chapter 10 by Skylar Tibbits in this book.

12 See Chapter 5 by Michelle Addington in this book.

13 Frazer, op. cit.

14 Pask, Gordon, "The Architectural Relevance of Cybernetics," *Architectural Design,* September (1969): 494–496.

15 See Chapter 1 by Branko Kolarevic in this book.

16 Fox, Michael and Kemp, Miles, *Interactive Architecture* (New York: Princeton Architectural Press, 2009).

17 This notion has been explored in several student projects described in this chapter.

18 Banham, Reyner, "A Home Is Not a House," *Art in America*, 53(2), April (1965): 75.

19 Ibid.

20 Addington, Michelle, "The Architecture of the Unfamiliar" (2008). Available at: http://fora-.tv/2008/04/17/Michelle_Addington_The_Architecture_of_the_Unfamiliar.

21 Armstrong, Rachel, "Material (or Chemical) Computing: Protocell Example" (2012). Available at:

http://grayanat.posterous.com/tag/protocell.

22 Ibid.

23 Koolhaas, Rem, "Whatever Happened to Urbanism?" in Koolhaas, R., *S, M, L, XL* (with Bruce Mau) (New York: The Monicelli Press, 1995), pp. 959–971.

24 Van Hinte, Ed, Neelen, Marc, Vink, Jacques, and Vollaard, Piet, *Smart Architecture* (Amsterdam: 010 Publishers, 2003).

14
Diffusive Architecture: A Manifesto

PHILIP BEESLEY

14.1 The spherical forms of dew and raindrops demonstrate the optimum of minimum enclosing envelope with the maximum enclosed mass.

Introduction

In this discussion, I pursue a relationship with the environment embodying the forms of diffusion and dissipation. Seeking essential qualities of emplacement affording subtle phenomena and expanded physiology and measured by mutual relationships of exchange, I will try to articulate a

manifesto for architectural design that offers near-living qualities. Rather than polarized working methods that follow only centrally controlled or opposing emergent, incremental models of organization, the fields of the method demonstrated here oscillate. An undulating, quasi-periodic method is evoked by the forms embedded within the projects illustrated here. Deliberate ambivalence is inherent in the approach, yielding qualities where things convulse and stutter in emerging vitality. This personal approach results in shifting boundaries that fluctuate between hard facts and hopeful fictions for exploring the future.

Ilya Prigogine, the great twentieth-century physicist, proposed dissipation as a key term for understanding how materials could interact in a constantly evolving and self-organizing world.[1] Prigogine's thought has special value for architectural design, offering a dramatic contrast to embedded traditions. Western architecture has been dominated for the past two millennia by paradigms of durability, clarity, and stability, enunciated by the first-century Roman Vitruvius in his famous paradigm of "*firmitas*." Vitruvian design education has in turn tended to preserve the ruling philosophy of his Greek predecessor, the philosopher Plato, whose maxims encouraged architecture to harmonize with the natural foundations of the world by following elegant reductions of primary geometry.[2] Applied to architecture, the reductive geometry of Plato's pure circles and simplified crystalline perimeters tends to favor the minimum possible envelope and the maximum possible territory enclosing interior territory. Inspiring such design, pure, reductive geometries can readily be seen within many aspects of natural form finding, exemplified by the space of dewdrops and raindrops (Figure 14.1).[3] Yet the reductive form language that guides such efficiency also makes a mechanism for resisting interaction. The sphere of a raindrop is indeed a reductive machine that rejects interaction. The surface tension of the meniscus encircling a drop of rain pulls inward, and the result is a kind of optimum where the least possible exposing surface encloses the greatest possible mass within. In proportion to its interior volume, there can be no less surface for interaction than that of a sphere. The potency of that equation can hardly be overestimated in its

influence on the practice of design.

14.2 Frost crystals demonstrate dissipation of thermal energy in their branching crystalline forms.

Similar equations guide the design of a fort that protects, a bullet that pierces, or a bathysphere that can fight the radical forces of the deep. As if guided by a moral compass founded in equations of distillation and purity, Western traditions of architecture have tended to value these kinds of pure forms.[4] The resulting architecture tends to seek strength and stability, resisting disruption. Yet why need we assume that the perfectly balanced optimum of a spherical drop of rain is obviously better than the alternate optimum offered by energy-shedding delicate outward-reaching branching spines that radiate from a frozen snowflake? Why, when we think of the myriad of forms that the natural world has offered, should we prefer closed, pure, gloss-faced cubes and spheres to tangled, dissipating masses of fertile soil?

The reductive form-languages of Platonic solids achieve the maximum possible territory and the maximum possible inertia by minimizing their

exposure to their surroundings.[5] Such forms can be effective in a cold climate that requires the retention of energy. However, cooling requires the opposite. The opposite of a spherical raindrop appears in the form of frost crystals and snowflakes (Figure 14.2). Snowflakes epitomize dissipation, optimizing release through an efflorescence of exchange with constantly unfolding bifurcations determining unique configurations as their thermal reactions expand. Such a form offers a strategy for a diffusive architecture in which surfaces are devoted to the maximum possible intensity and resonance with their surroundings. In turn, following Prigogine, the series of installations and assemblies documented in this chapter explore the opposite of reductive spheres and unified crystals. This diffusive architecture pursues qualities similar to those found in veils of smoke billowing at the outer reaches of a fire, the barred, braided fields of clouds; torrents of spiralling liquids; mineral felts efflorescing within an osmotic cell reaction. Such sources are characterized by resonance, flux, and open boundaries lying far from equilibrium.

Gases, Fluids, and Membranes

In the natural world, complex systems undergo constant states of perturbation, which generate disequilibrium. Uniformly organized materials can "bifurcate" and take alternative potential forms reacting to changes in energy. Simple fluids affected by a change in thermal energy can dissipate to a new state through thermal conduction, moving through states far from equilibrium.[6] Prigogine offers the example of a snowflake as an exemplary dissipative form

> [where] small vibrations around regularly arranged spatial positions … may lie at the vertices of a cube, or the vertices of a regular hexagonal prism and the centers of their hexagonal bases … a case of equilibrium-mediated emergence of order belonging to the class of phase transitions, an important class of natural phenomena that are largely responsible for the polymorphism of matter …[7]

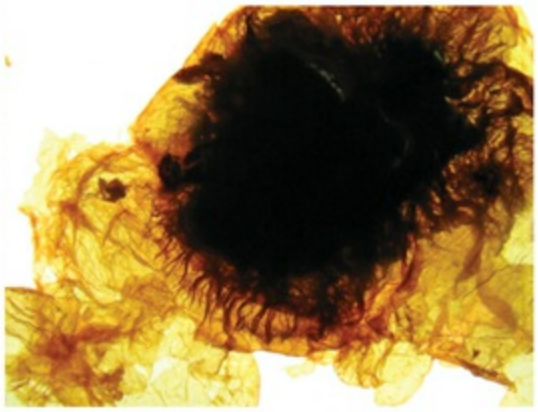
Following the need of sheltering enclosures to alternately retain and shed

heat, the kind of diffusive form-language embodied within snowflakes offers a paradigm of involvement with their surroundings.

Rather than prioritizing enclosed territory and maximum defense, a form like that of a snowflake seems instead to seek a maximum of involvement through its expanded perimeters. Such forms might instruct the design of new batteries, or perhaps can make more efficient bio-generators modeled after the reticulated interior membranes of mitochondria in human cells. By increasing exposure and engagement with the world, such radical exfoliation can also offer a paradigm for building design. At the scale of architecture, such principles might offer alternatives to the conception of enclosing walls and roof surface, reconceiving those surfaces as deeply reticulated heat sinks, and as layered interwoven membrane curtains that modulate the boundaries between inner and outer environments. A new form language of maximization and engagement implies that design may in turn embrace a renewed kind of stewardship.[8] Such a role replaces the sense of a stripped, Platonic horizon with a soil-like generation of fertile material involvement with the world.

Following Prigogine's conceptions, air, gas, and fluid can act as design media for architecture. The American mechanical engineer Michelle Addington suggests how energy flows around the body and buildings can be addressed in thermodynamic exchanges, exposing the dynamic of convective plumes around each of us and extending this dynamic into architectural scales.[9] Rather than regarding the air as a void, this approach implies that air is an addressable medium for designers. In contrast to prevailing Modern conceptions of space as a neutralized void, the matrix lying between objects may be seen as populated and structured. This sense of effusive matter also extends to the cell. The US-based cancer research of Dr. Donald Ingber has revealed structural systems occurring within the fluid realm of the cytoplasm, structured in ways that invite manipulation by designers.[10] Ingber's research has demonstrated how the fluid structure of the cytoplasm contains interactions between two protein modes: myocin, organized in microtubules offering compression, and actin, working as tensile structures, operating

together in a tensegrity grid structuring the viscous medium.



14.3 Traube protocells developed for *Hylozoic Ground* show osmotic pumping of delicate ferrous membranes, forming around copper sulphate vesicles suspended within varying densities of oil.

The American zoologist Steven Vogel's seminal research on the structural forms of organisms and their relation to the mechanics of moving fluids illustrates how dynamic forms can lead to highly effective adaptations. The design of organisms responding to drag, flow, and lift offers adaptive efficiency. Leaves, exposed to high winds, reconfigure by rolling into conical forms, decreasing their drag.[11] Plants can form themselves into shapes that interact with local airflows to act as pollen traps.[12] The physical adaptations observed in natural forms offer solutions for form-flexible architecture that exists in changing environments. These combined effects could be conceived as a kind of churn that fertilizes relationships between the occupants and the environment. The bidirectional exchange between instalment and ecosystem offers a means of constructing new frameworks to build hybrid structures that can mature into more hospitable bionetworks.

Extending the formal structures studied by Vogel and Ingber into the dynamic realm of chemical reactions, artificial life researchers Rachel Armstrong and Martin Hanczyc are part of a movement working with new protocells – prototype cells – exposing the ways designers can work with skin-making mechanisms and carbon-fixing mechanisms.[13] A formation developed by Armstrong and Hanczyc includes a version of a Traube cell, a

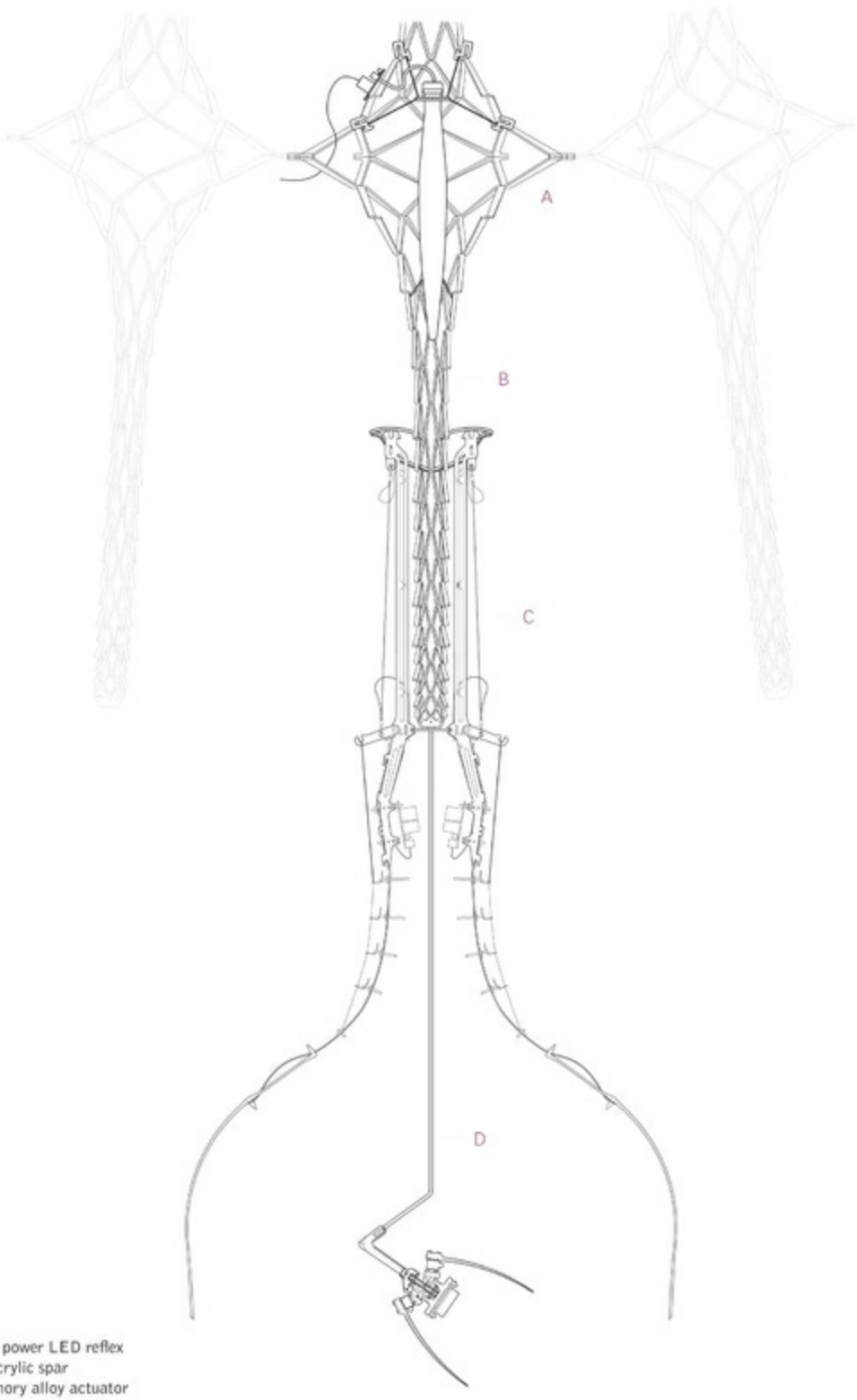
chemical formulation originally modeled in the nineteenth century as an analysis of the behavior of living amoebas. Their recapitulation of this study features a delicate copper salt suspended between varying oil densities that permit delicate formations to appear, resulting in the blooming of a mineral felt, powered by osmotic forces pumping solution around a copper sulphate fluid core (Figure 14.3).

The dynamic organizations revealed by Prigogine and related researchers invite architectural design to move from the Vitruvian idea of a static world into the dynamic form of a metabolism.

Projects and Methods

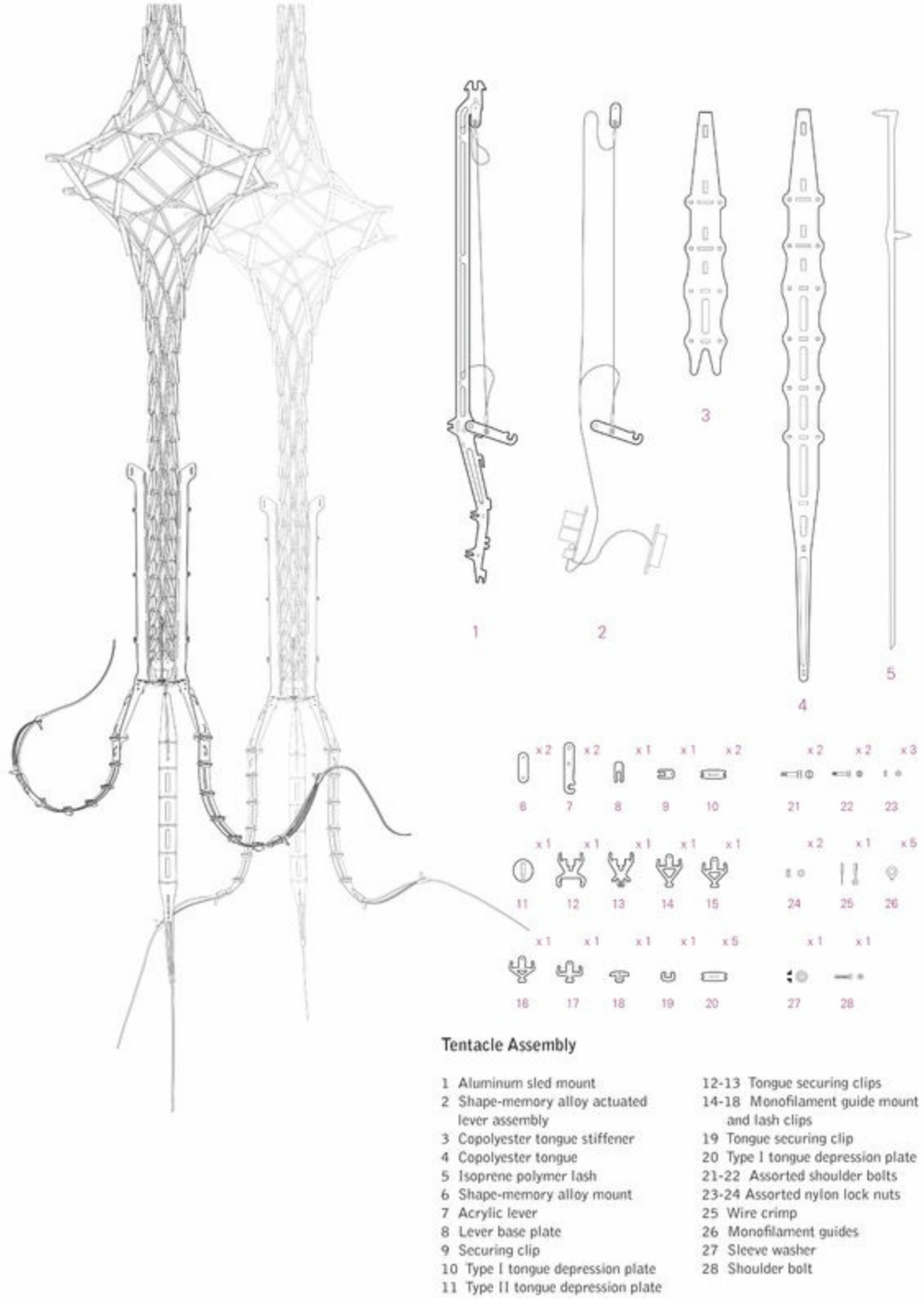
Following diffusive form-language, a steadily evolving series of collaborative projects have been developed by the North American and European collaborations of the Living Architecture Systems Group (LASG). The group's name comes from hylozoism, the ancient Greek conception that life can arise from physical material.[14] Recent projects have employed layered systems integrating lightweight scaffolds, simple chemical metabolisms, kinetic mechanisms, and distributed computational controls. Structures have tended to be lightweight and ephemeral, organized as resilient textile matrices. The work starts by setting out crystalline forms following diagrids and textile meshworks in order to make lightweight, resonant scaffolds. Flexible lightweight formations are overlaid with microprocessor systems. Kinetic responses are orchestrated by arrayed actuators and sensors, producing turbulent responses that ripple outward (Figure 14.4). Sheet-material derivations expand definitions of space by taking the notion of natural concepts like soil and transforming them into suspended interlinking clouds. In response to human presence, the installation can produce contractile movements, clutching and pulling. Geometries ordering the interlinking structural components used to construct these fields have included *quasi-periodic* systems where clusters and local arrays can multiply and effloresce,

supporting transitions in their interrelationships (Figure 14.5). A recent stage of

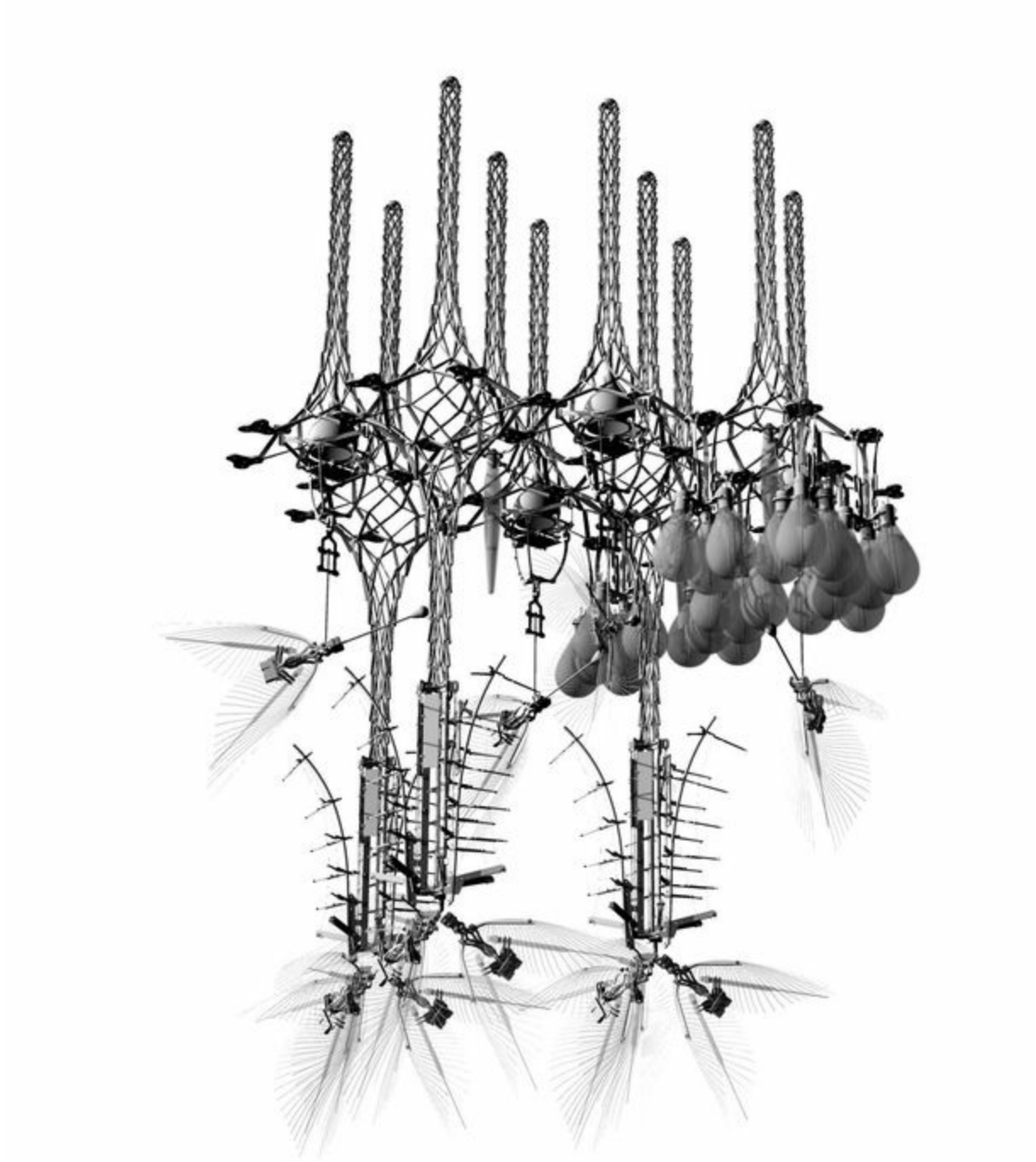


Tentacle Cluster

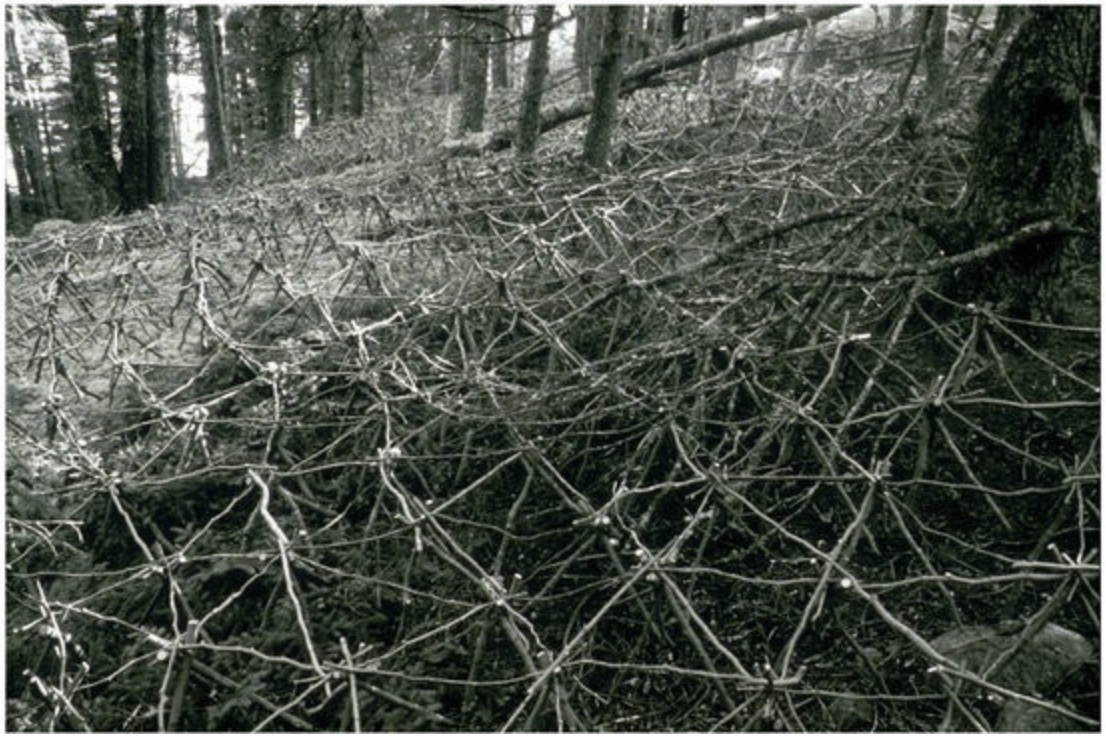
A Protocell flask with high power LED reflex
B Thermoformed diagrid acrylic spar
C Tentacle with shape-memory alloy actuator
D Infrared proximity sensor with LED reflex



14.4 Flexible meshwork systems arranged in clusters support mounted kinetic tentacles activated by optic sensors.



14.5 These interactive geotextile mesh environments include embedded machine intelligence and "living" chemical exchanges, conceived as the first stages of self-renewing functions that might take root within the architecture. The forms of the installations turn away from the minimum surface exposures of reductive crystal forms as they seek; to increase their exposure and interchange with the atmosphere.

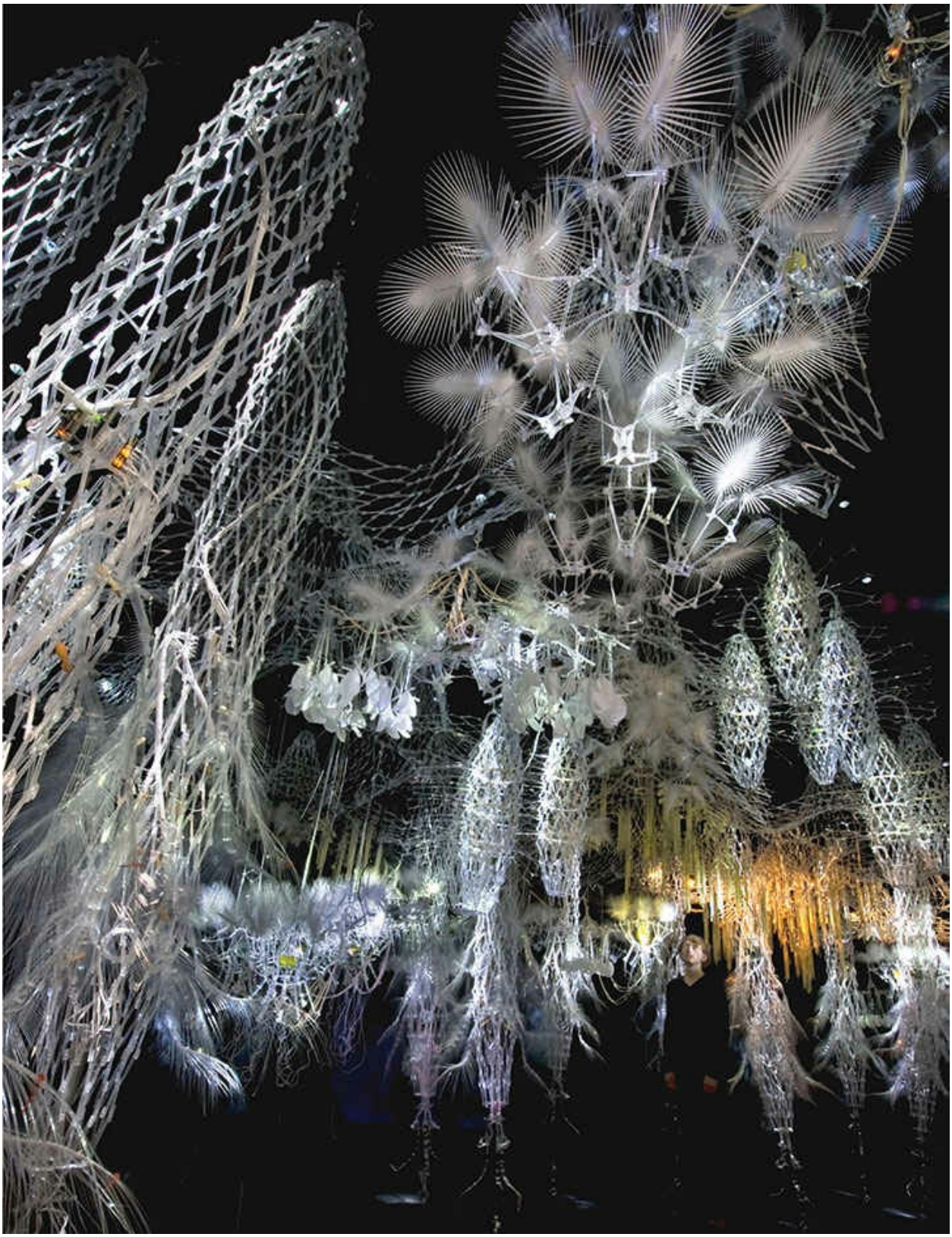


14.6 *Haystack Veil* is a landscape of cut saplings, laced together and used as a shelter for a nested organic growth. (Philip Beesley, Warren Seelig, and students of the Haystack School for Crafts, Maine, 1997.)

14.7 *Epithelium,* developed by Philip Beesley with Hayley Isaacs, is an automated geotextile, a lightweight sculptural field housing arrays of organic batteries housed within a lattice system that might reinforce new growth (*Endothelium*, CNSI, UCLA, 2008).

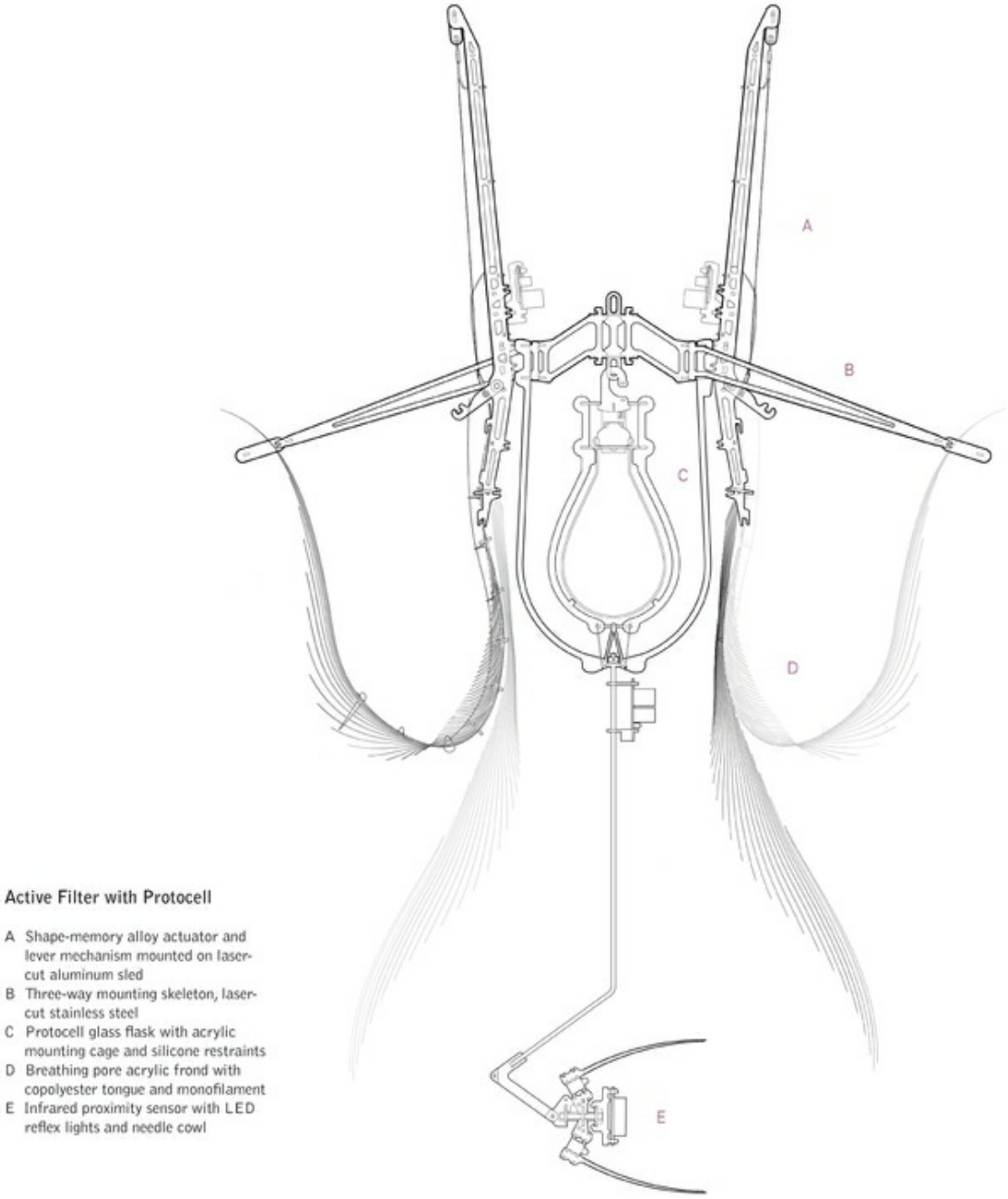
development has involved the construction of diffusive metabolisms containing protocol liquid reactions creating felt-like chemical skins. This integrated chemistry suggests that buildings could be designed to grow and renew themselves.

Early generations of this work pursued the design and construction of a kind of terrain, conceived as a hybrid geotextile. The twig-lattice of *Haystack Veil* (Figure 14.6) was made by clearing a farmer's field of alder and then using that material as a triaxial weave for a shelter for organic growth, nesting in it and catching turf to build up a kind of resilience. This can be considered as a minimally habitable space now primed for future development. In *Endothelium* (Figure 14.7), mounted in Los Angeles, a similar structure integrated weak sources of power generated from organic materials, using vinegar-filled latex bladders with aluminum and copper electrodes organized in series and moving through capacitors.



14.8 (left) *Hylozoic Ground*, presented at the Venice Biennale, integrates resilient meshworks, interactive

systems, and metabolic chemistry. These elements are drawn together to create a diffusive, near-living architecture (*Hylozoic Ground*, Venice Biennale, Italy, 2010).



14.9 (below) *Hylozoic Ground*: protocell flasks are contained within filter systems, shielded by kinetic acrylic fronds.

14.10 *Hylozoic Ground*: detail of Traube protocell showing formation of chemical felt.

The resulting trace currents powered LED lights and vibrators, chained to robotic feet configured like porcupine quills burrowing into the earth, each seeking its own pattern of fundament over the months of the installation until they ceased to function.

Hylozoic Ground (Figure 14.8), installed within the Canadian pavilion at the

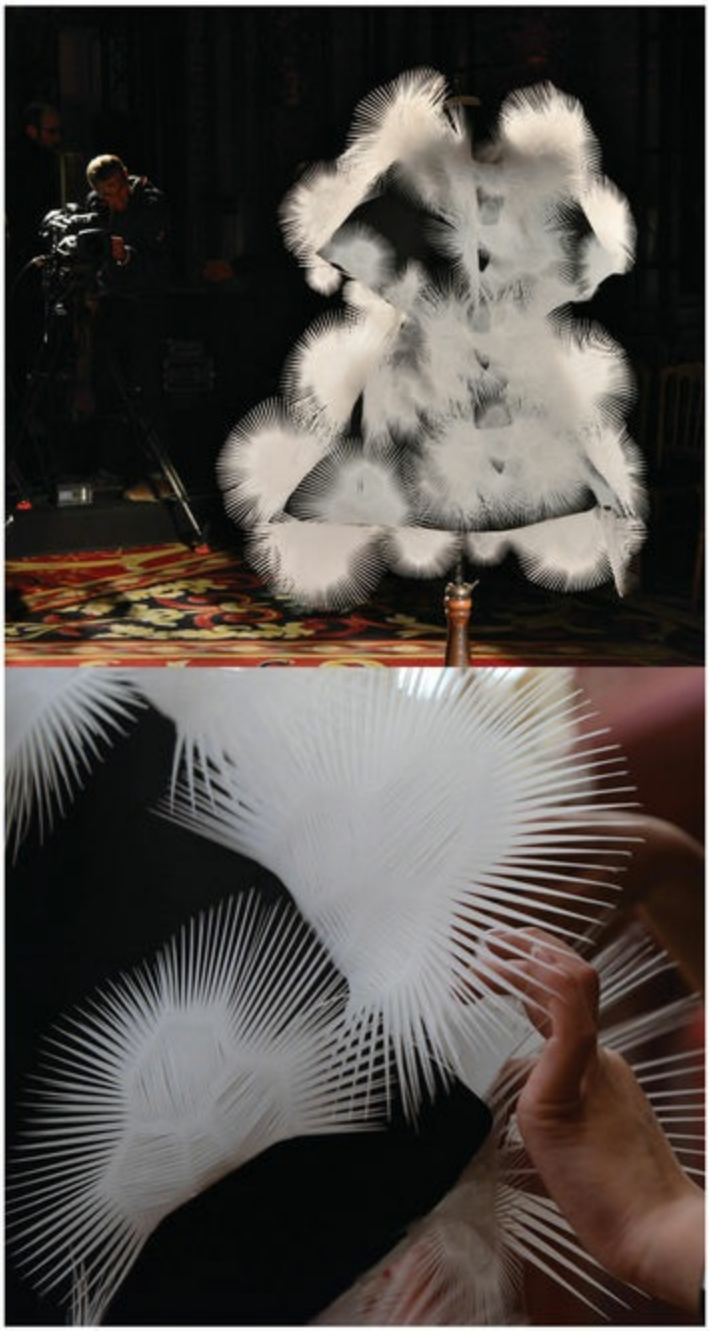
2010 Venice Biennale for Architecture, was organized by a hyperbolic waffle structure that could be pulled and pushed into continuous doubly-curved shell surfaces. Snap-fit chevrons connect to make duals of tetrahedron forms, multiplied to produce composite arrays. Hyperbolic meshworks and columnar forms are used as scaffolds clothed by mechanisms. A reticulum of many chambers forms humid layers within the matrix extruding into its interstitial space. Fluids and salts contained within a manifold of glass vessels pull and push and generate a blooming atmosphere. Flasks of protocell environments are worked into clusters within this assembly (Figure 14.9). These kinds of systems layer together and create a feedback loop that produce the operation of creating hybrid soil (Figure 14.10).[15]

The hyperbolic scaffold is a resilient network made of tetrahedral structures, clothed with hanging filters which pass gentle convective plumes of air and filter the environment. Kinetic components were grouped together, making tribal organizations of multiple clusters that would speak to each other and listen. In turn, these clusters would be organized into larger familial groups. Ripples of reaction and counter-reaction flow within these groups. The behavior is organized through the aggregation of multiple individual clusters of kinetic gestures. Electro-acoustic 'cricket' fields of polymer (Figure 14.11) are powered by miniature shape-memory alloy actuators. Protocell fields of glass flasks cycle water from the Venetian canal and contribute cleaning and refreshment. In concert, the mechanisms ripple out and resonate.

Each element within such an environment is gentle, exerting a small response, yet because they are chained together in the hundreds and sometimes the thousands, quite substantial crowd-like responses may occur, suggesting weakly emergent laws of organization. These elements call to mind Prigogine's

14.11 (right) *Hylozoic Ground*: detail of “cricket” acoustic actuators forming massed resonators powered

by miniature shape-memory alloy mechanisms within the installation.



14.12 and 13 Finely detailed flexible meshwork structures and translucent frond components form the outer layers of Iris Van Herpen's *Voltage* collection (*Voltage*, Haute Couture, Paris, 2013).

formulation of systems composed of lattices of identical variables interacting with each other in an environment, where activity from each element is

transmitted to its neighbors, in turn affecting the internal state of its "outputting" neighbors leading to emerging properties.[16] In *Hylozoic Ground*, the individual elements are generated in large arrays where a hyperbolic meshwork stands above the ground making a robust force-shedding structural system with peaks and valleys of doubly curved surfaces. Hovering filters pass convective plumes through them and contain a metabolic chemistry that processes and generates new mineral skins by fixing dissolved carbon dioxide from the atmosphere. The bladders, traps, and glands seen within these works form soil-like elements. The computation seen here is simple: individual elements chained together produce action akin to a chorus of crickets, or a swarm of insects, or perhaps the opening and closing of polyps in a coral reef. Shift-registers in recent generations of the custom digital control system provide a means of addressing many masses of actuators while using modest micro processing power as the system marches through data sets.

Changing scale in recent work is collaboration in fashion, starting to contribute to the sense of an expanded physiology in literal ways. Iris van Herpen's Amsterdam-based studio has developed clothing that offers a radical intimacy where the skin seems to be rendered as one boundary amongst many. Recent collaboration with Van Herpen[17] includes three-dimensional lace made of silicon and impact-resistant acrylic. In the recent *Voltage* series (Figures 14.12 and 14.13), individual components derived from architectural systems were reconceived in miniature form. The layers of this hybrid clothing encourage plumes of air to rise. Fabrics integrate fissured forms configured like leaky heart valves, hovering leaf-like layers that push and pump in gentle waves. A robust silicone meshwork swarms around the body. Individual elements chained together with small silicone tubes make a diagrid of corrugated mesh with diffusive, viscous performance. They make a live performance as they harvest your own energy and ripple around you. Layers lying immediately outside human bodies are organized in octaves of potential exploration, moving into turbulence. Musculature could be considered a mask, and an active fire-like metabolism can be sensed radiating through human skin. A corollary can be seen in a building composed of multiple layers. Traces are pulling at you. You become aware of the impact of your own tread in the

world.

Further Implications: Toward Design of Living Systems

The general principles underlying this work imply mutual relationships and distributed organizations. The hardened boundaries exemplified by Plato's world of spheres and reductive forms might be opened and renewed by form-languages that pursue intense involvement and exchange.[18] This implies a mutual kind of relationship between human occupants and their surrounding environments. In turn, it suggests a craft of designing with materials conceived as filters that can expand human influence while at the same time expanding the influence of the world in an oscillating register: catching, harvesting, pulling, and pushing. While personal boundaries can readily be found as functions of central systems – brain, and spine, and hearts define cores that we know well – parallel to those cores lie bundles of ganglia in our elbows or in our sternum and pineal. Neural matter is riddled throughout our bodies, making a series of overlapping networks. Much of our consciousness is bound up in loops and reflexes that happen at the outer edges of cognition. Such a model working internally could be expanded outward. In such a layered space, we could build up a deeply layered, deeply fissured set of relationships in which there are multiple sensitive boundaries. We might be able to build up in a sense of fertility reconstructing a kind of a soil and ground. We could measure values within that constructed ground by measuring resonance. Such a method suggests that the practice of architecture can move closer to the craft of creating living systems.

For twenty-five hundred years, Western artists and designers have been writing about emulating life. The imagery and forms from this tradition show potent hope for inanimate forms of craft and art coming alive. Yet the speech and evocations of visual art and architecture have often treated "life"as a kind of boundary defined by separation and distance from human craft. The

symbolism that evokes life has been maintained by distinguishing human artifice from the viable organisms of nature. The discipline of architecture seems to have been especially emphatic in maintaining this divide. Architecture seems a counterform to nature, staying deliberately distinct from the living world, preferring instead the role of a stripped stage that supports the living world by means of clear restraint. Perhaps that kind of separation has a moral kind of imperative, avoiding trespass. Yet the distinct progress of science and technology in recent decades invites a change to this strategy of restraint. The achievement of comprehensive information within the Human Genome Project,[19] the accomplishment of potent learning functions in computational control, and the increasing fluency in programming physical materials and projecting complex-system ecological modeling[20] can conspire to demonstrate that living systems no longer need be maintained as a sacrament separate from human intervention. The ability to see our traces and to understand the dimensions of the impact with which we tread forms an ethical key to this change. Emerging from the distancing functions of reverence into a new phase of stewardship, living systems can now occupy the space of architectural design.

The qualities of this work offer an alternative to reductive, purifying qualities that have tended to dominate traditions within Western architecture. The morphology described here stands distinctly against the prevailing Modern preference for stripped, minimal stages devoted to autonomous freedom. The formal language of this design method instead pursues culpable involvement.[21] Rather than polarized working methods that follow only centrally controlled or opposing emergent, incremental models of organization, the fields of this working method oscillate. Deliberate ambivalence is inherent in the approach, yielding qualities where things convulse and stutter in emerging vitality, characterized by mutual relationships of exchange with the surrounding environments. This study opposes Plato's idea of a sphere, the kind of evidently beautiful form embodied by a raindrop. While such a form might claim to be efficient and responsible by reducing consumption, this principle, guiding current minimalism, speaks arguably more of mortality than of fertility. In human

culture, spheres can speak of violence and of territorial claims. Instead of such reductive forms I have suggested that snowflakes offer a potent form-language that could guide emerging architecture.

In the footsteps of Prigogine, the diffusive, dissipative form-language described here offers a strategy for constructing fertile new architecture. The form-language discussed in this approach attempts to open up new spaces bursting with novel potential. The "maximizing" interface implied by Ilya Prigogine's conception can guide a fertile new generation of architectural design.

Acknowledgments

The projects of the Living Architecture Systems Group are collaborations. Credits are recorded at www.philipbeesley.com.

Notes

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5 Grimm, V., Revilla, E., Berger, U., Jeltsch, F., Mooij, W.M., Railsback, S.F., ... & DeAngelis, D.L., "Pattern-Oriented Modeling of Agent-Based Complex Systems: Lessons from Ecology," *Science*, 310(5750) (2009): 987–991.

6 Nicolis and Prigogine, op. cit., p. 10.

7 Ibid., p. 41.

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11 Vogel, Steven, *Life in Moving Fluids: The Physical Biology of Flow* (Princeton, NJ: Princeton University Press, 1994), p. 123.

12 Ibid, p. 43.

13 Armstrong, R. and Hanczyc, M.M., "Bütschli Dynamic Droplet System," *Artificial Life Journal*, 19(3–4) (2013): 331–346.

14 The Living Architecture Systems Group currently includes members of Waterloo Architecture and Philip Beesley Architect Inc., Rob Gorbet's laboratory within Knowledge Integration and the Adaptive Systems research cluster led by Dana Kulic within Electrical and Computer Engineering at the University of Waterloo, synthetic biology research led by Rachel Armstrong at Newcastle, component design led by Michael Stacey and the ATRG Group at Nottingham University with multiple collaborators including Iris van Herpen, Salvador Breed, Christian Derix, Lucinda Presley, and Sandi Chapman.

15 Armstrong, R. and Beesley, P., "Soil and Protoplasm: The Hylozoic Ground Project," *Architectural Design*, 81(2) (2011): 78–89.

16 Nicolis and Prigogine, op. cit., p. 140.

17 Van Herpen, Iris, "In Conversation with Philip Beesley," *A Magazine*, 13 (March 2013), pp. 2–7.

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20 Eliasmith, C. and Anderson, C.H., *Neural Engineering: Computation, Representation, and Dynamics in Neurobiological Systems* (Cambridge, MA: MIT Press, 2004).

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15
Rad: Make Alive

RODOLPHE EL-KHOURY AND CAROL MOUKHEIBER

Our research is premised on the notion that every building, city, and landscape component can be – and will be – equipped with communicative and computational capacities. The migration of computing from dedicated appliances to physical environments directly empowers architecture as a transformative agent. The fact that objects can now sense, think, act, and communicate with the help of embedded technology is opening up the potential for an architecture that is more closely aligned with the networked dynamics of living systems – a sentient architecture. Our projects establish an interdisciplinary platform involving artists, designers, scientists, and engineers spanning different institutions and continents in a technological approach to spatial problems that is attuned to the dynamics of living systems. The collective aim is to develop from the collaborative experiments a digitally enhanced architecture that is well equipped to handle persistent and emerging challenges in building a healthy and sustainable environment.

For designers, the ongoing merging of artifacts, information technology, and data requires new tools and methodologies. How do we design for the Internet of Things (IoT)? How do we embed technology in objects of everyday life? In tackling these questions we inevitably end up with more basic ones: what happens when an object gets connected to the internet? How do sensing and computing expand its agency? What should it do? How should it do it? What are the consequences of these new capacities on the object, and finally the most fundamental of all questions: what is an object?

The IoT is an advanced technological development, a $15 trillion business that is part of an unprecedented expansion of machine intelligence in our environment. With already 3.5 billion sensors in the world, Mark Weiser's

concept of ubiquitous computing conceived in 1991, with its implications of an embodied virtuality — a flight of miniaturized computational elements including sensors and actuators from the confines of a desktop computer's shell into the physical environment itself — has become a reality. As described by N. Katherine Hayles, this phenomenon extends a genealogy of cybernetic thought and ushers fourth-order cybernetics, or what Hayles calls the Regime of Computation.[1] First-order cybernetics (1945–1960) posited a feedback loop towards a homeostatic condition between an autonomous, self-directed subject and the environment; second-order cybernetics (1960–1985) ushered in the notion of autopoesis, whereby the subject, no longer a clearly delimited observer, became intertwined with environmental triggers in a closed self-reproducing system with reflexive and recursive information that enables more complex feedback; third-order cybernetics (1985–1995) saw the concept of emergence, order out of chaos, with the rise of artificial life in the form of virtual self-evolving programs no longer concerned with simply self-maintenance and equilibrium; and now fourth-order cybernetics with the pervasive penetration of computational processes into all facets of life in massively distributed, networked cognitive systems. Accordingly this process is reshaping us into posthuman subjects, as we become more deeply intertwined with other kinds of cognitive systems, contributing to a dispersed sense of self. Here the liberal humanist subject, the autonomous master, ceases to exist as such, and instead joins an intricate ecology of natural and artificial distributed cognition systems.

While Hayes shows how this computational regime and its algorithmic logic lead to a disembodied view of the world – rationalizing the exchange and processing of information and separating it from the physicality of matter within which or even through which information is processed – the possibility of ubiquitous computing, in its connection to the physical environment, invites an opportunity to activate and deeply engage the body, or the physical object in which this virtual computing capacity is activated. In other words, matter here really matters. In this sense, multi-scalar everyday objects from appliances to buildings, landscapes, and cities can be understood as having a newly gained virtual space of possibilities, what Weiser coined "embodied

virtuality." With the more recent development of the IoT, this virtual capacity is further tied to the vastness and incomprehensible scale of the Cognisphere.[2] This massive global network of interconnected objects consisting of ever more intelligent cognitive agents in which humans are embedded is an opportunity, as Hayles sees it, to re-evaluate "human agency, rationality, and affective capacities" and has the potential to initiate new relations between a myriad of distributed and diverse cognitive actors, human and non-human, animal, machine, and inert artifact.

In architecture, first- to fourth-order cybernetic movements played out in a mirroring sequence, with a lineage extending back to the notable cybernetic experiments of Nicholas Schoffer (1950s) based on first-order cybernetic notions of feedback and circular causality towards homeostasis, followed by Cedric Price and Gordon Pask (1960s) pursuing more complex behavior based on second-order notions of autopoesis through user-based participation. Gordon Pask's conversation theory epitomizes this phase of recursive complexity, creating a more engaging interaction between user and machine. These paradigms still guide current models of interactive architecture where interactivity revolves largely around the user and their inputs. Experiments with more bottom-up systems and artificial life prototypes were carried out at the Architectural Association in London by John Frazer in the 1980s and the 1990s began to move towards an evolutionary model based on abstract systems design. More recently, this responsiveness has engaged with the dynamics of external environmental conditions in an attempt to maximize a building's performance with respect to climatic changes. These projects range from purely mechanistic responses to more formally innovative experiments. The IoT capacity for linking objects to a vast information and communication network propels the object into situations of extreme social promiscuity, replacing direct causality with correlation, untraceable connections, and unpredictable patterns. We are interested in this condition and its repercussions on matter by means of design.

More precisely, it is the shift from a user-dominant (subject–object) interaction to broader notions of object-to-object considerations demanded by the IoT that motivates the work and its interrogation of the architectural

object. In the context of the IoT, what becomes of the architectural object?

What is Rad?

RAD is literally a space: a workshop with rapid prototyping equipment situated right off the Bay Street Station at the heart of Toronto's subway system. It is an outpost of the University of Toronto's campus that is well poised for partnership with the private sector, in full public view through a storefront window. Most importantly, RAD is a research platform that provides a home for projects we develop with our research and professional teams and with an interdisciplinary network of collaborators across the university. The projects fall under the thematic umbrella of the following terms: *Internet of Things*, *Embedded Technology*, *UbiComp*, *Physical Computation*, and *Everyware*.

The themes or technologies defined by these terms all point from different disciplinary and discursive perspectives to the tendency for computation to migrate from its familiar dedicated appliances towards a seamless and ubiquitous integration into the built environment, into the very substance of our homes, cities, and landscapes. RAD is premised on a mandate for architecture to take an active role in shaping this emerging informational landscape as it becomes literally spatial and material.

Since RAD has a pedagogical ambition, we use a graphic motto to diagram and clarify our process. Most of the work at RAD can be reduced to this formula that also comes in different iterations to cover several variations on a common theme. They envision possibilities for embedding different forms of technology into a brick (Figures 15.1a–d). They show it incorporating computational power, harvesting energy, or communicating online with a dedicated IP address. The brick, the most basic and universal building block, stands by extension for all architectural elements and the diagram for their capacity or necessity to assimilate emerging technology.

Three years of RAD activity inspired by these diagrams is documented in

The Living Breathing Thinking Responsive Buildings of the Future.[3] The book details a variety of approaches in bringing architecture while demonstrating eight common defining premises.

Rad Premises

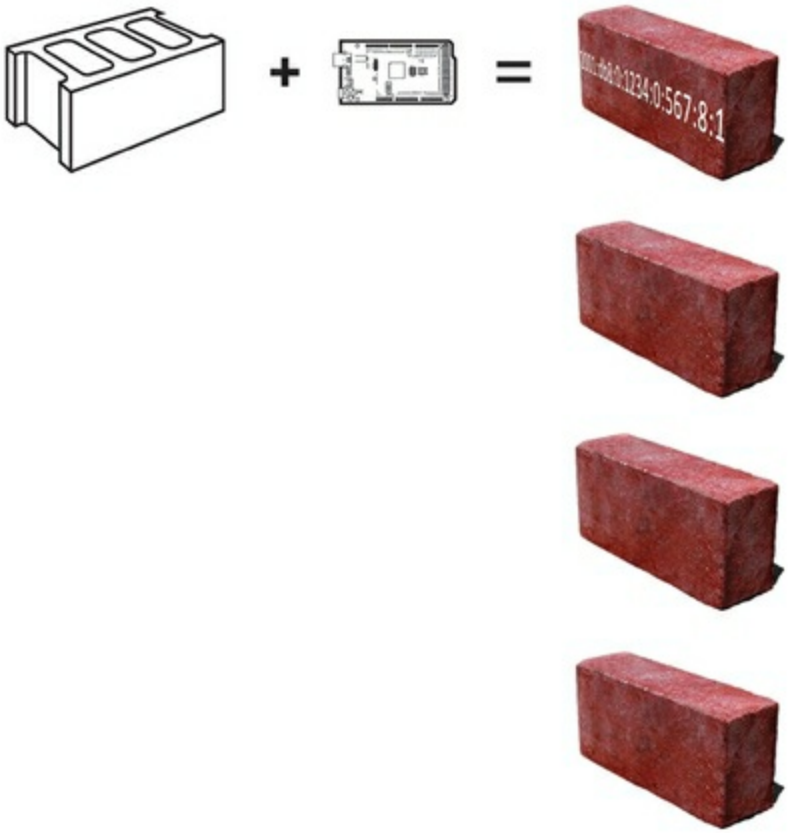
1. Make It

We are committed to prototyping the ideas we develop in our lab. Drawing and diagraming concepts falls short in demonstrating the relevance of the emerging technology and its potential for transforming our environments. We take our projects through all stages of development from initial concepts to fabrication and prototyping (Figure 15.2). The primary mission of RAD — and its well-equipped rapid prototyping facilities – is to manifest ideas in concrete functioning objects. Our approach is bottom-up, open source, DIY, and opportunistic; it aligns the ethos – technological and entrepreneurial – of the Maker's movement with established forms of funded university-based research.

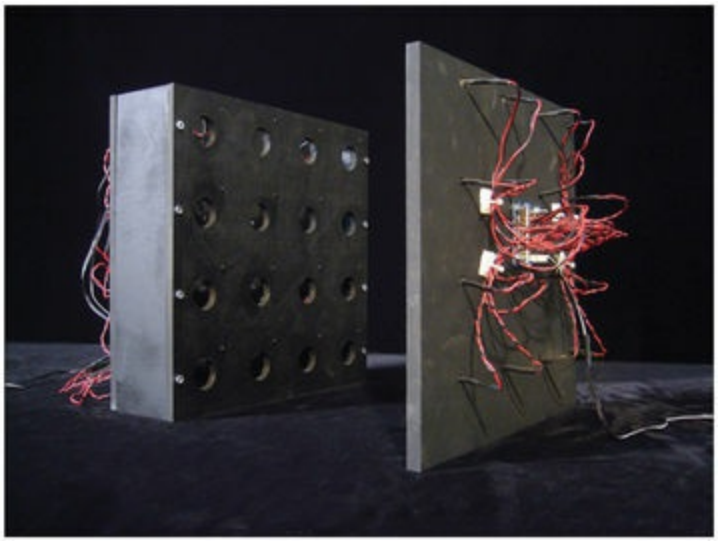
2. Ask Basic Questions

We start with basic questions. For instance, we explore what happens when we substitute an LCD screen and a camera for a windowpane. This is a startlingly simple operation. We think of it as the "degree zero" of electronic mediation. Yet it has significant consequences in the potential of reconstituting reality by means of digital signal processing. The possibilities are endless once you start to imagine how a window is not simply an aperture that gives visual access to the world outside but also an active agent with a capacity to transform this visual experience with spatial and temporal manipulation. With "degree-zero" *Digital Window* (Figure 15.3), we

reimagined the visual function of the window. In the *HVAC Window* series (Figure 15.4), we tackle the environmental role of the window as a thermal and atmospheric mediator. In one instance a pair of modified CPU cooling units (heat sinks and fans typically used in cooling a computer's CPU) were integrated into the window pane. Back-to-back CPU cooling units act as a Heat Recovery Ventilator, conditioning incoming fresh air with the energy of outgoing stale air. In another prototype a Peltier device inserted between the cooling units enhances the conditioning effect.[4] Subsequent attempts rethink the aluminum frame itself. One instance has the Peltier module replacing the thermal break to function as a thermal pump that transforms the window frame into a heating and cooling surface (Figure 15.5). The *HVAC Window* series thus aims to decentralize infrastructure by means of embedded technology. Such experiments replace heavy HVAC machinery with distributed and networked miniaturized devices integrated into building components. They enable responsive local interior micro-climates with the assistance of a digital technology.



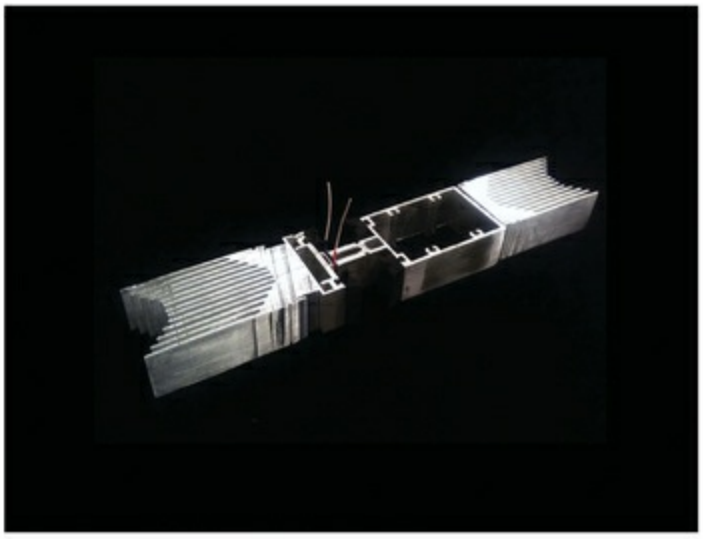
15.1a–d Brick plus (a) Arduino; (b) flexible solar panel; (c) wind turbine; (d) heat exchanger.



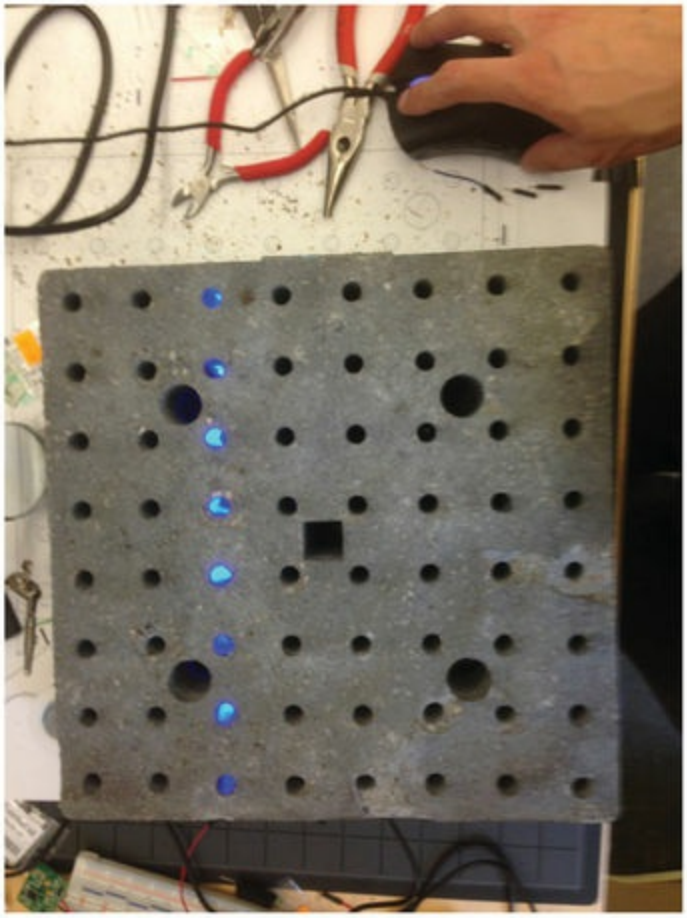
15.2 *Dynamic Illumination System* (from the *Invisible House*): prototype of floor and ceiling tiles that dynamically illuminate a person walking; ceiling tile LEDs are triggered by an interruption in the infrared beams aligned with the floor tile.

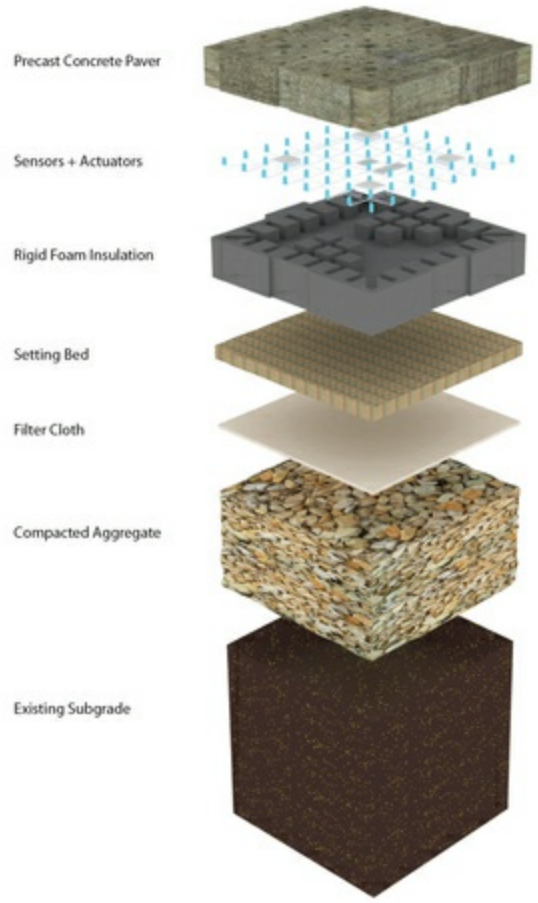
15.3 *Digital Window*: a digitally mediated transparency is achieved by connecting a camera on one side and an LCD screen on the other.

15.4 *HVAC Window*: a typical curtain wall glazing system with back-to-back CPU cooling units act as a Heat Recovery Ventilator.



15.5 *HVAC Curtain Wall Frame*: a Peltier device replaces the thermal break; the frame's surface area is multiplied to maximize surface to air exchange.





15.6 *Digital Paver*: a precast concrete paver is embedded with sensors and actuators – LEDs and speakers.

3. Put It on the Shelf

We prototype products for the shelves of Home Depot. This is not only due to the entrepreneurial spirit that animates much of the activity at RAD. This desire has a conceptual basis in the necessity we see for this technology to address the realities of the construction industry. In order to have any traction in this world, our projects would have to be designed with a capacity to integrate into the current modes of fabrication, distribution, and construction.

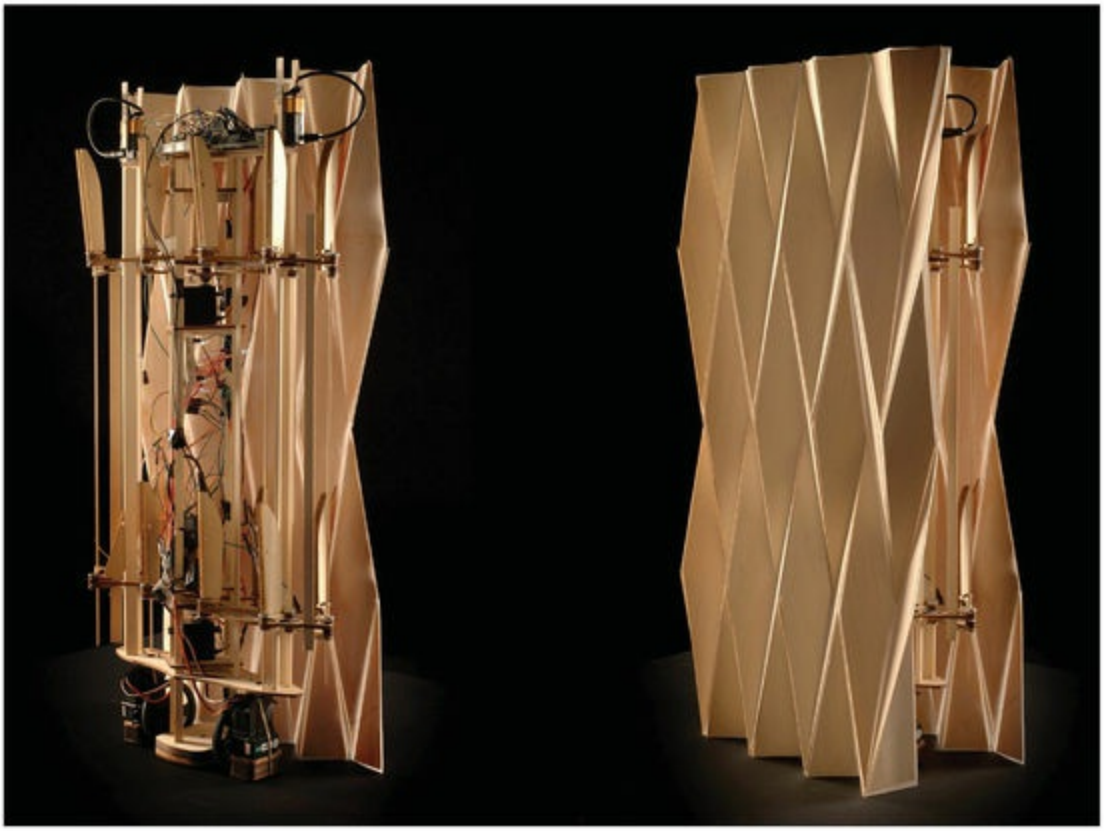
A light harvesting brick, which can be aggregated like Lego blocks into larger fields, to gather light and channel it by means of fiber optics into the deeper recesses of a building is designed for plug-and-play installation. It

could be bought off the shelf as a single item or in great quantities for large wall sections. Another example is a *Digital Paver*, a concrete tile with embedded LEDs, sensors, and transducers (Figure 15.6) that is designed for use on large surfaces to equip public spaces with digital broadcasting capabilities. We imagine *Digital Paver* as one of the many options that a designer could choose when selecting a material for a public square or a side-walk, and that this choice wouldn't push the project into a different category of budget and building technology.

15.7 *Variable Geometry Truss*: the design uses a swarm logic allowing each actuated truss member to continuously and independently adapt in response to local pressures measure, and relayed by an array of sensors.

4. Think Bottom-up

The preference for bottom-up organization is a consequence of the commitment to off-the-shelf and plug-and-play products. We are invested in the possibility of aggregating small units into large configurations that would have a greater impact. We hence explore bottom-up set-ups that do not require centralized wiring and command. This strategy enables the deployment of technology with wireless communication and distributed light infrastructure. It is particularly suited for retrofitting existing structure while forgoing prohibitive heavy upfront investment. For instance, a structural truss with a responsive variable geometry (Figure 15.7) that reacts to live loads is designed with each structural member responding independently and individually to local loads. The overall shape of the truss emerges from the sum of individual parts reacting in a swarm dynamic. There is no input from a central command computing and dictating the geometry. *WallBot* (Figure 15.8) is a system of moving self-propelling and guiding partitions which will reconfigure the plan of your loft to suit your use habits or following environmental inputs and various programmable scenarios. Imagine the floorplan reconstituting continuously to adapt to changing conditions. Each partition is acting individually but in communication with others as they swarm into various configurations throughout the day.



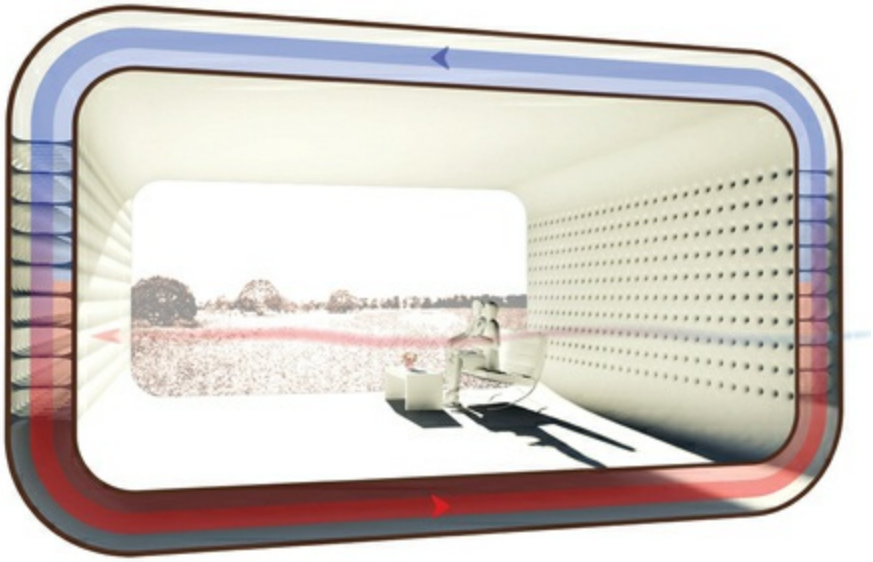
15.8 *Wallbot*: the prototype stretches from 1 m to 1.5 m by expanding its origami skin and kinetic skeleton.

5. Work with the Flow

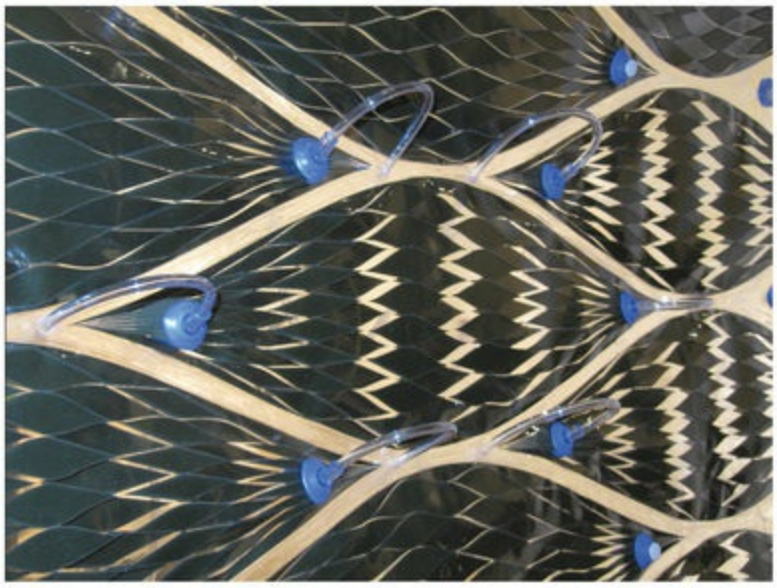
Responsive technologies are very well equipped for dealing with the dynamic aspects of the environment. The projects use the technology not so much with the aim of achieving homeostasis, but rather for their potential in domesticating turbulence. *Breeze-Thru Wall* is a project where micro heat pumps integrated into building blocks condition the air as it traverses the building's entire envelope (Figure 15.9). A gentle breeze would literally flow through the building just as if in an outdoor space with no obstacle in its path. Embedded responsive technologies here work in sync with the dynamic flows of the environment rather than struggle against them.

In another instance, a wall features individually motorized and sensor-

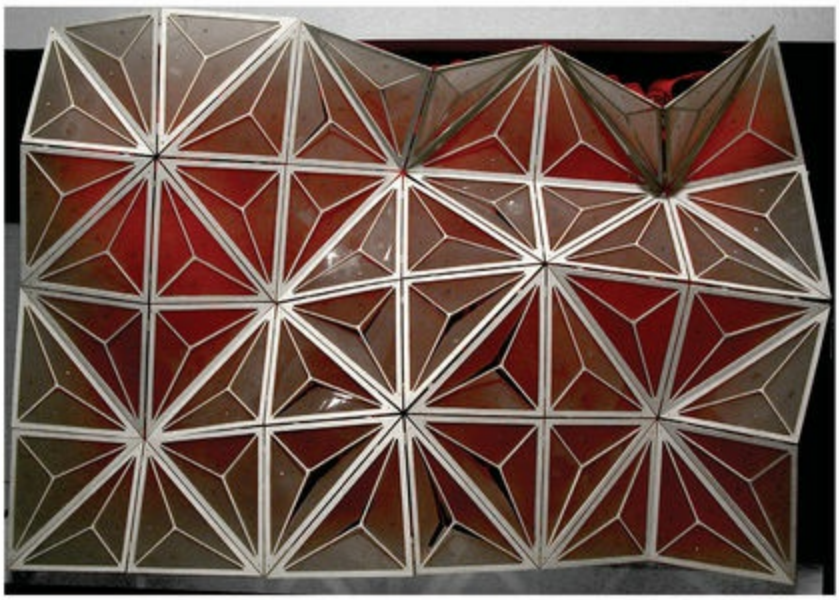
equipped bricks that react independently to programmable environmental and use-related scenarios. Imagine the ensuing flux of continually adjusting patterns adapting in real time to anything from a shadow of a passing cloud outside to the presence of an occupant in need of privacy inside. In *Pneumatic Envelope*, a system of inflatable pillows (Figure 15.10) embedded within a standard wall adjusts in real time the insulating capacity of the building envelope in reaction to environmental dynamics and in response to user input. The possibility of modulating insulation vertically by differentiating between lower and higher sections of the wall would also aid in the circulation of the air within the room.



15.9 *Breeze-Thru Wall*: in the exchange cycle, incoming cool air blows through the wall, where it is heated by warm air housed within the wall cavity; in the recovery cycle interior warm air exits through the wall where it heats up the air circulating within the wall cavity.



15.10 *Pneumatic Envelope*: each pillow inflates or deflates as necessary to provide local thermal comfort; a variation in insulation levels across the wall's vertical section allows for the generation of convective flows within a space, alleviating the problem of vertical heat entrapment.



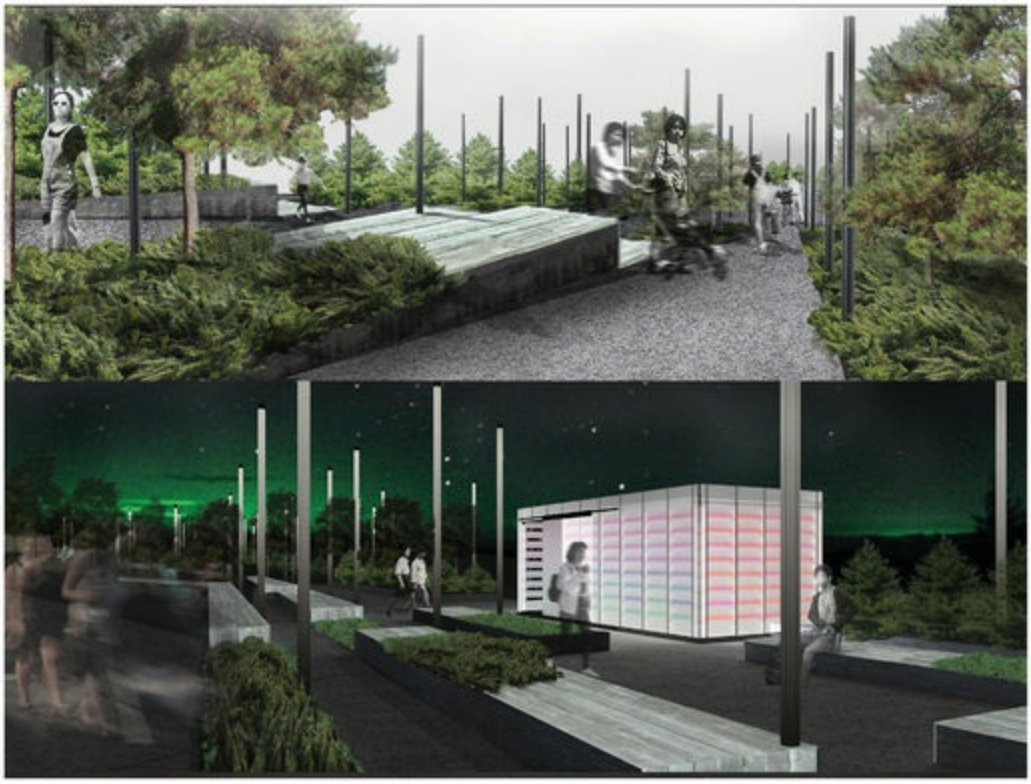
15.11 *Tunable Cloud*: the application can be manually adjusted for customized spatial moments, or programmed to allow the software to autonomously calibrate the system through a series of feedback loops; the modular design allows for large-scale expansions and site-specific installations.

6. Construct Atmosphere

We have a growing interest in the possibility of using embedded technology to precisely mobilize non-substantial means for the orchestration of ambience and atmosphere. *Tunable Cloud* is a digitally augmented acoustical tile (Figure 15.11) that modulates the acoustical signature of a room in real time in response to stage events, performance genres, or other inputs and criteria. *Scent Garden* (Figure 15.12) was commissioned by the Xi'an International Horticultural Exhibition. It features scent diffusers doubling as light fixtures. The diffusers build on experiments with *Scentisizer* (Figure 15.13), a device that is designed to digitize scents and perform the digital files of recorded olfactory compositions. The diffusers of *Scent Garden* overlay a sensor-controlled olfactory image on top of the landscape to complement natural fragrances with a curated artifice.

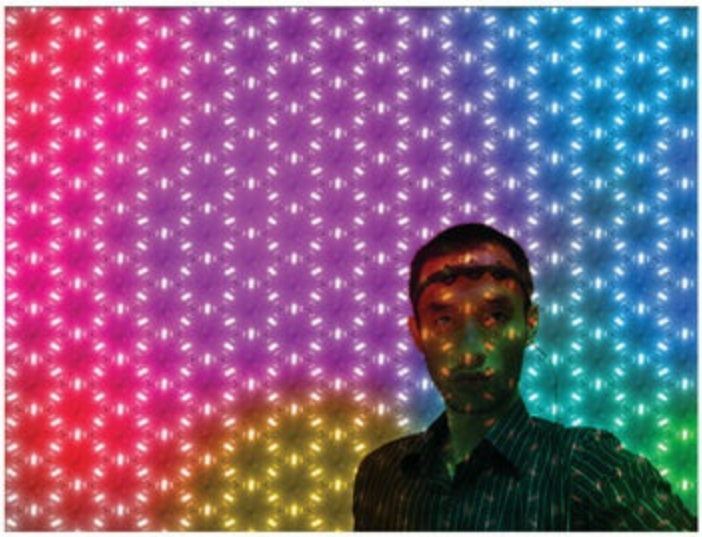
7. Calibrate Experience

The possibility of precisely customizing environments for an individual's use is often touted as a promising potential of digital embedded technology. We are not so much interested in optimizing the delivery of services to individual preferences. We are more invested in the possibility of a sensuous and affective resonance between people and spaces. *Chameleon Lounge* features stools that imitate the color of people's clothing. While *Auratic Chamber* (Figure 15.14) responds to the mood of individuals, it does so by reading the brainwaves with a brainwave controller – a device that has had limited applications in the gaming industry.



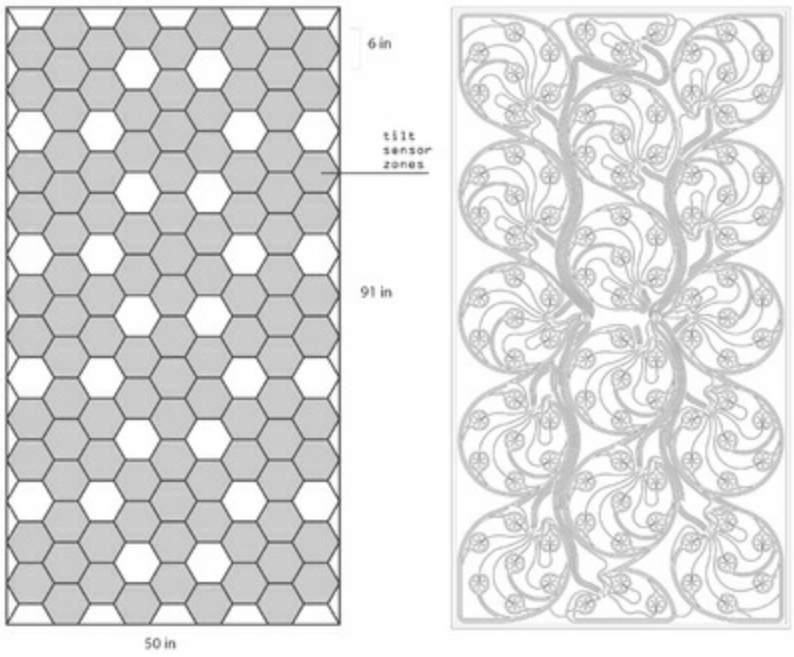
15.12 *Scent Garden*: the scent poles double as light fixtures; they consist of stainless steel tubes with integrated scent cartridges and LED lights.

15.13 *Scentisizer*: the prototype consists of an actuated matrix of scent dispensers. The scents assigned to each dispenser are mapped according to a variation on a taxonomy developed by the fragrance industry to classify scents into distinct but related families: Floral, Fresh, Oriental, Woody, and Aromatic Fougere.

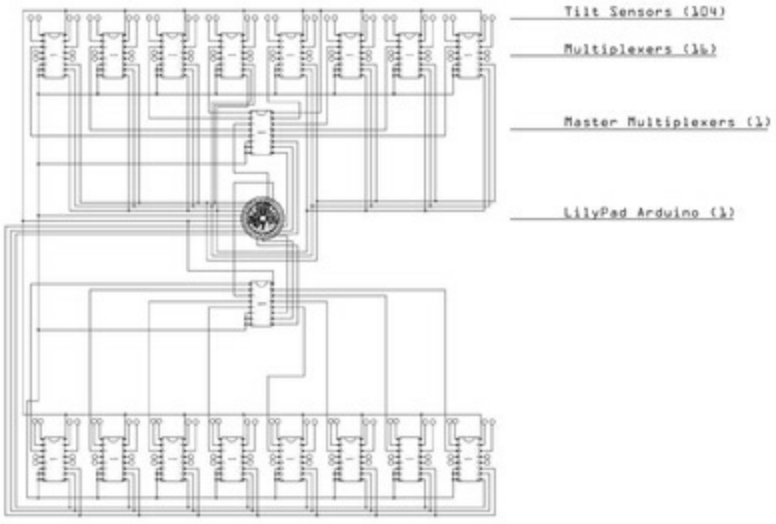


15.14 *Auratic Chamber*: the chamber consists of interlocking tiles that line the interior surfaces of a space; the environment uses light and color to become an extension of one's psychological state.

15.15 *IM BLANKY*: dimensions: 230 x 127 cm; materials: green taffeta, nickel-coated silver taffeta, conductive beads, glass beads, conductive thread, and resistors; components: Arduino LilyPad, XBee, Multiplexers.



15.16 *IM BLANKY*: sensor array with 104 tilt sensors, arrayed in a hexa-grid formation and distributed uniformly over the entire field.



15.17 *IM BLANKY*: circuit schematic; 16 Multiplexers receive seven inputs each from the tassle's contact; the inputs are relayed to two master Multiplexers and in turn to the Lilypad.

15.18 (below) *IM BLANKY*: stills from a video depict real-time digital replication of actual movement; the blanket embodies simultaneously a physical and digital presence.

8. From Embedded to Embodied

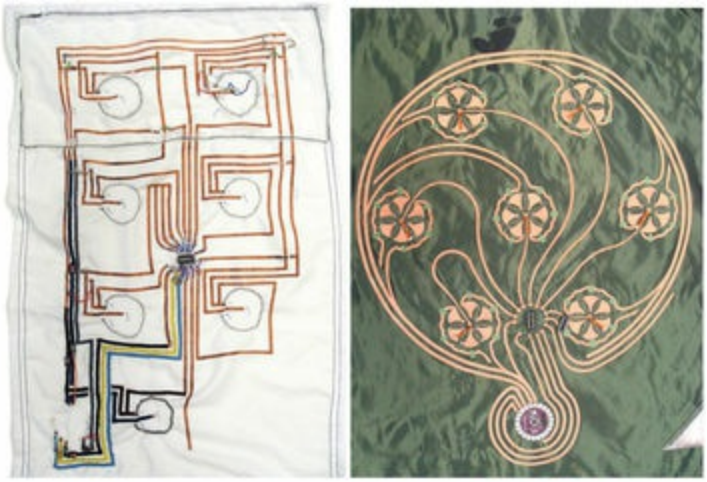
Our intervention in familiar objects of everyday life is not merely an additive operation but also a qualitatively transformational one. Technology is not simply layered onto an indifferent object. The object, through its reinvented morphology and materiality, becomes the sensual embodiment of the technology.

IM BLANKY (Figure 15.15) harnesses the intricacies of traditional ornamental patterns for the sake of functionality, enabling the blanket to become a soft computational surface. Sensitized with an array of soft tilt sensors (Figure 15.16), the blanket is a digitally empowered interface (Figure 15.17) capable of registering and relaying in real time its own position and shape in time and space (Figure 15.18).

The blanket's technical and aesthetic innovation is based on the functional and formal convergence of electronic circuit and plant morphology, complete with branching patterns, stems, petals, and pistils (Figure 15.19). Using conductive fabric and beads, the tilt sensors and their attendant circuitry are constituted by the very material and ornamental techniques of textile itself (Figure 15.20). The blanket relies on the movement of the body along with gravity for its own sensory stimulation, turning movement directly into usable information. The sensing components and their organization are integral to and not external to its form. In other words, *IM BLANKY*'s body is

also an information-processing system.

The project began with an invitation to rethink the craft of stitching and embroidery in the twenty-first century, bringing digital processes to bear on issues of craft and ornament.[5] Capitalizing on potential healthcare applications, next generation *IM BLANKY* senses additional biometric data such as breathing. It belongs to an eco-system of domestic objects that capture a variety of vital signs, forming over time a dynamic evolving profile of the embodying subject.



15.19 *IM BLANKY*: multiplexer hub break-out iterations; various casting and molding techniques were tested to secure the incoming tilt sensor input/connections to the Multiplexer hub.

15.20 *IM BLANKY*: close-up view.

What Next?

Recent projects at RAD recognize how environments designed with densely woven informational links and feedback loops are suited to interface with natural systems. They hybridize living organic material with building components to capitalize on their environmental benefits and responsiveness. A series of projects explore the ceiling as an untapped site for interior landscapes. It is an undisturbed zone that can be reclaimed by nature and linked to resilient outdoor ecosystem by means of networked embedded technology. In a departure from its focus on the object RAD is also currently invested in the development of a user interfaces and communication platform for the deployment and navigation of the Internet of Things.

Notes

1 N. Katherine Hayles, "Unfinished Work: From Cyborg to Cognisphere," in Ariane Lourie Harrison (ed.), *Architectural Theories of the Environment: Posthuman Territory* (New York: Routledge, 2013), p. 39.

2 N. Katherine Hayles uses this borrowed term to describe not just the Internet but all data networks and programmable systems across the electromagnetic spectrum that feed into the Internet.

3 Rodolphe el-Khoury, Carol Moukheiber, and Christos Marcopoulos, *The Living Breathing Thinking Responsive Buildings of the Future* (London: Thames and Hudson, 2013).

4 A Peltier device is a thermoelectric heat pump that is customarily used for cooling CPUs but could also be used for heating. This is a solid state module with no moving parts. Its technology is evolving rapidly and is expected to gain in efficiency.

5 *IM BLANKY* was commissioned in 2011 by Workshop Gallery, Toronto, for "Re-Stitching," an exhibition of traditional Chinese embroidery and new works that project the tradition into the twenty-first century.

16
Architecture of Participation: Smart Citizens, Not Smart Cities

USMAN HAQUE

The domain of architecture has been transformed by developments in interaction research, wearable computing, mobile connectivity, people-centered design, contextual awareness, RFID systems, and ubiquitous computing. These technologies alter our understanding of space and change the way we relate to each other. We no longer think of architecture as static and immutable; instead we see it as dynamic, responsive, and conversant. Our projects explore some of this territory.

We are interested in an architecture that can *only* exist in time, an architecture that is a choreography of sensations, an architecture that both *changes* over time and *responds* to changes in time. Such a conception can never be fixed, static: it is responsive, dynamic, and emotive. It welcomes the interactions (and interruptions) of people who occupy such spaces. Rather than employing traditional architectural materials like stone, steel, and glass (which imply permanent, inert structures), this approach to architecture employs more ephemeral materials like smell, sound, and electromagnetic waves. Just as computer hardware needs software to make it useful, so too does architecture require an ephemeral materiality to animate it. It is at this point that architecture and virtual systems converge and in the process, the distinction between "real" and "virtual" becomes less clear.

Architecture, the original broadband interface, has traditionally been understood as the combination of physical, static elements that make up our environments and enclose us, like walls, roofs, and floors. One might call these the hardware of space. An alternative approach is to think of

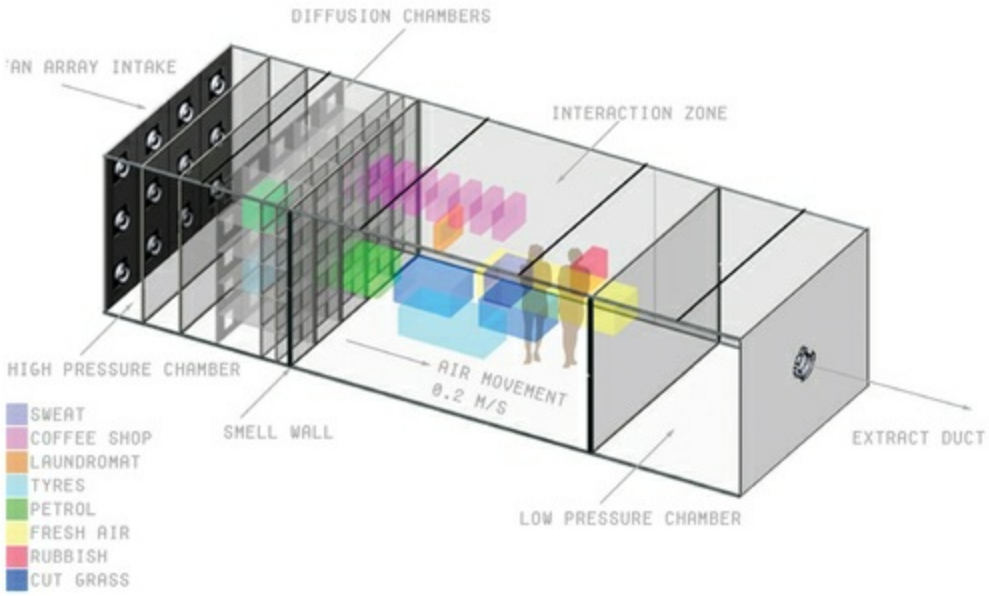
architecture as software: the ephemeral sounds, smells, temperatures, radio waves, even social relations that surround us and program the way we interact with space. Pushing this analogy even further, we can think of architecture as a whole as an operating system, within which people write their own programs for spatial interaction. Virtual environments that are influenced by an architecture-as-software approach consider spatial frameworks, not as rigid, absolute structures, but as a collection of fluid relationships. These relationships (between people and objects, objects and spaces, people and spaces) grow out of conversations in an environment. People give meaning to their environments by using them. This requires an approach that focuses not just on sensing and computation, but also on providing rich, suggestive outputs. The challenge is to develop architectural systems that nourish the imagination without adding further layers of prescriptive control.

Most advanced spatial interaction research these days is produced by non-architects. Technologists at both academic and commercial research labs are developing responsive systems that allow people to interface with their spaces, working, for example, on projection walls, remote devices, and "intelligent" sensors. These developments throw into question the very role of designers, because such user-responsive and environmentally responsive mechanisms allow people to take the prime position in configuring (that is, designing) their own spaces. As in architectural design, designing virtual systems involves developing spatial configurations that provoke interactions between people, and between people and their spaces. In enhanced environment design, where traditional architecture and virtual systems unite, users can be the designers of their own spaces, and, since spatial experience is a collaborative project, one might call these "open source" spaces.

However, in an age where we are approaching the design of what industrial design theorist Anthony Dunne has called "post-optimal objects" (i.e., objects one designs once practicality and functionality can be taken for granted),

> the most difficult challenges ... now lie not in technical and semiotic functionality, where optimal levels of performance are already attainable, but in the realms of metaphysics, poetry and aesthetics where little research has been carried out.[1]

Architects contribute to the discourse because their expertise lies in designing spatial and environmental "situations." However, while virtual system design has often tended to emphasize efficiency, convenience, punctuality, and predictability, architecture, on the other hand, can give clues to ways to develop spatial poetries. Softspace interfaces need to be developed or reinvigorated to encourage diverse interactions. These interfaces do not rely on accuracy or communicability of information. Rather, they presuppose instability and precariousness, emphasizing metaphor and suggestion. A good example is the use of smell as a spatial output: "unlike the other senses, smell needs no interpreter. The effect is immediate and undiluted by language, thought or translation."[2]



16.1 *Scents of Space:* diagram of interior airflow.

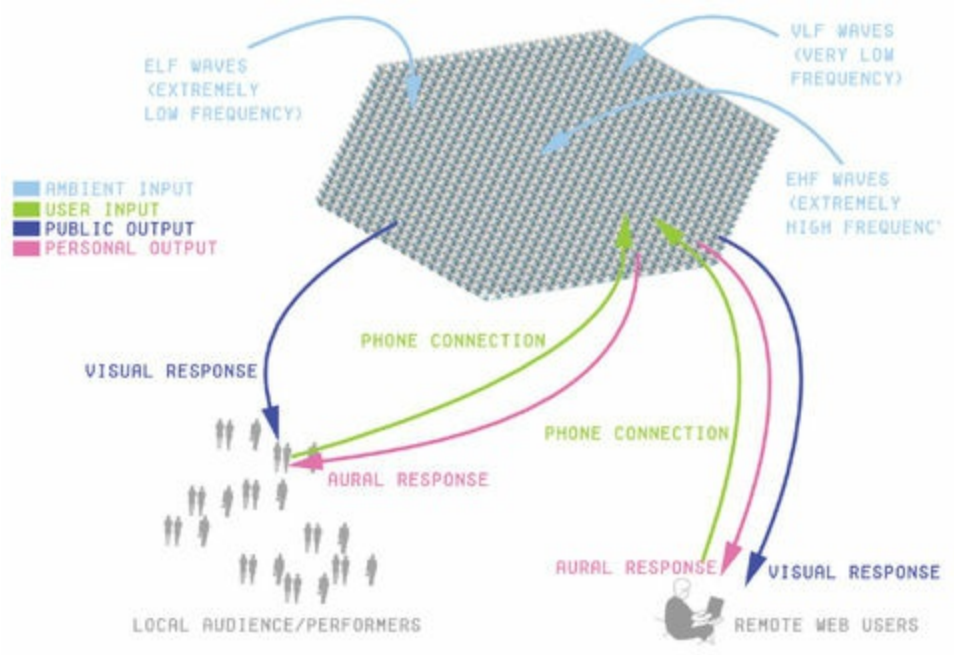
Choreographing Sensations

Our explorations have taken two distinct approaches. The first has been to look at what might be called softspace technologies: systems that incorporate the ephemeral qualities of architecture, including smell, sound, light, heat, and

electromagnetic fields. This approach has concentrated on the interactions that make up our experience of space and has proposed systems to affect these interactions. It has also explored the psychology of spatial perception, helping to expand the boundaries of those perceptions. The second approach has been to investigate how people operate within such environments. Movements in art that challenge accepted dichotomies between audiences and performers have parallels in spatial investigations that challenge the distinctions between architects and occupants. These investigations propose new models for environmental design, based on systems that welcome the active participation of people operating within those systems, informed by the ways that culture provides frameworks for social interaction. Together, these two approaches confront our relationship to designed space and enhanced environments because they encourage us to think not of static silent structures that surround us but rather of fluid, transient, dynamic systems within which we can be both consumers and contributors. Described below are three architectural design research projects that have a direct relationship to the design of enhanced environments.

Scents of Space, a collaboration with Josephine Pletts and Dr Luca Turin, is an interactive smell system that allows for the three-dimensional placement of fragrances without dispersion, enabling the creation of dynamic, soft olfactory zones and boundaries that are configurable on the fly. The project posits that if an architectural space could be precisely "tuned" with scent collages, it would be possible to create completely new ways of experiencing, controlling, and interacting with space. Smells are emitted singly or in "chords" in combination with a visual cue in the form of glowing cubes (Figure 16.1). Each of the dozen smells can be precisely and dynamically located in three-dimensional space, allowing visitors to encounter new scent boundaries as they move along the horizontal and vertical axes of the interaction zone. The fragrances are both pleasant and unpleasant; recognizable and unfamiliar; natural and artificial. The primary interaction occurs between the space and the visitors: scents are output in response to the position and movements of people. The system builds up a database of responses to smell, from which it develops strategies for being either "alluring" or "repelling." In this way, the

installation is constantly evolving in its responses to the movement patterns of visitors. A secondary level of interaction occurs between the visitors and the smells themselves. Visitors' movements mingle conjoining smells to create turbulent "third" smells; no two people could ever experience the space the same way.



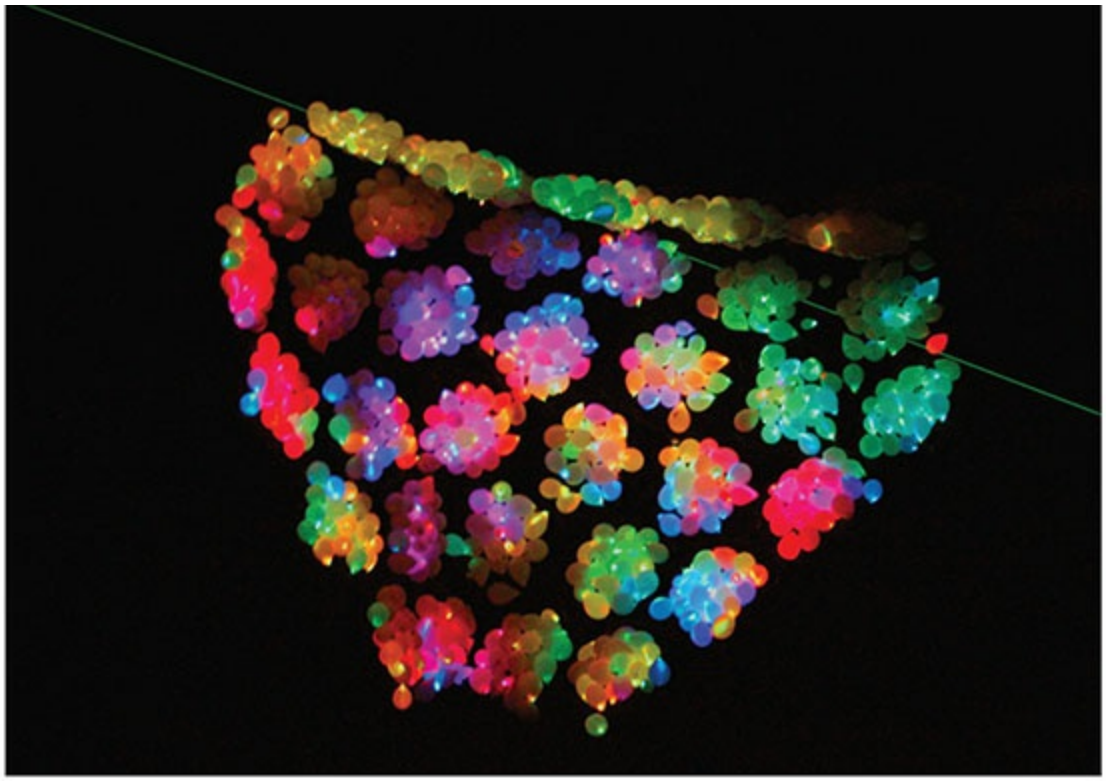
16.2 *Sky Ear* interaction diagram.

Architecture is a discipline that is inherently informed by psychology; similarly the psychology of individuals is affected by the architecture that people inhabit. *Haunt* is a series of continuing experiments that explore the psychology of perception through phenomena such as infrasound and electromagnetic fields that give rise to haunted sensations. To talk about haunted spaces is to talk about two things that are phenomenological: (1) the subjective sensation of haunting; and (2) the perception of space, which again depends on the particular occupant of that space. We built an environment that feels "haunted" by using subtle air flows,[3] different humidity levels,[4] temperatures,[5] and particular electromagnetic[6] and sonic frequencies[7] that parapsychologists have associated with haunted spaces. These spatial qualities are reconfigured dynamically, adapting constantly to real-time biofeedback

measurements in people in order to heighten the experience and to build up a large database of response patterns. The *Haunt* project considers how supposedly "objective" phenomena can affect our reasoned though subjective responses to external stimuli. To evaluate responses to the system's outputs, we developed a biofeedback system that works in real time to track fluctuations in people's reactions. A galvanic skin response (GSR) meter has been adapted to allow wireless untethered monitoring of people's emotional responses as they move around the programmed spaces. The values obtained from the GSR are used in real time to alter the outputs of infrasound, air, and electromagnetic fields on the fly to create a dynamic interactive system. For example, if a certain frequency of infrasound is provoking a particularly strong response, the system might either reduce that frequency, or continue it for a certain amount of time, or vary it in combination with one of the other outputs. Alternatively, if a person is not responding to a particular output combination, the system can reconfigure outputs until a response is achieved (for example, by changing the frequency of infrasound). As a constantly adapting system responding in real time to the physiological state of visitors, *Haunt* tends to reinforce the idea of an unknown "controlling" force and touches on issues of feedback and control in enhanced environments.[8]

Sky Ear is brought to life through interactions with electromagnetic fields (EMF), which are all around us. This abundant, invisible territory is altered in shape and intensity by both natural and human-constructed landscapes. We find ourselves walking around a room trying to find good signal on mobile phones; we set up wi-fi networks that are intricately affected by the positioning of furniture, doors, and walls, etc. One can imagine the undulating qualities of this invisible topography that surrounds us and affects the way we relate to space in much the same way that traditional architectural elements do – it guides us to certain parts of a building, it conditions the movements we make and how we make them, and, through devices like mobile phones, it has direct impact on the way we associate with other people. *Sky Ear* gives form to this electromagnetic environment that envelops us, making visible the invisible richness that exists just beyond the threshold of our natural perceptions. The original concept was to create a "radar sweep" that would

move through space and light up as it encountered varying intensities of EMF. The final structure consists of a 25 m in diameter carbon-fiber framework supported by 1000 extra-large helium balloons (Figure 16.2). The *Sky Ear* "cloud" is released from its ground moorings and slowly floats up into the sky like a glowing jellyfish sampling the electromagnetic spectrum as it rises, changing colors as it encounters varying electromagnetic fields (Figure 16.3). The balloons function both as buoyancy/flotation devices and as diffusers for the six ultra-bright LED lights (which mix to make millions of colors), controlled by individual sensors inside each balloon. The balloons can communicate with each other via infrared, allowing them to create larger patterns across the entire *Sky Ear* cloud. Embedded in the cloud are several dozen mobile phones; as people call the different regions of the cloud, they change the local electromagnetic topography and cause disturbances in the EMF inside the cloud that alters the glow intensity and color of that part of the balloon cloud. Feedback within the sensor network creates ripples of light reminiscent of flashes of lightning. As an architecture project, *Sky Ear* makes visible our daily interactions with the invisible topographies of electromagnetic space.



16.3 *Sky Ear* in flight.

The projects described above are first steps, more experiments with color in a palette than finished paintings. They explore ways that enhanced environments might interface between real and virtual spaces, though this distinction is becoming less important as the interfaces become more robust. The precise nature of such environments is ambiguous because people themselves interpret, appropriate, design, and reuse such spaces within their own frames of logic. These spaces do not merely enable people to develop their own ways of responding, they are actually enriched by them doing so. As people become architects of their own spaces (through the use of such spaces), the word "architecture" ceases to be a noun and becomes a verb. Such an architecture is explicitly dynamic, a shift that opens up a wealth of poetic possibilities for designers of space.

16.4 *Open Burble,* commissioned by Singapore Biennaie in 2006.

Architecture of Participation

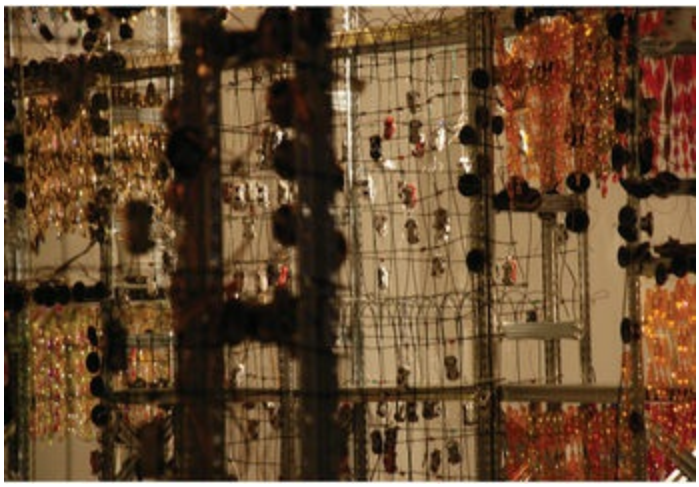
As I was working on the *Sky Ear* project, which is large and had to be assembled in a short amount of time, we faced the challenge of having to inflate a thousand balloons; obviously, that would take some time for a few people to do. We estimated that within five hours or so we would lose about 20 percent of the buoyancy, so I had to figure out how to inflate balloons quickly. It was purely such pragmatic reasoning that led me to involve members of the public, which made the project truly participative – and made me think of public participation, which hadn't been my preoccupation up to that point. Many of the people who had helped inflate the *Sky Ear* actually wanted to control it too, which brought to the fore the issues of risk

assessment, health and safety; as a consequence, we had to keep people behind barriers.

When I was asked to do a project for the opening of the Singapore Biennale in 2006, the organizers wanted *Sky Ear*, but I was interested in reimagining the project as a modular system where members of the public could actually design the structure, assemble it, and then fly it; they would also control it, even the way that the colored patterns mixed on the surface of the structure would be explicitly determined by how they designed it in the first place. So in *Open Burble*, as the project was named, members of the public came together to compose, assemble, and control an immense rippling, glowing, bustling *Burble* that swayed in the evening sky, in response to the crowd interacting below. That massive structure (Figure 16.4), the form of which the public had themselves designed, existed at such a large scale that it was able to compete visually in an urban context with the skyscrapers that surrounded it.

The *Burble*, soaring upwards like a plume of smoke, was constructed from a set of 140 modular and configurable carbon-fiber units approximately 2 m in diameter.[9] Each unit was supported by seven extra-large helium balloons for a total of about 1000 individual "pixels," which contained sensors, LEDs, and microcontrollers, enabling balloons and units to co-ordinate and create patterns of color that rippled up towards the sky. Just as the participants were the composers of the *Burble*'s tall form, so too were they the ones controlling it. They held onto it using handles with which they positioned the *Burble* as they liked. They might curve in on themselves, or pull it in a straight line – the form was a combination of the crowd's desires and the impact of wind currents varying throughout the height of the *Burble*. The *Burble* moved, rustled, tangled, folded in on itself, and created turbulence as the wind caught it like a sail. Suddenly, the entire construction ignited with color, sparkling in the evening sky. As people on the ground shook and pumped the handle bars of the *Burble*, they saw their movements echoed as colors through the entire system.[10] They saw their own individual fragments, perhaps even identifying design choices they had made. Their individual contributions became an integral part of a spectacular, ephemeral experience many times their size that

they had come together to produce. Part installation, part performance – for the design and assembly by the public was as much a part of the project as the actual flying was – the *Burble* enabled people to contribute at an urban scale to a structure that occupied their city, albeit for only one night.[11]

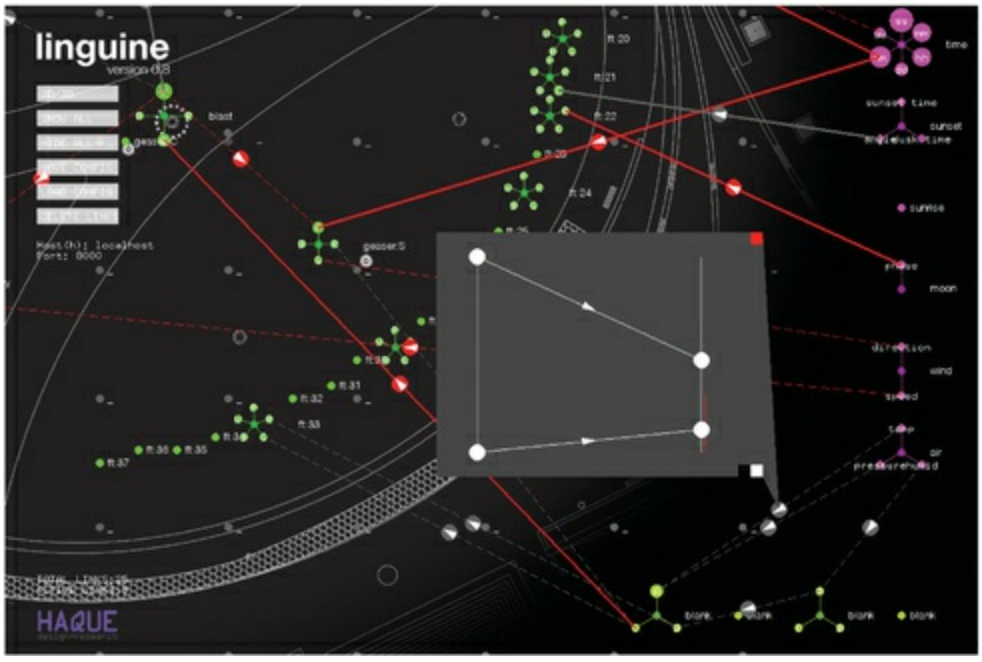


16.5a and b *Reconfigurable House* (2008).

The *Reconfigurable House*, developed in collaboration with Adam Somlai-Fischer, is an environment constructed in 2008 from thousands of low-tech components that can be "reconfigured" by its occupants (Figures 16.5a and b).[12] Any sensor/ actuator can be connected to any other sensor/ actuator – it is the occupants of the house who determine the systems that run inside it. The project is a challenge to ubiquitous computing "smart homes," which are

based on the idea that technology should be invisible to prevent DIY. Smart homes actually aren't very smart simply because they are pre-wired according to algorithms and decisions made by the designers of the systems, rather than the people who occupy the houses. In contrast to such homes, which are not able to adapt structurally over time, the many sensors and actuators of the *Reconfigurable House* can be reconnected endlessly as people change their minds so that the *House* can take on completely new behaviors. Some people may walk into the *House* and find that things are too noisy, too reactive, or maybe not reactive enough. Perhaps some people may prefer sound outputs, others may prefer lights. Still others may prefer the delicate feeling of mist. Each visitor is able to use a simple interface to configure the reactions and interactions of the house in a completely different way.[13] The "hardware" stays the same, but visitors completely transform the "software";[14] in this openness, the *Reconfigurable House* also demonstrates authentic interaction: where the system not only reacts to visitors, but, at a higher level, also changes the way that its reaction is computed. And if the *House* is left alone for too long, it gets bored, daydreams, and reconfigures itself ... The *House* consists of walls and devices that respond to sound, light, touch, footsteps, phone calls, mp3 players, and even distant remotely connected spaces. Through elements like the *Cat Brick Wall*, *Mist Laser Garden*, *Monkey Corridor,* and *Radio Penguin Ceiling*, constructed from hacked low-tech toys and gadgets, the *House* can be inexpensively recreated by even those who are not experts in electronics; this means that not only is the software of the *House* open, but the hardware is too.[15]

16.6. *Another Life,* an interactive public artwork installed in 2009 in Bradford, England.



16.7 *Another Life*: "urban operating system."

16.8 *Marling*, a mass-participation interactive urban spectacle, Eindhoven, the Netherlands (2012).

Another Life is one of Europe's largest permanent interactive public artworks, installed in 2009 in the heart of Bradford, England.[16] Integrated into the infrastructure of the City Park, the project brings the environment to life and plays on the idea of urban myths by controlling fountains, mist makers, ambient lighting, and multiple RGB lasers that draw unexpected dancing patterns of light on and around visitors in response to their movements through it (Figure 16.6). Never the same on two days running, the work encourages people to become players upon the urban stage by choreographing the projections, fountains, and ambient illumination of the park in a symphony of interactive urban experiences. *Another Life* includes interactive projections on the water and mist of the Mirror Pool that respond to the movement and actions of visitors. In order to achieve the complex interactions, we created a software engine and "urban operating system" (Figure 16.7) that choreographs and coordinates the activity of various elements within and around the pool, determining what happens when, and how the projections and fountains respond to visitors. The system continually adjusts its outputs in response to various environmental and infrared camera sensors, as well as external factors and community requirements, and in the

future may be easily modified according to designs created by local artists using control templates we have written for Processing and openFrameworks. We also created our own drivers for the RGB laser equipment, enabling us to produce distinctive lighting effects; and we developed a novel system for blurring the lasers to ensure safety while maintaining sufficiently colorful luminance in the context of relatively bright urban ambient lighting. *Another Life* gives the City Park development an adaptive and distinctive "personality," which changes over time and according to varying conditions. The richness of the interactions (created by the choreographies and the sensors and outputs) will gradually develop as visitors and the local community engage with the artwork over the course of several years.

Marling is a mass-participation interactive urban spectacle, sited in 2012 in a public square in Eindhoven, the Netherlands, brought to life by the voices of the public. In *Marling* the voices of citizens are given form through spectacular effects that hang in the air above the crowd, forming a delicate, intricate ceiling of animated color (Figure 16.8). People become players on the urban stage, together bringing the space to life through their actions and sounds, and building a shared public memory of collaboration that, hopefully, will last long after the event. It was an experiment to understand how one could actually trigger or seed activity in people and so bring out their creative side.

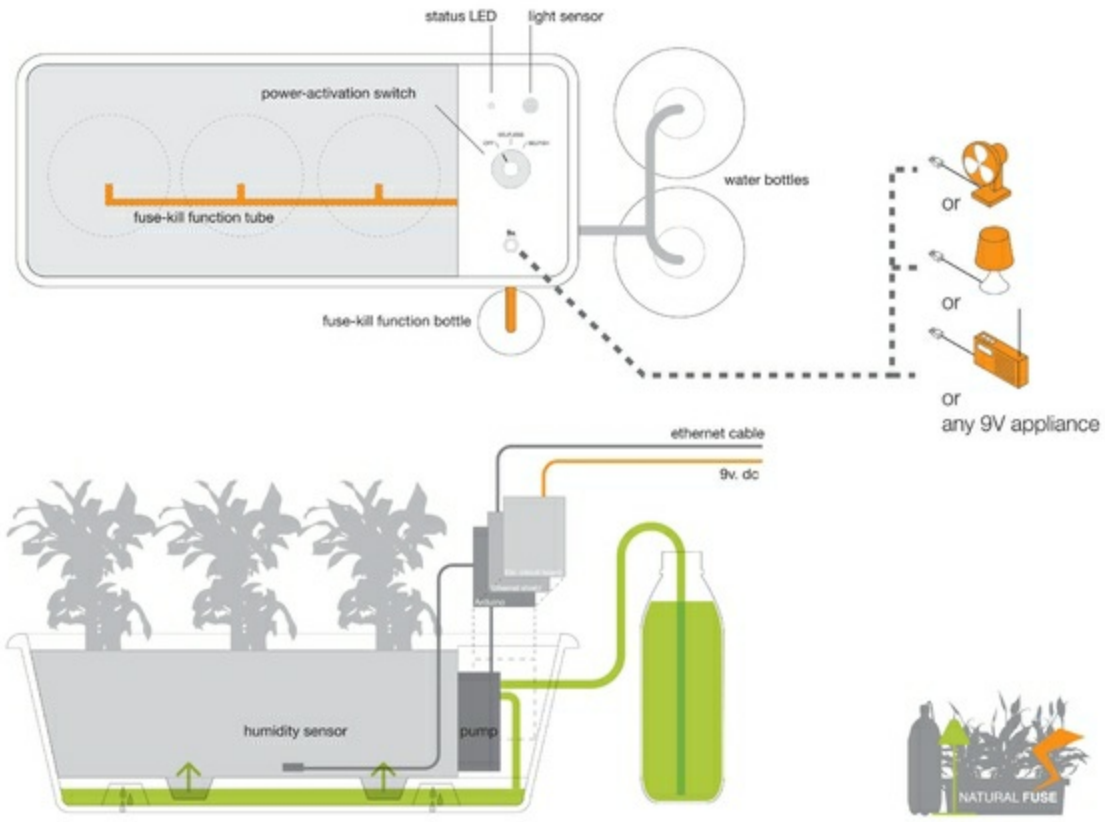
Around 2005, I built a very simple system for remotely monitoring what was going on in the *Reconfigurable House*. Two years later I launched *Pachube* as a web service that enables people to store, share, and discover real-time sensor, energy, and environment data from objects, devices and buildings around the world.[17] It was conceived as a convenient, secure, and scalable platform that helps people connect to and build the "Internet of Things." As a generalized realtime data brokerage platform, the key aim was to facilitate interaction between remote environments, both physical and virtual. Apart from enabling direct connections between any two responsive environments, it could also be used to facilitate many-to-many connections: just like a physical "patch bay" (or telephone switchboard) *Pachube* enabled any

participating project to "plug in" to any other participating project in real time so that, for example, buildings, interactive installations, or blogs can "talk" and "respond" to each other. *Pachube* was a little like YouTube, except that, rather than sharing videos, *Pachube* enabled people to monitor and share real-time environmental data from sensors that are connected to the Internet. It acted between environments, able both to capture input data (from remote sensors) and serve output data (to remote actuators). Connections could be made between any two responsive environments, facilitating even spontaneous or previously unplanned connections. Apart from being used in physical environments, it also enabled people to embed this data in webpages, in effect to "blog" sensor data. With a rapid development cycle (it can take just one line of code to start prototyping), and a sophisticated development path (working with both web-protocols and data formats that are interoperable with construction industry formats), people have used *Pachube* to build sensor-logging systems, remote monitoring apps, to integrate building management systems, to develop geo-tracking systems, to create mashups and networked objects and a whole host of other things. *Pachube* quickly became one of the central repositories for sensor data from weather stations and all sorts of monitors — for energy, pollution, radiation, etc. During the radiation crisis in Japan following the disaster at Fukushima in 2011, *Pachube* community members in Japan and around the world used it both to store real-time and aggregated radiation data, as well as to build applications on top of that data for use by others. Now, occasionally people get excited to see this kind of thing because they think there is so much data out there and there is so much we can do with the data. I don't get so excited about that — the point was not just to do something with the data, or make data public, it is for the *public to make data*. The important thing for me was to enable people to make a decision to measure something and do their own analysis of it.

The *AirQualityEgg* is a sensor system that measures urban air pollution.[18] It is a project aiming to give citizens a way to participate in the conversation about air quality. It allows anyone to collect very high-resolution readings of NO_2 and CO concentrations outside of their home. These two gases are the most indicative elements related to urban air pollution that can be sensed by

inexpensive, DIY sensors. The *AirQualityEgg* consists of a small sensing system designed to sit outside your home to take regular pollution readings. It has an RF transmitter that sends the data wirelessly to an egg-shaped base station inside (hence the name), which then relays the data into *Pachube* (now Xively), which will store and give open access to the data. That data can then be used by others to build applications, maps, etc. It is a community-developed, open source project that is driven by people who care about the air they breathe.

This project led to an interest in agency and accountability, i.e., why we are actually measuring things. I think it is because we want to hold ourselves accountable for the things that we are doing. It is about developing our own hypotheses for things that are going on in our environments, about ways in which we can actually change those things.



16.9 Schematic diagram of the *Natural Fuse*.

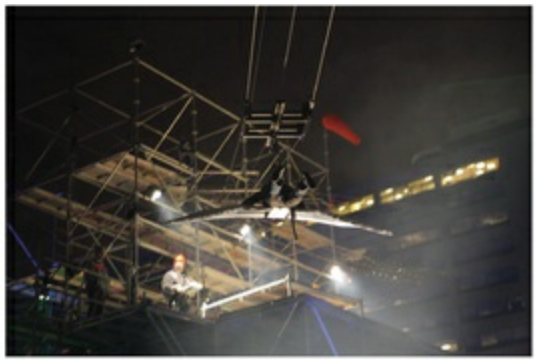
Agency and Accountability: Responsive and Responsible

Why do we want responsive dynamic interactive spaces? For me, it is fundamentally about giving people agency; it is about enabling people to feel that they are actually responsible for their environments, that the spaces are their own, that the cities and buildings are not just there to be occupied. The city is created by each of us with every single step that we take, every conversation we have, every nod to a neighbor, every wink and a smile … So when someone talks about users, I think they have already taken a step in the wrong direction, because we should be talking about people, the things that we citizens want to do, why we want do them, why we want our cities to be in a certain way. The following three projects deal with the issues of agency and accountability.

Natural Fuse is a micro-scale carbon dioxide overload protection framework that works locally and globally, harnessing the carbon-sinking capabilities of plants.[19] Generating electricity to power the electronic products that populate our lives has consequences on the amount of carbon dioxide present in the atmosphere, which in turn has detrimental environmental effects. The carbon footprint of the power used to run these devices can be offset by the natural carbon-capturing processes that occur as plants absorb carbon dioxide and grow. *Natural Fuse* units take advantage of these phenomena. They are now distributed in households in London, New York, and San Sebastian. *Natural Fuses* allow only a limited amount of energy to be expended; that amount is limited by the amount of CO_2 that can be absorbed by the plants that are growing in the system: the natural "circuit breakers." By networking them together, the plants are able to share their capacity and take advantage of carbon-sinking surplus in the system since not all *Natural Fuses* will be in use at any one time. If people cooperate on energy expenditure, then the plants thrive (and everyone may use more energy); but if they don't, then the network starts to kill the plants, thus decreasing the network's electricity capacity. Each *Natural Fuse* unit consists of a houseplant and a power socket

(Figure 16.9). The amount of power available to the socket is limited by the capacity of the plant to offset the carbon footprint of the energy expended: if the appliance you plug in draws so much power that it requires more carbon-offsetting than is available, then the unit will not power. The problem is that even low-power light bulbs draw more power than can be comfortably offset by a single plant. Therefore, all the units are connected together via the Internet so that they can communicate and determine how much excess carbon-offsetting capacity is available within the community of units as a whole. For example, if you use an appliance that draws 4 watts, and there are six *Natural Fuse* units out in the community that are not currently drawing power, then you can switch on your appliance at full capacity and comfortably offset the carbon footprint of your appliance by borrowing from the other units.[20] Building on what is known as the prisoner's dilemma in game theory, the project is as much about the structures of participation as it is about energy conservation. Rather than just having an "on/off" switch for your appliance, you are provided with a "selfless/selfish" switch. If you choose "selfless," then the unit will provide only enough power that won't harm the community's carbon footprint. But, if the carbon sequestering capacity of the community is currently low, the electricity may switch off after a few seconds – though it could be on long enough for what you need to do. If, on the other hand, you absolutely must have electricity (e.g., you hear an intruder in your apartment and you must switch on your light at full power), then you might want to choose "selfish" – which will give you as much power as your appliance needs. But, if you harm the community's carbon footprint (i.e., it goes from negative to positive), then the *Natural Fuse* system will kill somebody else's plant! Each unit actually has three lives to lose, before a vinegar shot is dispensed to the unlucky plant. So as it loses each life, an email is sent both to the owner and the owner that sent a "kill" signal; this provides the capability to communicate and explain situations to each other prior to the final execution of the plant. People's decisions to be selfish or not have a visceral impact on others in the community. By networking *Natural Fuses* together, people share their capacity and take advantage of carbon-sinking surplus in the system since not all *Natural Fuses* will be in use at any one

time. If people cooperate on energy expenditure, then the plants thrive (and everyone may use more energy); but if they don't, then the network starts to kill plants, thus decreasing the network's electrical capacity.[21]



16.10a and b *Flightpath Toronto* (2011) proposed reimagining the city with a transportation mechanism using zip lines.

Inspired by the birds of Nathan Phillips Square, *Flightpath Toronto* (2011), developed in collaboration with Natalie Jeremijenko, was a mass-participation spectacle that invited citizens to rediscover the possibilities and wonder of urban flight, with interactive lasers and hundreds of members of the public flying above a public square (Figures 16.10a and b).[22] What we wanted to do was to re-imagine the transportation systems for the urban context. We humans have become accustomed to reading a city in two dimensions but urban birds reveal a city that is fluid and three-dimensional. They pull our eyes through the spaces between buildings, on to inaccessible planes and perches; they show us the texture of the wind, and give us access to an immersive experience of urban natural systems. Birds make visible the very

medium we have difficulty seeing and the shared airspace that we need to reimagine. The square hosted an urban flight school, an interactive visual airscape, and fly-lines that enabled hundreds of people, enwinged, to re-imagine the city and the way we move through it. People learned how to fly in the flight school on the square; they strapped on wings because we wanted them to re-imagine themselves as birds. They learnt about the qualities of air, how it moves, etc. They had to go through a test to make sure that they had actually learnt what they had been going through. Then they went through a little practice run, just before sort of graduating from flight school, and then they launched off the tower platforms and went flying on a zip line[23] across the public square. *Flightpath Toronto*'s swarms of flying people experimented with an urban-scale participatory proposition: one that demonstrates the pleasures of emissionless urban mobility and creates a shared memory of a possible future.

16.11 *Vitis Veritas* is an interactive building façade lighting system that generates a living, breathing engagement with the passing public.

Vitis Veritas is a building façade lighting system (Figure 16.11) that generates a living, breathing engagement with the passing public. In contrast to most interactive façade lighting systems, it directly harnesses people's

creative interactions, improves environmental health, and even retains a neutral carbon footprint. Although the lighting system has a considerable carbon footprint even before it is switched on, climbing plants (e.g. clematis and honeysuckles) grow up the rails, helping sequester carbon as their biomass increases. The plant growth only offsets the base level energy consumption of the simplest (and least interesting) lighting effect; to generate more spectacular lighting effects, members of the public can help offset a larger carbon footprint. At the base of the façade, a "prescription" dispenser offers advice on how to help offset increased energy use by the installation. Prescriptions include things like "Pee in the shower for a week," "Ask someone a question instead of Googling," "Reuse a plastic bag instead of getting a new one," or "Plant a flower" – each of these actions has a carbon value that can be applied to lighting effects on the façade. Once somebody confirms via the *Vitis Veritas* website that they have completed an activity, they can use their "carbon budget" to paint their own patterns and animations directly on to the building façade. The more people participate, the more carbon is saved and the more spectacular the façade becomes.

As we have discovered on these projects, cooperation is difficult. Even when everybody agrees on an end goal, and even when everybody agrees on what is needed to achieve that end goal, it does not mean that everyone (or even anyone) will be able to take the first step, which is the most important step. We are interested in exploring these and other paradoxical structures of collaboration, and ways that the paradoxes can be harnessed in constructing participative architectural systems, with specific reference to interactive urban spectacles, collaboration platforms, etc.

What is a Smart City?

We see the co-mingling of the terms "smart" and "technology," where the implication is that the newly designed artifacts have some capacity to perform better than humans alone – even though that has often been the case with

new technologies. I would argue our longing gaze towards smart technologies is an inferiority complex of sorts that has arisen as daily life appears to grow more intricate and complicated. Our schedules are too busy, our roads too clogged, and our interactions too fraught, but smart devices, infrastructures, and homes promise to help us manage such complexity. Out of this, the smart city claims an even greater logical inevitability, because what use would all those smart devices, infrastructures, and homes be if they were unable to negotiate at an urban scale? Far from being inevitable, I would argue that part of the plea for smartness in cities is simply a general plea for the importance of cities themselves and an attempt to differentiate the new from the old – an ancient public relations strategy. A smart city is where city-makers want you, the networked citizen, to feel you belong. Note that, in contrast to the notion of a person being part of the city – a city remade every day through the interactions of its citizens — these smart cities are somehow conceived apart from humans. They are simply to be inhabited and connected to as necessary, not created by citizens but their progenitors – developers, master planners, and investors.

It is worth considering what it is that we mean by a "city" and why we would want, or not want, a city to be smart. Cities arise where humans and non-humans have clustered in dense geographical proximity, and one of the corresponding characteristics of such massing is that the populations differentiate themselves according to varying specialties and perspectives. Trade in general and the exchange of ideas in particular are foundations, because in dense populations one is more likely to encounter novel concepts and goods generated by others than in more sparsely populated rural areas. *Heterogeneity* is fundamental to cities and city-making.

Proclamations of urban smartness often include assurances of increased efficiency, predictability, and security. We hear of transportation infrastructure that will enable us to get to work on time, or interactive mechanisms to improve our shopping experience, or safeguards that deal with the potential dangers of urban life.[24] But these are things that make city-dwelling bearable, not an imperative, and one wonders why the creators of

such cities believe we need to be thus coerced into living in them.

My concern is that the benefits of smart cities, as they are being sold to us, sound awfully similar to the benefits that urban planners decades ago were assuring us would accrue if only we had more highways and high-rises – whose social, cultural, and environmental impact we are now bearing the brunt of. We have no idea what the smart city equivalents might be of Robert Moses' tangled, congested, and polluted freeways or the failures of the Pruitt Igoe housing complex.

I see three specific motivations behind the call for smart cities. The first is an idea that has gained a lot of currency as the Internet has become increasingly important in our lives, individually and collectively: that anything networked must necessarily be good and desirable. From connecting up all manner of sensors, devices, and environments to the web, to the frequent geographical separation inherent in our interactions with each other, the blending of network, social, and physical space is now so engrained that there are those who believe that the conduct of everyday life in me@space should look for inspiration in the social mechanisms that have evolved in cyberspace. A networked city, this argument tells us, enables better collaboration and coordination among its citizens, and any increase in participation is necessarily good. But, as Adam Greenfield has pointed out,

> Networked sociality is different from urbanity. Online, we tend to surround ourselves with people just like ourselves, in a series of concentric circles organized by affinity and affective propinquity. But this isn't how urban socialization has worked, historically, and in my view it isn't what cities are for.[25]

We cannot merely export the relatively young and naïïve interaction protocols of the web to our urban lives, since the increased participation may simply be more segmented and therefore neither sustainable nor desirable in the physical world.

Second, in a world of increasing complexity where we are far more aware that our actions can have unforeseen consequences, people – especially city managers – desire control and understanding. They aim to reduce uncertainty. This is not surprising: part of the Enlightenment project has been

an attempt to know the universe more deeply, fully, and rationally, essentially in order to control it. The often-explicit assumption that the universe is formed with knowable and definable parameters assures us that if we were only able to measure them all, we would be able to predict and respond with perfection accordingly. This is best exemplified in the "Data ->Information ->Knowledge ->Wisdom" paradigm, which is founded on the mistaken notion of data purity.[26] In smart cities, where everything is measured, managed, and manipulated as data, city managers have a Panopticon-like perspective on all aspects of city-making and city-living – what Aaron Straup Cope has referred to as a "thinly veiled god fantasy"[27] – and can therefore make apparently rational, logical, and impartial decisions. City-makers need such freedom from ethics and accountability in decision-making. They want to say: "It's not me, it's the data!," but this attempt at predictability and homogeneity, which erases any capacity for agency or accountability, is counter to everything wonderful about cities, and we find tacit acknowledgment of this dichotomy in the way that projects that engineer serendipity often round out smart city marketing material.[28] Moreover, in an attempt to measure and record everything at ever-finer resolution – building the kind of futile one-to-one map of the world that Borges described[29] – we reinforce passivity and discourage constructive creativity, since everything becomes somehow equally (un) important.

The third motivation that I see behind the promotion of smartness in cities arises from increasing competition for investment and influence at the global scale, which requires at its most basic level an attempt to develop new urban marketing strategies. Initiatives like PlanIT Valley[30] and Masdar[31] actually relied heavily on tax breaks and the promise of jobs to attract future citizens and resident businesses within a country to relocate. But a come-hither to multinationals outside the country is far more appealing when it contains within it the promise of technocratic stability, modernity, and progress. The smartness of cities appeals most to major corporations that are not themselves (though a large part of their worker populations may be) burdened by the restrictions placed on labor movement: they could be anywhere in the world,

why not move to those places that assure them of a compliant workforce, predictable infrastructure, and the capacity to underline their own innovative technology-focused marketing strategy? The fact that both PlanIT Valley and Masdar failed to materialize in their original glory after the global financial meltdown of 2009 is a testament to the investment-led nature of these projects to attract businesses. The billions of dollars that would have gone into developing the corporation-friendly city had to be diverted to baling out economies. The promotion of the inevitability of smartness in cities rather cynically preys on both individuals' fears for the future and organizational desires to rationalize their self-importance.

Smart Citizens, Not Smart Cities

It is worth noting that much of the publicity for smarter cities and a smarter planet centers on what "will" happen, rather than what "might" or, more importantly, what "is" happening; for all the advertising dollars spent on insisting on the inevitability of various futuristic scenarios, in my view the most interesting and creative urban technology developments are taking place in the hands of citizens, citizen-groups, and small agile businesses.

We have seen dozens of "Internet of Things" Kickstarter campaigns in the last year for products such as light bulbs that citizens themselves can reprogram to alert them to environmental conditions,[32] and we've seen citizens self-organizing around phenomena that concern them, like air quality (there are now dozens of *AirQualityEgg* citizen groups around the world)[33] or radiation (community groups in Japan united following the Fukushima disaster to measure and make sense of radiation data in a way that the government was incapable of).[34] What is common among these initiatives is that individuals, organizations, and hardware and software companies deal with actual urban reality, and the real innovation – the reinvention of what city-making can be – is found in the entrepreneurial and creative actions of citizens, not big

businesses, real estate companies, or the omniscience of city planning.[35] Smart citizens, not smart cities, are key.

In some senses, it is expedient for citizen participation individuals and companies to play the smart city game by adopting the language of techno-optimism, since their capacity for scale is tempered somewhat by industrial behemoths. But you can be sure that, for many of them, the real appeal of smart cities is how dumb these cities will actually be, opening themselves up to radical reimagining and re-appropriation of technological systems at an urban scale. Smartness arises in expanded human interactions and creativity, not in physical infrastructures and this is most important in the urban context. As Jane Jacobs said: "Cities have the capability of providing something for everybody, only because, and only when, they are created by everybody." [36]

Acknowledgments

Parts of this chapter have been published previously by the author.

Notes

1 Dunne, Anthony, *Hertzian Tales* (London: Royal College of Art, 1999).

2 Ackerman, Diane, *A Natural History of the Senses* (New York: Vintage Books, 1991).

3 When air moves across our skin without any apparent cause, it can seem "spooky." Air movement (by itself and in combination with temperature and humidity) is key to a "haunted" sensation.

4 In apparently haunted spaces, one often encounters wide fluctuations in humidity from bone dry to uncomfortably muggy.

5 In most spaces, large temperature change can occur as one rises vertically. Wide fluctuations in temperature can make one's hair stand on end and have been associated with apparently haunted spaces.

6 Studies have been undertaken to gauge the effects of electromagnetic fields (EMF) on people's perceptions. Some argue that electric fields from appliances, antennae, or power stations create sensations of haunting. Others note cases where none exist nearby. The gaussmeter is therefore one of the main instruments of parapsychologists. A variable electromagnetic frequency generator or Helmholtz coil will create weak electromagnetic spaces that are beyond the threshold of direct senses.

7 Humans hear sounds of approximately 20 Hz–20,000 Hz. Frequencies of 18 or 19 Hz are just outside our ability to hear — as infrasound, our bodies may perceive them subliminally, causing feelings of unease and upsetting sense of balance. A multichannel sound system creates intricate subsonic topographies while digital acoustic cancellation systems and anechoic materials minimize other noises.

8 We have shown that infrasound can correlate to feelings of unease and haunting.

9 The *Burble* is constructed from over 1 km of 6.35mm carbon-fiber rods, over 1 km of Excel D12 high performance sailing rope, approx. 1,000 latex balloons (24" and 36"), 1,000 fishing lock-swivel clips, and 1,000 *Sky Ear* boards by Senseinate/Seth Garlock. The handlebar, which controls the *Burble*, consisted of 30 m of hard black bamboo, 22 consoles, each containing an ST Micro triple-axis accelerometer provided by Spark.

10 As long as there were about a hundred people holding onto the handlebar, the 60-meter-tall *Burble* structure would stay on the ground. If they all decided to let go of it, it would fly away, which referenced the idea of the prisoner's dilemma. As long as everyone participated, everything was fine.

11 For more information, see Haque, Usman, "Notes on the Design of Participatory Systems – for the City or for the Planet", *Habitar*, June (2010).

12 *Reconfigurable House* was developed with Adam Somlai-Fischer/Aether Architecture and the Reorient team.

13 It was actually the people in the *House* who would use the touch screen to connect things to create the systems, so someone could connect "monkeys" to "penguins" to create a burglar alarm: the monkeys would go "I love you, I love you" and then the penguins would go "Waq, Waq …"

14 The software is constructed using open source programming language, Processing, and the electronics are controlled by Arduino, an inexpensive open source micro-controller. All code

used in the project can be found at: http://house.propositions.org.uk/.

15 People visiting the exhibition will find a phone number; when they get home, they will still be able to trigger devices in the room by calling a number; depending on what the occupants have decided to connect the phone to, the call can have an effect on sound, light, or movement in the walls of the *House*.

16 *Another Life* was commissioned by the City of Bradford for the City Park development designed by Gillespies and Arup.

17 *Pachube* was acquired by LogMeIn in July 2011, and is now known as Xively.

18 The *AirQualityEgg* is developed by a community effort, born out of groups from the Internet of Things meetings in New York and Amsterdam. It was successfully funded via Kickstarter on April 26, 2012, by 927 backers who pledged over $140,000.

19 See www.naturalfuse.org/.

20 Calculations of course include the energy cost of powering the electronics inside the unit itself.

21 During research and development we encountered several issues that have affected the design process. These highlight the kinds of challenge faced by "carbon sinking" initiatives in general. For example, the amount of CO_2 that a single houseplant can sink is much smaller than expected. What would you do? Use less energy? Or supersize the fuse? You might need 420 plants to offset your 50W light bulb! Second, when a plant dies, any carbon sequestered during the growth period is, in the absence of continued sequestration (e.g., by sealing it deep within the earth), soon released back into the atmosphere. A zero-sum situation depends entirely on where the arbitrary boundaries of the system are drawn. What would you do with your plant? Eat it? Bury it? Weave it?

22 *Flightpath Toronto* was commissioned by the City of Toronto for *Scotiabank Nuit Blanche 2011* and took place on Saturday, October 1, 2011. It was developed in collaboration with Natalie Jeremijenko.

23 Zip lines are a very efficient form of transportation, because it is basically gravity at work; there is little carbon footprint to maintaining a zip line.

24 As an example, see: IBM's "Smarter Planet" initiative; or the Thales Group's smart city "building blocks", published at: www.thalesgroup.com/Markets/Security/Newsletters/Critical_Infrastructure/2011/Issue_1/Newsl

25 In an email to the author, November 5, 2012.

26 In *OneTrees Frequently Asked Questions*, published by Pond and the Sanchez Art Center, Natalie Jeremijenko describes how "Smart Trees" along the Champs Elysées in Paris, embedded with chips, provide a radically reductive representation of the trees as three data points which are then interpreted by a scientific expert. Curiously and entertainingly enough, this reliance on technology and scientific authority contributes to the mystification of otherwise self-evident information about the trees' growth. She further explains that OneTrees, in contrast, demonstrates how "information can be 'read' from material phenomena itself, not as a pre-interpreted digested data packet, not delivered by an expert, not wrapped in the incontestable authority of science."

27 In "The New Aesthetic," blog post by Aaron Straup Cope, March 13, 2012. Available at: www.aaronland.info/weblog/2012/03/13/godhelpus/.

28 As Greg Lindsay describes in "Not-So-Smart Cities," in the *New York Times*, September 25, 2011: "To the folks at Living PlanIT and Pegasus, such programs are worth it because they let planners avoid the messiness of politics and human error. But that's precisely why they are likely to fail." Available at: www.nytimes.com/2011/09/25/opinion/sunday/notso-smartcities.html.

29 Jorge Luis Borges, "On Exactitude in Science," in *A Universal History of Infamy*, trans. Norman Thomas di Giovanni (New York: Dutton, 1972).

30 "Portugal granted the PlanIT Valley project 'potential national importance' status, which among other things means cheap land and generous tax breaks," in "Living on a Platform," *The Economist*, November 4, 2010.

31 "Masdar City is a special economic zone providing business benefits such as a hundred percent foreign ownership, zero income and corporate taxes, and no currency restrictions", in a press release published by Reuters, October 21, 2012. Available at: www.reuters.com/article/2012/10/21/idUS35170+21-Oct2012+BW20121021.

32 See "Internet of Things and Kickstarter – A Perfect Match?" for a good round-up at http://postscapes.com/internet-ofthings-and-kickstarter.

33 For example, the *AirQualityEgg*, a crowd-sourced initiative to monitor and respond to indoor and outdoor air quality. See www.wired.co.uk/news/archive/2012-03/29/pachube-air-egg.

34 See "Radiation Monitoring in Japan Goes DIY." Available at: http://spectrum.ieee.org/tech-

talk/energy/environment/radiationmonitoring-in-japangoes-diy.

35 See, for example, initiatives such as No-Park and Civic Action launched by Natalie Jeremijenko, Director of the Environmental Health Clinic, New York University.

36 Jane Jacobs, *The Death and Life of Great American Cities* (New York: Vintage, 1992).

17
Powerlines

KAS OOSTERHUIS AND ILONA LÉNÁRD

Since our decision to embark on a new enterprise – ONL [Oosterhuis_Lénárd] bv – that we describe as a fusion of art and architecture on a digital platform, we have realized a series of innovative projects at various scales. They are the living proof of the chosen fusion concept, showing along the way the progress of our efforts and insights that we have gained in implementing various digital technologies in the design process.

In this chapter we describe the most relevant and iconic features of our projects. Our aim of fusing art and architecture on a digital platform has been a radical attitude from the beginning. We have lived up to this initial ambition so far, having realized a number of public works of art and some larger building complexes as well. We tend not to categorize our built constructs as either art or architecture; rather, we consider them to be sculpture buildings or building sculptures. The artistic dimension led each project from the start, while the technological novelties were invented along the way with the sole purpose of realizing our vision. Typically, we invented for each project a new procedure, a new technology, and a new way of connecting the vision to the real world. We challenged ourselves to be visionary and practical at the same time. We managed to link our intuition to logic, to train our intuition as to steer our logic.

We have theorized and practiced our signature Powerlines to give shape to the swarming cloud of reference points, which forms the basis for all further design and execution decisions. The Powerlines are seen as intuitive top-down decisions imposed on otherwise bottom-up open design systems. In complex adaptive systems the information, sculpted by a combination of intuitive gestures and performative data from functional requirements, takes over the

role of the Powerlines.

Vectorial Body

The commissions we received in the early years of our joint art and architecture practice were to a large extent initiated by the art sector. In the first year, the request to organize a symposium, exhibition, and workshops entitled, "The Synthetic Dimension,"[1] which took place in Gerrit Rietveld's cute pavilion De Zonnehof in Amersfoort, came from Paul Coumans, art director of De Zonnehof and head of the local art council. Next year, an invitation to join a competition for the Garbage Transfer Station Elhorst/Vloedbelt in Zenderen (Figure 17.1) came directly from Rudolf Krudop, the curator of a regional art council.[2]

The art sector has always seen the relevance of the fusion of art and architecture on a digital platform. This is perhaps understandable since art has typically been subordinated to architecture (whereas "old-school" architects would consider architecture to be the "Mother of Arts"). We take a different point of view. We stated that art and architecture could only fuse successfully when artists and architects operate on the same scale and consider the same budget in their initial design concepts. This requires, especially from architects, an open mind with respect to the non-functional input in the design process. The architect must accept the absurd, the alien, the intuitive as the main driver for the design. On the other hand, the artist must accept the fact that the design concept should embody spaces that can be used according to some preconceived idea, often described in a program of demands. However, neither the architect nor the artist should interpret the program of demands in a spatial sense but as a description of activities without any spatial preconceptions. It is exactly this point that turns out to be the most challenging aspect of the fusion of disciplines. The moment that one draws the program as a rectangular shape, or in any other shape, one has chosen a design concept, most likely without even realizing it. It is extremely hard to

get rid of that unconsciously shaped interpretation of the program. Before one realizes it, the diagrammatic content becomes a floor plan, the walls are erected upright and that becomes the shape of the space. The fusion of art and architecture must overcome this trap.

The oval shape of the building emerged from an animation based on an intuitive 3D sketch. While the ellipsoid shape is geometrically well defined, the freeform 3D computer sketch is devoid of any meaning – it is just communicating the thrill of a complex entanglement in space. We presented the animation as an abstract design concept; there was no program, no function, just a spatial challenge in virtual reality. After seeing the animation, Mr Krudop, Director of the Cultural Council of Overijssel, invited us to take part in the competition, which we won eventually because our abstract design concept resonated with his ambition to see the building to sort out garbage in a different way. In his imagination, he already saw a well-functioning building as a large, stretched ellipsoid with an alien content, while we had no program in mind when designing. It was our intuition that made that animation, which then triggered the imagination of someone whom we did not know.

17.1 Garbage Transfer Station Elhorst/Vloedbelt (1993) in Zenderen, the Netherlands.

The competition design and subsequently the realized design were largely a continuation of the abstract animation. The 3D gesture of the sketch basically reappeared as the movements of the big dumpers driving in, dumping the garbage, sorting out the urban trash, and driving out to the trash mountain, while the ellipsoid evolved into a generous gesture shaping the doubly curved roof. By doing this we were able to combine the alien with the known, the intuitive with the functional, in surprising but equally falsifiable ways. The curvature that we introduced with the bold 160-m-long gesture embodies the series of programmatic functional blocks more effectively than a simple collage of rectangular functional blocks would have been able to achieve. The surface area of the doubly curved skin, embracing the whole building from head to neck to trunk to tail, is circa 15 percent less than the envelope of a rectangular arrangement would have covered. This discovery inspired us to attach falsifiable data to the design model from the start of any project. The fusion of art and architecture on a digital platform started to take shape.

The Elhorst/Vloedbelt building was recognized by the architectural community, receiving several awards, both internationally and nationally. We were disappointed, however, that the building was mentioned in the *Dutch Architecture Yearbook* of 1995[3] as an example of streamline style; the critic did not realize its potential and the rise of a new paradigm, that of *nonstandard complexity*. Peter Cachola Schmal, curator of the Blobmeister exhibition and the accompanying book,[4] did recognize the paradigmatic significance of our project by featuring it alongside the work of Marcos Novak, author of the ground-breaking "Liquid Architecture" essay,[5] and Bernard Cache, the pioneering master of parametric design.[6] We adopted the theories of liquid architecture and parametrics, and developed them, in combination with our own intuition of the fusion of art and architecture on a digital platform, into our own theory and praxis of building bodies, as structures conceived as whole bodies, whether to be seen as sculptures thriving in the realm of the arts or as a built form of architecture.

Sculpture Buildings

Seen in retrospect, the 1994 Sculpture City event,[7] which we organized with the support from Berry Koedam, owner of the RAM Gallery in Rotterdam, was a milestone in maturing the theory of the fusion of art and architecture on a digital platform. Almost every aspect of modern digital life – the Internet, 3D milling, virtual environments, interactivity, complexity, global connectivity, CNC manufacturing, associative geometry, serious gaming, the participation society, intuition and logic, sculpture buildings, programming, scripting, entropy levels – came together in that project two decades ago. The main driver for the event was not the innovative technology but the force of intuition, the force that wants to invade the designing and making of architecture, into the very pores and hidden niches of the design process; not intuition *per se*, though, but intuition directly coupled to data, much in the manner of an idiot savant who would have direct access to massive data.

We challenged ourselves and the young professionals we were working with to do things we had not done before, and which had not been done by anyone else before. The only thing we knew instinctively was that in theory it should be possible to do it. The *Sculpture City Cloud* series of sculpture buildings (Figure 17.2) were based on intuitive handmade sketches by Ilona Lénárd, who is trained both as an actress and sculptor. Gestures are her natural way of expression. Each of her fast and furious intuitive sketches is completed very quickly. It was that energy that we wanted to keep in Sculpture City's building sculpture proposals. We struggled to translate the powerful 2D sketches into 3D volumes that would frame that energy somehow. Later we learned how to sketch directly in 3D and how to transpose them directly into 3D structures. Some proposals are more convincing than others, but all of them share that curious ambition, that level of absurdity that overtakes the cool functionalist reasoning, which is so strongly embedded in traditional program-based architecture. We succeeded in proposing structures that could be built using state-of-the-art CNC technology, structures that could live their lives in a marriage between the real and the virtual, structures

that would behave in conversations with their users. That was in 1994, long before interaction design and social media became a major commercial component.

17.2 *Sculpture Building Cloud012* (1994) at RAM Gallery in Rotterdam, the Netherlands.

Inside the *Cloud* sculpture buildings, a virtual environment was running in real time, navigated by the users of the structure. That virtual environment was projected from within onto the surfaces of the *Cloud*, anticipating LED technology. We built for the exhibition a 1:20 scale model of *Cloud010*, including the projected navigable virtual world. The virtual environment consists of all 12 *Cloud* buildings, each of them having a characteristic behavior, expressed through synthesized sound samples. The closer the navigator – a tourist of the virtual *Sculpture City* – got to one of the *Clouds*, then their specific sounds would become more intense. After having pierced through the skin of that *Cloud*, the navigator would hear its heartbeat, an

experience that is as equally reassuring as it is disruptive.

At that point it became obvious to us that buildings could have a *behavior*, not as mimicry of natural life, but as a new alien life form, something that was not known before. In the fusion of the real and the virtual, sculpture buildings would form a new nature, displaying behavior that feels natural but is fully constructed on the basis of simple design rules, using state-of-the-art digital technologies. Some would call this artificial but we recognized it immediately as a new, very attractive form of life. From then on, for us, the building bodies were no longer formal constructs but living entities with a right to live.

Real-Time Behavior

In 1996, we were invited by Arno van Roosmalen, one of the curators of the multidisciplinary art festival R96, to propose a temporary project in public space. We came up with the concept of *paraSITE* (Figure 17.3), which was the first in a long series of parasite proposals afterwards. The way we spelled *paraSITE* had multiple meanings. We wanted the notion of the parameter to be in the name of the project, given that various parameters were used to bring *paraSITE* to life. We proposed not only a parasite in the classical sense, but an object that went through different sites by its rich connections to a variety of websites on the Internet. We designed *paraSITE* to be a multidisciplinary web lounge that was driven by sound samples taken from its immediate environment. *ParaSITE* was a true field lab; inside, one had the feeling of being on an expedition into unknown territories, of being inside an alien. We invited composers who were somewhat familiar with digital technologies to work inside *paraSITE*. The structure itself was conceived as an inflatable sculpture, always slightly under pressure. One entered *paraSITE* through a slit in the skin. For the design, we modeled intuitively interlocking volumes using a lofting technique in 3D Studio software. It was the same software we used for the *Clouds* of *Sculpture City*, but now we knew how to

make the volumes appear softer, smoother.

17.3 *paraSITE* (1996) at the R96 Festival in Rotterdam, the Netherlands.

The composers created new musical forms using the SuperCollider synthesizing software released in 1996, importing into the program sound samples from passing trams, cars, and people. We agreed to give *paraSITE* a lifecycle of 15 minutes; within each lifecycle period, a new synthesis was programmed and a new executable behavior was performed. Depending on the samples used and on the parameters chosen, the *paraSITE* would be calm and contemplative or wild and furious. We coupled the intensity of the sound to the ventilators that kept *paraSITE* under pressure, thus changing the level of pressure and therewith manipulating the level of inflation. Thus, the performances made *paraSITE* dance and shiver until midnight. After R96 *paraSITE* went on a European tour, to Budapest, Vienna, Helsinki, and The Hague, absorbing new local influences, being reprogrammed by local composers, displaying new local behavior. The *paraSITE* thus became many *paraSITEs* in one, the seed of our understanding of multimodality in time and place that formed a few years later the theoretical underpinning of the provocative *Trans-Ports* project.

17.4 *Sensorium Waterpavilion* (1997) at Neeltje Jans, the Netherlands.

E-Motive Architecture

The black volume of our *Sensorium Waterpavilion* (Figure 17.4) is a stranded sculpture; a bipolar building body; a furious sketch inside a bundle of slow curves in space; intuition coupled to logic; an alien life form; a multimodal experience; a participatory environment; an oceanic spaceship; file-to-factory CNC production; scripting; programming; real-time behavior; sound and vision; real and virtual; wet and ephemeral. Our saltwater sector of the *Waterpavilion*, in the most minimal way linked to NOX's freshwater sector, is the manifest expression of truly *e-motive* architecture. In the *Waterpavilion* all the above comes together in the serious form of a robust 1000 m^2 black body. The driving force behind the choice of architects was again a representative

from an art council, Abe van der Werff, Director of the Cultural Council of South-Holland (Culturele Raad Zuid-Holland), acting in close cooperation with master planner Ashok Bhalotra, who asked NOX and ONL in December 1993 to express the cyclic global water system; hence the choice of freshwater and saltwater sectors. Who said the client is not a co-designer? We should not underestimate the huge influence of the client's vision on the content of any project, including iconic projects. Without the client's vision, in a bandwidth between narrow-sighted and open-minded, we would never have achieved what was realized. That simply proves that everything we do is a joint effort of businessmen, the creative team, the engineers, and the end-users in an environment that changes all the time.[8]

The *Waterpavilion* was one of those rare opportunities to build both shape and content. For the shape, we were determined to realize on the building scale what we had previously developed at the scale of models and simulations; it had to be a sculpture building, without compromises. Yet, we had to work within a strict budget. We faced the questions of how not to compromise, how to stay in control from start to delivery of the body and its content. We needed to develop new design tools so we could stay in control. We quickly found out – since no one would fully understand our ambitions and certainly not the new trans-architectural language we were speaking – that we needed to be precise and specific in terms of geometry and the procedures for translating complex geometry into built form. After several iterations, we found what we were looking for – a smooth black body, shaped by the wind and sea, with a navigable colorful interior, informed by a weather station on a buoy on the sea.

The knowledge that steel manufacturer, Henk Meijers of Meijers Staalbouw, brought to the project turned out to be crucial for its success, for both NOX and our sector. He had had the CNC machines in his factory for 15 years, but no architect had ever requested using those machines in a nonstandard way. They were used only for repetitive jobs; we were the first architects to actually use these machines to their full potential. Meijers knew what his machines were capable of, and we sat together to find out what data the CNC

machines would need to do their work, which was cutting steel at angles that changed all the time. Basically, what he needed was a spreadsheet with angles. We realized that the most effective way to produce the data needed by the machine was to describe the structure through scripting, i.e., not by a CAD drawing. That was revolutionary; from then on, we knew that the making of architecture does not require drawings – all that is needed is data and communication protocols between one machine (our computer) and the other (the fabricator's CNC machine). We needed to create machine-to-machine communication, a direct link between the file and the factory. It quickly became clear to us that this file-to-factory method implied an explosive threat to traditional contracting procedures.

The behavior of the *Waterpavilion*'s building body is defined in real time by the raw data from the weather station, which are used as parameters in our lights and sound design algorithms, transposing them through a pop concert-style mixing table into MIDI numbers (1–128) for the lights and sounds inside the *Wetlab* and the *Sensorium*. Since the incoming data from the weather station monitoring wavelength, the wind speed, the percentage of salt and temperature, were always changing, the interior atmosphere was always changing too, creating new combinations of the color-lit glass fibers stretching from one pole of the body to the other and the sound samples. The behavior would never repeat itself. The body that was now enriched by its emotive factor became a disruptive technology; it was so close to one's senses that it was such a deep experience for many unprepared visitors – it was more a nightmare than a trip to paradise: it propelled them out of their comfort zone. Our best friends were discomforted by the experience. Kas' father, who was 88 years old then, refused to enter the building after a few steps, because it destabilized him; it made him insecure, not sure whether he could trust the floor. His reaction was common: we take it for granted that floors are flat, that walls are built straight up, that lights provide so many lumens, etc. Basically, one expects buildings to operate within certain comfort zones, and even optimize the expected comfort. That implies that improving buildings would require making the floors flatter, the indoor temperature more constant, the walls more flush, the lights just right … The *Waterpavilion* challenged all that;

a new paradigm was born at the scale of building: from then on, the comfort zones became the focus of our design intent.

Multi-Player Game

In 2000, Massimiliano Fuksas invited us to take part in the Venice Biennale.[9] Building upon earlier projects and having become aware of the potential of game development platforms (games are played in real time), we imagined back in 1999 a joint project with Marcos Novak. We imagined a building structure that would respond to action taken on the other side of the world. Since we both lived in port cities – Marcos in Los Angeles and we in Rotterdam – we wanted to use the word "port" in the name of the project. Since Novak had already coined the term transarchitectures (following liquid architectures), the project was named *Trans-Ports*.

Our intention was to build two prototypes, one in Los Angeles and other one in the Netherlands, but in the end only our version was realized. This was a unique opportunity to build the first virtual prototype of a responsive and, in essence, pro-active structure. We built an interactive arena covered by an array of infrared sensors located in the ceiling. The arena was divided into three concentric zones that would trigger a specific interaction with the virtual environment projected on three large, 4 x 6 m screens located around it. Moving through the arena meant triggering one or more of the infrared sensors,[10] which would affect the parameters driving the content of the virtual environment. There were three distinct modes of operation in the interactive *Trans-Ports* installation: *Handdrawspace* (Figure 17.5), *Floriade*, and *Trans-Ports* self-explanatory mode. *Handdrawspace*, designed by Lénárd, is best understood as an abstract interactive painting that consists of 3D freehand sketches emitting particles in real time.[11] We built the *Handdrawspace* as a parametric system where the size and number of dots and the background colors are subject to change. The visitors to the venue in Venice, at the Biennale, could change these parameters simply by changing their position in

the arena. We were aiming at the process of continuous operation as a condition of built constructs that people could interact with simply by stepping into it, by participating as an actor. We took a bold step from the experience economy into the participation economy, where citizens are no longer considered as consumers but as active players in the multi-player game of life. In our view, that should be the basic condition buildings should be in from the very first design concept; we consider buildings as *vectorial* bodies that can change shape and content in real time.

17.5 *Trans-Ports Handdrawspace* mode (2000) at the Architecture Biennale, Venice, Italy.

17.6 *Web of North-Holland* (2002) at the Floriade World Flower Expo in Haarlemmermee, the Netherlands.

Spaceship

Five years after the *Waterpavilion* project, we were invited by the Director of the Cultural Council of North-Holland to design their pavilion for the Floriade World Expo 2002 in Haarlemmermeer.[12] The *Web of North-Holland* (Figure 17.6) was the last commission we received via the cultural council system.[13] After the first round of design proposals we found out that the budget for the building was limited to exactly 1 million guilders (the euro came in 2002), with another million for the design of the interior experience of the North-Holland project. Unfortunately, the Board of the Cultural Council decided that the commission for the interior experience could not be given to an architect, but to a media specialist, even though we have proved to be one of those too.[14] So, we had to focus on the body, not on the content. To get through to the second round we proposed a pure flat ellipsoidal shape, beautifully made by a

metal workshop, that would land softly on the Floriade exhibition terrain like a spaceship. We remained faithful to the spaceship metaphor in the later stages of the project, but we changed its shape to become a nonstandard building (without compromise). The Board accepted our proposal.

The making of the spaceship was another story. After lengthy discussions and several unsuccessful attempts to materialize our design proposal by the space-frame builder Octatube, we decided to develop the structure ourselves. Within a week we had come up with a structural proposal that was adopted and financially backed by Meijers Staalbouw, the steel manufacturer. We took the nonstandard paradigm to the extreme, both for the structure and the skin. After we had shaped the body in Maya modeling and animation software, we invented a structural system that followed the double curvature of the shape.[15] We constructed a system of reference lines for the steel structure that were perpendicular to a surface of a twisted dodecahedron. Since the reference lines are not parallel because of the double curvature, we had to impose a fold on the steel components. We ended up with hundreds of unique steel components bolted together to form the assembly of the *Web of North Holland*. All the nodes are different; doors were special nodes, where we inserted a hinge while doubling the component. Not a single component was taken from a catalog of standard components; we built our own project-specific catalog. That became the procedure for the realization of our nonstandard buildings from then on. We consider the nonstandard to be one level up from the standard method, because the nonstandard includes all possible configurations, including every possible boxy building as well. If one considers it the other way around, the standard method of operation based on mass produced products simply excludes the nonstandard. Interestingly enough, that makes the nonstandard a generic method, with traditional Modernist architecture a specific instance of the nonstandard.

A Very Long Straight Line

17.7 Cockpit in Sound Barrier (2005), along the A2 Highway in Leidsche Rijn, the Netherlands.

Thus, complexity is generic, and the complicated is specific. To fully understand the power of the nonstandard, it is necessary to make a clear distinction between the complex and the complicated. After five years of conceptual design that started in 1998, we were given the opportunity by Mrs Nora Hugenholtz, Director of the Projectbureau Leidsche Rijn in Utrecht, to build the 1.6-km-long Sound Barrier with the A2 Cockpit building (Figure 17.7) embedded inside its long elastic lines. The project was completed by the end of 2005. She was charmed by our design concept and was taken by the advantageous commercial concept as well, since we embedded a complete 6,000 m^2 building in the sound barrier, thereby seriously increasing the amount of gross floor area the city could sell. This design concept actually is sustainability in its pure form due to the double usage of the earth, due to changing the separation of functions into the integration of functions; CIAM was finally challenged.

17.8 *CET/Bálna* (2012) in Budapest, Hungary.

The making of the Sound Barrier implied inventing a parametric design-to-manufacturing system that would allow us to produce and fit together 40,000 unique pieces of steel and 10,000 unique pieces of glass. This would not have been possible without a scripting-to-production process. We wrote in Maxscript a procedure to measure the swarm of components and their mutual relationships. That script produces a dataset that was used to directly drive the new CNC machines that were acquired by Meijers Staalbouw. Working together in a Design & Build fashion, we were able to offer the city a complete structure at a fair fixed price, contrary to the calculations made by Witteveen & Bos, an established engineering firm, who estimated the structure to be exactly twice as expensive as the budget allocated to the project. Only by taking control of the data and by taking full responsibility for its correct implementation, could we secure the project.

Projects like the Sound Barrier and the Cockpit are simply not feasible

when following traditional linear methods of tendering. By taking control of the data flow, and by ensuring that nothing is lost in translation, we were able to save 20 percent of the costs in each step of the building chain, eventually leading to a 100 percent reduction with respect to traditional risk analyses by established engineering firms and contractors. But that only works when data for the manufacturing process is an integral part of the design system. Nonstandard production does not work as a post-optimization process; it must be part of the designer's thinking from the very first conceptual thought and applied at least to the integrated structure and skin of the building.

Buildings that are conceived according to the paradigm of complexity based on simple rules and on an open design systemic approach are not shapeless. Explicit shape does matter, but it is different from what comes out of a traditional linear design process. While the complex webs of nodes and edges of the Sound Barrier and the A2 Cockpit follow their own internal rules, at the same time those rules unfold within the boundaries of a shaped boundary box, which is part of the 3D model. The 3D model is defined by long elastic lines, and one of those lines is, as seen from the top, a perfectly straight line of 1.6 km. Therefore, we are very reluctant to categorize our buildings as blobs.

17.9 *LIWA tower* (2013) in Abu Dhabi, United Arab Emirates.

Blobby designs done by some designers such as Greg Lynn, Erick Van Egeraat, Lars Spuijbroek, Jakob + MacFarlane, among others, can be adequately typecast as "streamlined potatoes" since these architects do not *vectorize* their complex design systems. They let their systems "boil and bubble" in an otherwise earthbound position, while we always inform our complex adaptive systems with a vector, so as to fly and float, i.e., to choose a direction. The vast sea of possibilities that digital technology offers requires one to choose a direction, based on a developed opinion on the direction, strength, and curvature of the vector. In our view, each complex adaptive system represents a node in a web of surrounding and invading complex adaptive systems of various dimensions, exchanging data and information via information highways that are woven as invisible filaments between them.

Powerlines

The fusion of art and architecture on a digital platform brought us what we wanted way back in the early 1990s. Our larger projects like the *CET* in Budapest (Figure 17.8) and the *LIWA tower* in Abu Dhabi (Figure 17.9) are sculpture buildings with vectorial bodies and without compromise. At the same time, they are a testimony to innovative digital design strategies. They can be seen as an intricate fusion of bottom-up and top-down strategies, whereas the signature *Powerlines* are top-down imposed on open design systems that are generated bottom-up. The powerful gesture is always there in our projects, a direct heritage from the critical-paranoid method of intuitive sketching. Salvador Dali described the critical–paranoid method as a "spontaneous method of irrational knowledge based on the critical and systematic objectivity of the associations and interpretations of delirious phenomena."[16] The generic rationale is always there in our work, and these seemingly opposite attitudes are fused in a painfully precise way, by exchanging the essence of the immediate and the emotive with the deliberate and systemic via data, written in a project-specific digital language that both the intuitive and the logical can learn to speak.

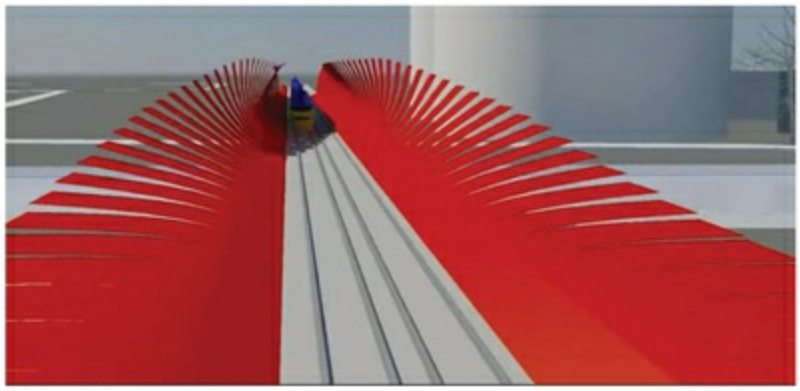
17.10 *Parametric Building Blocks* at *ProtoSPACE 3.0* in TU Delft, the Netherlands.

Interacting Swarms of Building Components

17.11 *Interactive Wall* (2009), Stuttgart, Germany.

The Hyperbody group was founded in 2000 by Kas Oosterhuis at the TU Delft Faculty of Architecture to develop and further research and education on complex geometry and interactivity, subjects that had been explored in 1990s in events such as the *Synthetic Dimension* (De Zonnehof, 1991), *Sculpture City* (RAM Gallery, 1994), and the *Genes of Architecture* (Academy of Architecture, Rotterdam; TU Vienna; Academy of Arts, Budapest, 1995), the web lounge *paraSITE* (Rotterdam, 1996), and the *Waterpavilion* (Neeltje Jans, 1997). In the early years of *Hyperbody*, several ground-breaking projects were developed, such as the *Emotive House* (TU Delft, 2001), the *Virtual Operation Room* (Delft Science Center, 2002), and the interaction laboratory *protoSPACE* (from 2003). *ProtoSPACE* became the vehicle to investigate real-time interaction using a variety of sensors and speech recognition tunneled into the

game development software NEMO/ Virtools. As long ago as 2001, we invited interactivity specialist Bert Bongers to experiment with a variety of sensors enhancing the interactivity of the relation of the designer with the virtual environment. Shortly after, the media artist Dieter Vandoren was invited to participate in the development of *protoSPACE*. Since 2000, *Hyperbody* has attracted a dozen PhD students who have investigated in detail and explored in depth the themes of complexity and interactivity. The vision leading the work of the *Hyperbody* group at this moment is that we consider buildings as *interacting swarms of (inter)active components* (Figure 17.10). Each swarm is characterized by a specified performative task, such as providing for natural daylight (windows), fresh air (ventilation), temperature (heating/cooling), seating arrangement (furniture on command), or electricity (components with embedded solar panels), etc.



17.12 *Dynamic Sound Barrier* (2010), Breda, the Netherlands.

Just That, Just There, Just Then

One project that highlights many aspects of an interactive architecture is the *Interactive Wall* (Figure 17.11), developed in close collaboration with the Festo company from Stuttgart.[17] The leading motto for both ONL's and Hyperbody's interactive projects can be adequately described as "just that, just there, just then." *Just that* means that according to the rules of nonstandard

architecture each building component is unique in its shape/configuration, either in static form (as in the built projects) or in the continuous variation of the shape (as in the dynamic projects). *Just there* means that each component fits only in one place, either in the static form, as in our built projects, occupying one particular position in a complex constellation of unique components, or driven by locally triggered actuators, as in the continuous variation of individually informed parts. *Just then* means that each component behaves in time as to respond to information that is given by moving objects like people, as in the *Interactive Wall*, trains, as in the *Dynamic Sound Barrier* (Figure 17.12), or as in future projects informed by the behavior of other dynamic constellations.

Each building component is thus considered to be an *actor* in a network of actors. Each of the thousands of actors that constitute a building plays a unique role, in a unique location, and at a unique moment in time. The train triggers a wavelike movement that takes on the role of the *Powerline* in such a dynamic constellation. As always, the trajectory of the real-time *Powerline* is subject to design, since the designer sets the rules for the behavior of the dynamic components. Naturally, the designer could reduce their role to have the components respond to exact information from the train and its noise level only, but our preference is for the designer to expand their role and instruct the components to behave in a more unpredictable and intuitive manner, while respecting their default function to reduce the noise caused by the train. That vision leads eventually to a situation where functional objects such as walls and furniture pop up only when there is a demand for them.

We seriously speculate on a possible built environment that in its default state is an empty open space, only to come to life when a specific function is required. The other way of describing the essence of the interactive projects is then: “There is only a sound barrier when you need one,” which forms the basis for the *Dynamic Sound Barrier* project.

Notes

1 Ilona Lénárd and Kas Oosterhuis, *The Synthetic Dimension* exhibition (De Zonnehof Amersfoort, 1991).

2 Mr Krudop attended a lecture by Oosterhuis in 1993 in Amsterdam, at "The Power of Now" symposium, where Lebbeus Woods was invited as the keynote speaker. The building was expected to fit into a masterplan designed by Ashok Bhalotra, who supported Krudop's choice.

3 Brouwers, Ruud (ed.), *Architecture in the Netherlands: Yearbook 1994– 1995* (Rotterdam: NAi Publishers, 1995).

4 Schmal, Peter (ed.), *Blobmeister* (Basel: Birkhäuser, 2001).

5 Benedikt, Michael (ed.), *Cyberspace: First Steps* (Cambridge, MA: MIT Press, 1992).

6 That was a few years after Robert Aish's projects on associative geometry, but a decade before Patrick Schumacher's fashionable steps into what he now promotes as *parametricism*. We are not in favor of any "isms"; we were the pioneers of an elementary philosophy back then, disclosing a new paradigm, eventually leading to a shift from Euclidean geometry towards complexity based on simple rules.

7 The *Sculpture City* exhibition, workshop, web event, book with interactive CD-ROM. Marcos Novak, Stephen Perrella, Lars Spuybroek, Maurice Nio, Leonel Moura were our guests, among others.

8 In fact, all the projects are somehow linked to the financial world market.

9 Fuksas assigned to us the upper central room in the Italian Pavilion, the same room that was taken in later editions by Peter Eisenman and Rem Koolhaas. In retrospect, we think that Fuksas' Biennale was by far the most experimental one we have seen. Today, the Biennale tends to be more and more a platform to re-stabilize the foundations of architecture and to retroactively search for basics, which are to large extent basics from the 1950s and the 1960s (Koolhaas' Biennale theme for 2014), and those are certainly not ours. Our basics are: industrial customization, file-to-factory, interacting agents, smart building components, real-time behavior, complexity, and synthesis. Koolhaas' basics (regarding building) seem to come to a full stop at the typical Modernist fascination with mass production, based on a cynical view of architecture's potential to recognize paradigm shifts.

10 The sensor arrays were designed and installed by Bert Bongers, who now runs the Interactivation Lab in Sydney.

11 *Handdrawspace* was created in the NEMO game development platform, which was later renamed as Virtools, later taken over by Dassault and renamed again as 3DVIA Virtools.

12 Ben van Berkel of UN Studio was first considered for this project. Hani Rashid and Lise-Anne Couture of Asymptote realized their first building at the Floriade World Expo 2002 in Haarlemmermeer.

13 The cultural councils used to be very strong in the Netherlands. They lost much of their power in the previous decade due to severe budget cuts by the populist governments Holland had since 2002, when the provocative anti-Islam politician Pim Fortuijn was shot to death.

14 According to the bureaucrats, one can only be a single specialist at a time.

15 That was a different and better approach than the one we used for the structure of the *Waterpavilion* where we used the standard linear structural components.

16 See: www.salvadordali.com (accessed 15 April 2014).

17 Festo is a big international player in the field of the processing industry, producing among others electronic pistons and the flexible muscles, which we used as the actuators for the Interactive Wall.

18
It is All About Particles

ENRIC RUIZ-GELI

Our interdisciplinary architectural team in Barcelona works at the interface between architecture and art, digital processes and technological material development. Our projects include stage sets and buildings, installations, and industrial products, and are realized together with various collaborative partners. We are committed to the use of new technological developments and the performative character of architecture, which creates intelligent structures in emulation of nature. We are constantly sourcing new materials and forms for our projects. We consider our buildings as moving and constantly evolving shapes, architecturally and technologically. We see architecture as alive.

Cloud 9, the name of our practice founded in 1995, is inspired by the clouds, because clouds are fiction; clouds are shapes, drawings, images; clouds are science; they are particles of water suspended in the air, tons of water suspended in the air. For our architecture, fiction is very important; it is an idea of indetermination, abstraction, poetry, music … Nine stands for the parametric, for the technology.

For us, the role of architecture is to function as a platform, stage, or landscape – a place for hosting the performance of other arts. Balanced architecture can welcome artists, map contents, or be a base or network for the ceramics industry. As a result, architecture can integrate with other arts. The architect becomes the programmer, the designer of that platform or place that functions like a mechanism or device, to be occupied by other arts. A total work of art can welcome other authorships, other identities, and other outlooks. Architecture that can lead can also accommodate; its structure disappears, and it becomes like a "score" of music for the other arts.

According to Bob Wilson, "the greatest actor is the one best at listening to

his audience." Our buildings are actors of the cityscapes and rural landscapes. They listen to local "music" and perform in a universal language. They are fully loaded with technological "weapons." They also work in harmony with nature and the balance of energies. They generate know-how in the humans who are their audience, as well as in a social context. That's our responsibility, our performance architecture: a tree (an aviary at Barcelona Marine Zoo), a wave (the San Sebastian project), a vertical cloud (the Media-TIC building), a salt mountain (the Expo 2008 SED Pavilion), or a forest (the Habitat Hotel) …

Biosphere Politics

The number one cause of global warming is architecture, i.e. buildings. Buildings are responsible for 40 percent of the CO_2 that is emitted into the atmosphere. Architects must accept this responsibility and move from geopolitics to biosphere politics.[1]

Modernism looked at nature in terms of images with their colors, details, and shapes, but we have another outlook. We try to work from the question: What is the function of nature? Basically, a tree is like a building. Can buildings work in harmony with nature like trees do?

If what matters is the process, then I think about a 1 cm^2 seed going through its process of germination, growth, mutation, and propagation as a positive, productive process. In this way, architecture can learn from nature – not from its outer image – but from its science, its activities and outcomes, its "performance laboratory."

If we knew how nature performed, about its science, formulas, inputs and outputs, we would have a parametric system – architecture from information – parametric architecture capable of dealing with its own complexity. But maybe it is dead, or programmed but not activated. We need, just as in nature, logic with blurred, vague boundaries that function as randomly and chaotically as particles of radon. We also need a creative rhythm in order to produce a certain "accident," a Virilian accident. This in turn will create

tension; an open door, a certain piece of music, visual poetry, time out from the world of information. A system error is necessary; a system error can be a "beautiful" error.

18.1 *Habitat Hotel* (2006-) in Barcelona (unbuilt).

We live in the age of information, or in other words, the digital era. We have the information of the Internet at our fingertips, and we can create information architecture. From this, we can create what are known as datascapes. Following another line of thought, we have John Cage, who

defends the indecisive nature of music. For example, 20 minutes is a piece of music that allows the musician to read the music score precisely, at the same time allows for a performance with a tempo that can be interpreted and is flexible. Thus we have music that changes with each moment and each "repetition." An unrepeatable repetition – now, that's very interesting …

Habitat Hotel: Your Room in a Tree

In 2006, we designed for the hotel group Habitat a hotel building (Figure 18.1) to be situated on the Gran Via de L'Hospitalet in Barcelona. The building emulates the natural functions of a forest; it attempts to harness the forces of nature in its new urban façade. It is based on the concept of "your room in a tree," which proposes a façade composed of a mesh with 6,500 devices – each with a photovoltaic cell, a battery, and three LEDs, which will vary their color according to the weather and the seasons. These devices, as well as illuminating the façade differently according to the day, will store solar energy to then reproduce it inside the hotel, thus seeking a saving in energy. With the aim of demonstrating its commitment to environmentally conscious architecture and of taking the guests into a forest, the hotel's design features a kitchen garden on the ground floor, designed by Vito Acconci, plus an Amazon garden on the top floor, designed by Ruy Ohtake, with seeds to be brought from Brazil. There is also a bubble-shaped meditation room designed by Evru and the staircase proposed by the Dutch studio Droog Design, which will mark on each step the number of calories used when climbing them.

On one hand, the building is a concrete structure with extremely functional glass façades. On the other, the daytime and night-time image of the hotel, combined with the developer's sustainable energy philosophies, have resulted in a surface "skin," a stainless steel mesh that wraps itself around the building's "compact" external shell. This creates a microclimate in the space between the regular façade and the outer skin of the building. The experience of these in-between spaces is determined by the forces of nature, the spaces'

vertical positioning, and the "green" cladding applied to the building's façades and roof. However, there is also an artificial aspect to the project. The building's outer skin is made of metal Inox cables supporting thousands of intelligent LED lights (color particles) and photovoltaic plates (the "leaves").

18.2 *Thirst Pavilion* at Expo 2008 in Zaragoza, Spain.

Thirst Pavilion

The city of Zaragoza hosted the international "Water and Sustainable Development Expo" in 2008, which was held along the banks of the River Ebro. Cloud 9 designed the *Thirst Pavilion* (Pabellón Sed, Figure 18.2), which was situated in the middle of the Expo grounds. The dome-shaped structure, which is 36.7 m in diameter and 10 m high, is constructed to resemble the molecular map and structure of a salt crystal, reproducing salt's microscopic

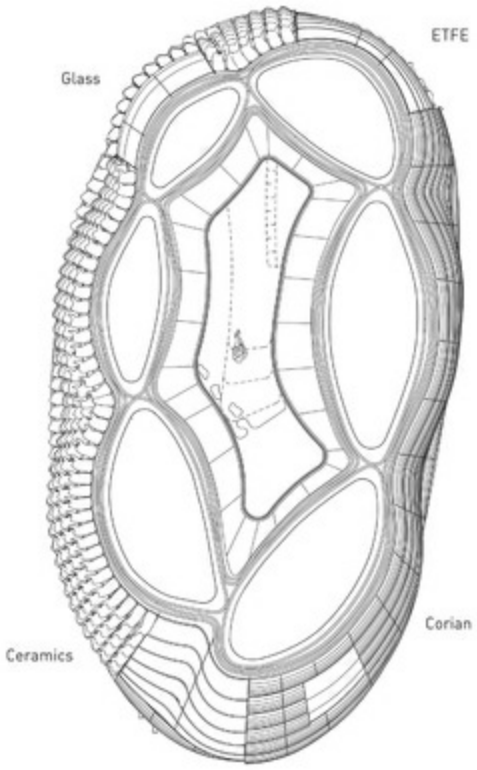
structure and natural organic form. Salt and water were flowing across the building's façade; as the water evaporated, the salt was deposited on its surface, thus creating a natural icon in the form of a "salt igloo." The pavilion's steel frame was sheathed in white hexagonal panels made of a multiple-ply ETFE membrane that allows natural light to enter, but heat to escape. It was constructed in such a way that it could be easily disassembled if needed. The whole structure supported a layer of salt that was produced by a metered system of water and salt irrigation, therefore allowing the thickness of the salt layer to be controlled and so prevent the mixture of water and salt from trickling down the inflatable ETFE plastic façade surface. This system also helped the water to evaporate and the salt to adhere immediately to the building. More importantly, however, the building was meant to host the public functions that were the project's main purpose.

18.3 *Villa Nurbs* (2009) in Empuriabrava, Spain.

Villa Nurbs

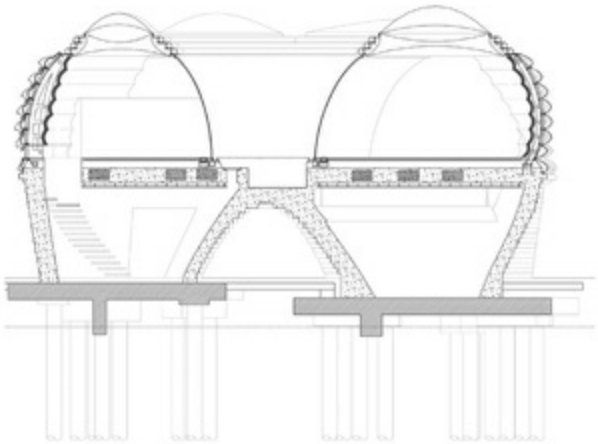
Villa Nurbs in Empuriabrava, Spain, completed in 2009, is an organically formed, ecological, futuristic house (Figure 18.3), a morphing of space between car space and the space of a boat (the house is accessible by both the car and the boat). We wanted to create the experience of forms that suggest the accidental breaking of ice – the volumes of water produced by the crashing of ice. Then we wanted to find out how natural materials define a landscape, a landscape of pavilions. The construction of that landscape had to become a platform to be inhabited. Other considerations were the routes, the movement of people, and seasonal exposure to the wind and sun.

We measured and constructed this inhabited landscape as topography in 3D, using NURBS[2] to digitally model its surfaces, its curved shapes in 3D (Figure 18.4), which is how the house got its name. We used a different resolution for that topography, by creating contours at 5-cm increments, using 15 cm for the concrete on the lower level, and 45 cm for the steel at the upper level (Figure 18.5). The digitally modeled NURBS geometry became a reference for defining materiality of the house (Figure 18.6), which was one of the goals of the project.

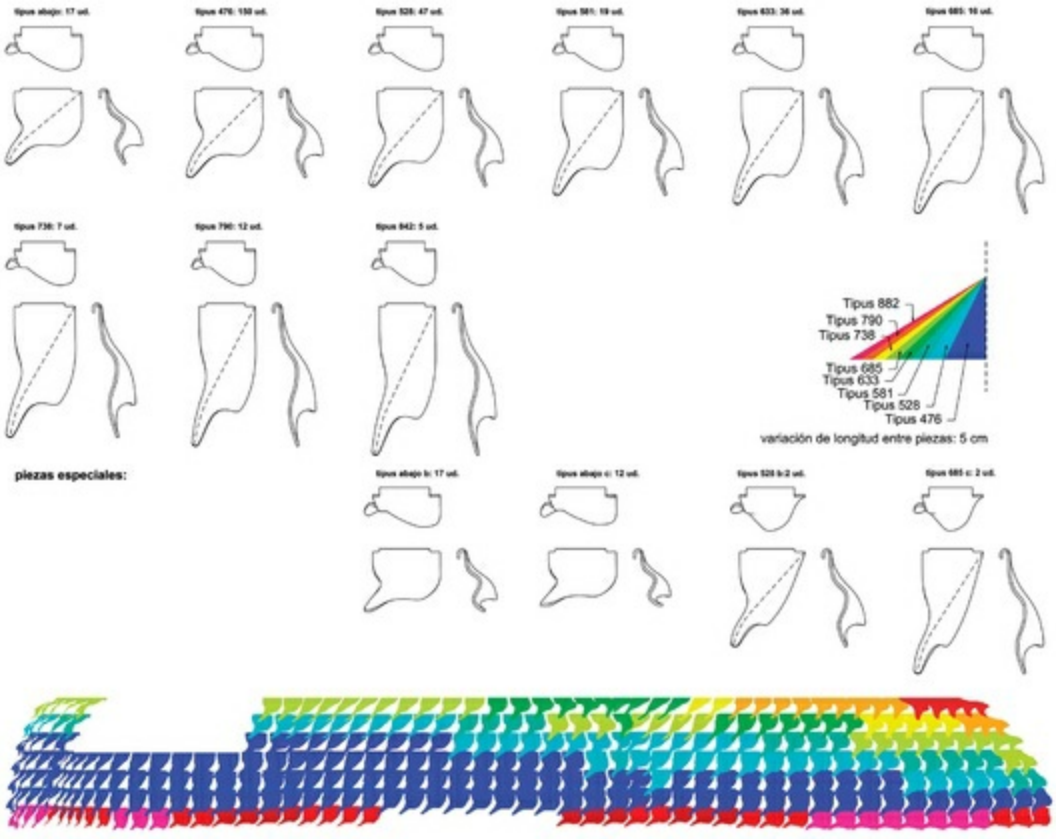


18.4 *Villa Nurbs:* top view.

The original idea was to have a series of separate pavilions, but as the design evolved, the pavilions were amalgamated into one structure organized around a central swimming pool (Figure 18.7). The house is located on the Costa Brava in Spain, so it gets a lot of sun year round. We were looking for alternative materials to regulate the building's interior temperature (see Figure 18.4). The house has a heavy concrete base but it gets lighter as it rises. The south-facing wall of the house is covered with wavelike ceramic tiles that insulate the interior from solar radiation; the north-facing wall is covered in translucent panels made from Corian (Figure 18.8). The roof is covered with six ETFE pillows made from patterned layers (Figure 18.9), which inflate and deflate, creating different pattern densities to control levels of light and solar radiation.[3]



18.5 *Villa Nurbs*: cross-section.



18.6 *Villa Nurbs:* definition of the geometry for the ceramic tiles.

18.7 *Villa Nurbs*: the house is organized around a central swimming pool (photographed during construction).

18.8 *Villa Nurbs:* ceramic tiles cover the south-facing wall; translucent Corian panels are on the north side of the building.

18.9 *Villa Nurbs*: the roof is covered with six ETFE pillows made from patterned layers (photographed during construction).

18.10 *Villa Nurbs:* each tile had a different firnish by Frederick Amat.

Particles of fiberglass are embedded into the concrete to reinforce its strength; we also had particles of aluminum in it. All installations, i.e., building systems, are embedded into the concrete, which is post-tensioned. The complex topography of the building's concrete base was contoured with the resolution of 15 cm. We were looking for a specific texture, mixed with the salt in the air. We also used translucent concrete. There are also LEDs behind the concrete and an Arduino board with an IP address, allowing text messages to be displayed in the concrete, such as "We are not home," "Who are you?," etc. For us, that is the idea of architecture and content. When technology is embedded, then content is material – in the concrete.

There are no standard parts in the house – everything is bespoke: the cable system in the concrete structure, the car body-like steel frame, each Corian façade panel, every single ceramic tile, every ETFE pillow, etc. We developed the steel structure at a resolution of 45 cm, using CAD/CAM production processes. We discovered that the CNC machine that curves the steel works

with Excel files, so we could go directly from the 3D model in Rhino to Excel, and then directly to the machine that curves the steel, without any intermediary steps. That enabled the continuous evolution of the design because we knew we could go directly into production. We were also looking at architecture and engineering that are driven by performance. The ring of steel in the middle, around the pool, is suspended structurally, and it was changing constantly as we fine-tuned the design of the house. The structural engineers, BOMA, would daily calculate the steel structure, as it changed, in a simultaneous interplay of architecture and engineering.

The wave-shaped ceramic tiles and the Corian plates, and the glass panels surrounding the pool were all produced on CNC-milled molds, directly from the 3D NURBS model. Each sheet of clay was custom-shaped (see Figure 18.6) and CNC cut, which ceramist Toni Cumella would then place over the CNC-milled polystyrene mold. The clay would then deform by its own weight, thereby taking the shape of the mold. Painter Frederic Amat would then apply layers of black and transparent glazes (Figure 18.10), using particles to create a different finish for each tile, giving life to ceramics. Vicky Colombet applied particles of blue paint to each of the 25 uniquely shaped pieces of glass around the pool; where there was more solar radiation, more particles were applied, making the glass more opaque. (We don't want to be space-driven or object-driven – we are particle-driven.)

18.11 The *Media-TIC* building (2013) in Barcelona, Spain.

Media-Tic

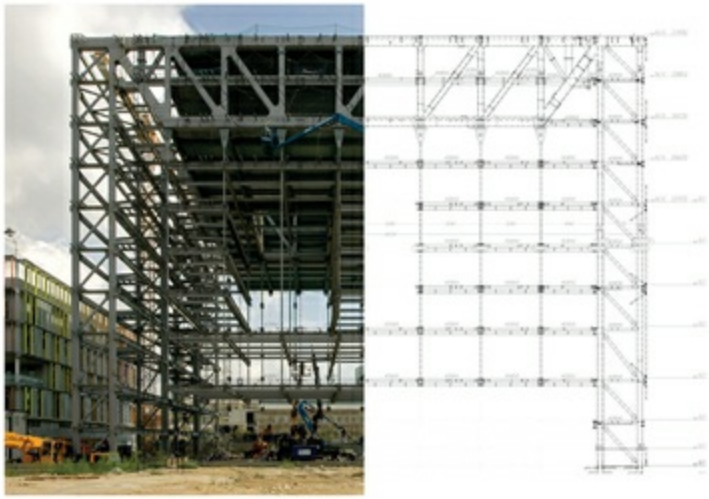
While buildings are responsible for 40 percent of global CO_2 emissions, architects have the responsibility to construct buildings that only consume the energy they produce – that would be an architecture that performs the way nature does. We approached the design of the *Media-TIC* building in Barcelona (Figure 18.11), completed in 2013, with such an all-in-one ethic and aesthetic: unlike other buildings, which consume huge amounts of energy, the *Media-TIC*[4] is designed to be a great generator of energy that also optimizes

energy use. The building was developed by the Zona Franca consortium in the city's new science and IT technology district (22@ Barcelona) to house communications and information technology companies and organizations under one roof, with a publicly accessible auditorium, exhibition space, and workshop spaces at the ground level. It functions as a container and a platform at the same time; it is a technologies house, a place of diversity projecting an image of unity.

The building volume forms a cube of 44 m x 44 m x 37.82 m high; the site is 3,572.45 m^2, in which the basement occupies the entire area, while the above-ground structure occupies a little over half of the total area. In total, the *Media-TIC* has 16,000 m^2 above ground and two floors below ground (7,100 m^2), with a 200 parking spaces capacity. The building is divided vertically: the upper floors (from eighth to fourth) are rented to large companies; smaller spaces on the second and third floor are for emergent companies; the first floor functions as a public civic area, with the Cibernarium and an auditorium, offering educational programs open to the public. The ground floor provides a large, column-free open space that is 36 m x 40 m in size, which is accessible by the public and is used to host exhibitions, workshops, and events.

We collaborated on the *Media-TIC*'s structural design with Agustí Obiol from the engineering firm, BOMA.[5] In our view, the structure for the digital environment of *Media-TIC* should not be about gravity, or mass, or tectonics; it should be about connectivity, links – it should be tensile, with ties. The building's steel structure is made up of four large, rigid, braced portal frames that are 14.25 meters apart.[6] The frames work principally in tension rather than compression, with floors suspended from the trusses at the top of the building (Figure 18.12). As a consequence, the floors were constructed from the top, moving downwards, after the load-bearing portal frames were erected. BOMA braced the structure against deformation with an irregular steel lattice over the surface of the building (Figure 18.13), using parametric processes to calculate an optimal steel structure. The impact of the structure is minimal; it takes only 8 percent of the total floor surface area, leaving about

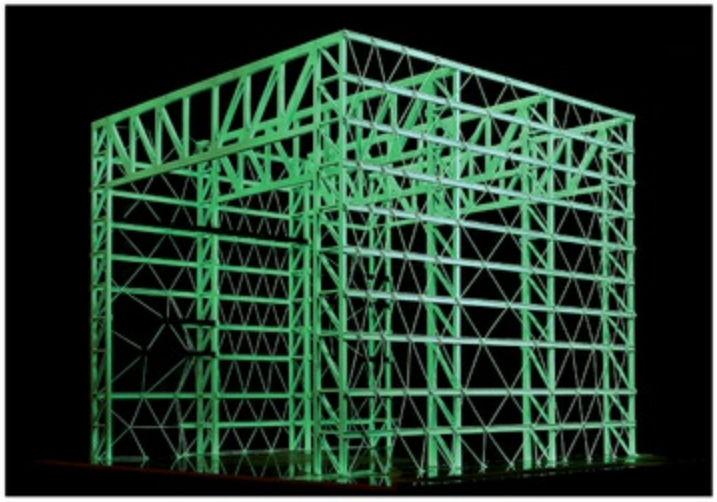
1,500 m^2 of column-free space at the ground level. The structural elements are coated with green luminescent paint, making the building look bio-luminous at night, without the need for additional lighting (Figure 18.14).



18.12 *Media-TIC*: floors are suspended from the trusses at the top of the building.

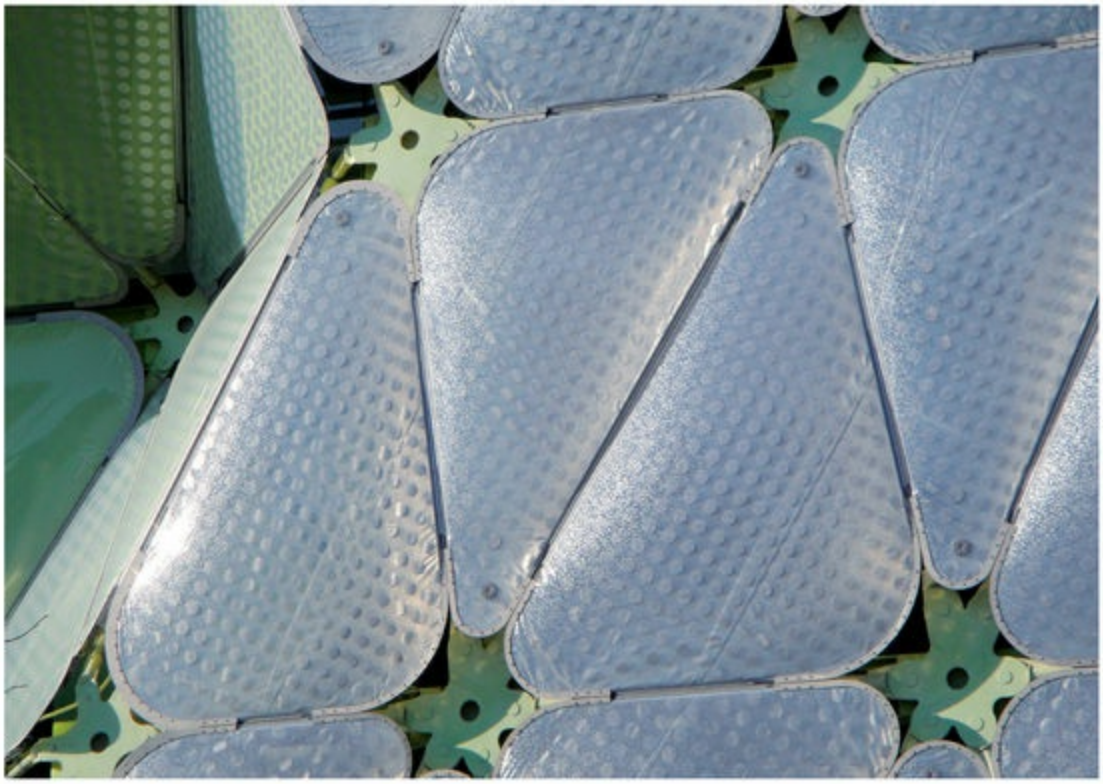
The sun-facing façades of the building are covered in ETFE (ethylene tetrafluroethylene) inflatable cushions, which act as the building's energy-saving dynamic skin (see Figure 18.11). The south-east façade, facing Calle Sancho d'Avila, has a network of triangular air cushions (Figure 18.15). Each cushion has several layers of 0.6 mm thin ETFE foil, creating inflatable/deflatable air chambers between them that work like a diaphragm. The first layer is transparent, while the second (middle) and third layer have a reverse pattern design; when the air chamber between these two patterned layers is deflated, they are joined together, creating shade by forming a single opaque layer. Such a dynamic skin can provide different degrees of shading and thermal insulation through inflation or deflation of the air chambers, responding in real time to the location of the sun. The south-west façade is covered with 40-m-long vertical air cushions that are filled with "fog," made of nitrogen mixed with oil particles, as the sun moves westward to create a milky-white translucent envelope (a "cloud" sunscreen) that blocks 80 percent of the incoming UV radiation (Figures 18.16a and b). The ETFE membrane's

light and anti-adherent nature maks it very versatile, protecting the building's interior with a sun-filtering factor of 0.20. Its 2,500 m^2 are estimated to provide energy savings of 20 percent and will score 42 points of the maximum 57 points envisaged by the degree on environmental criteria and energy eco-efficiency for buildings.[7]



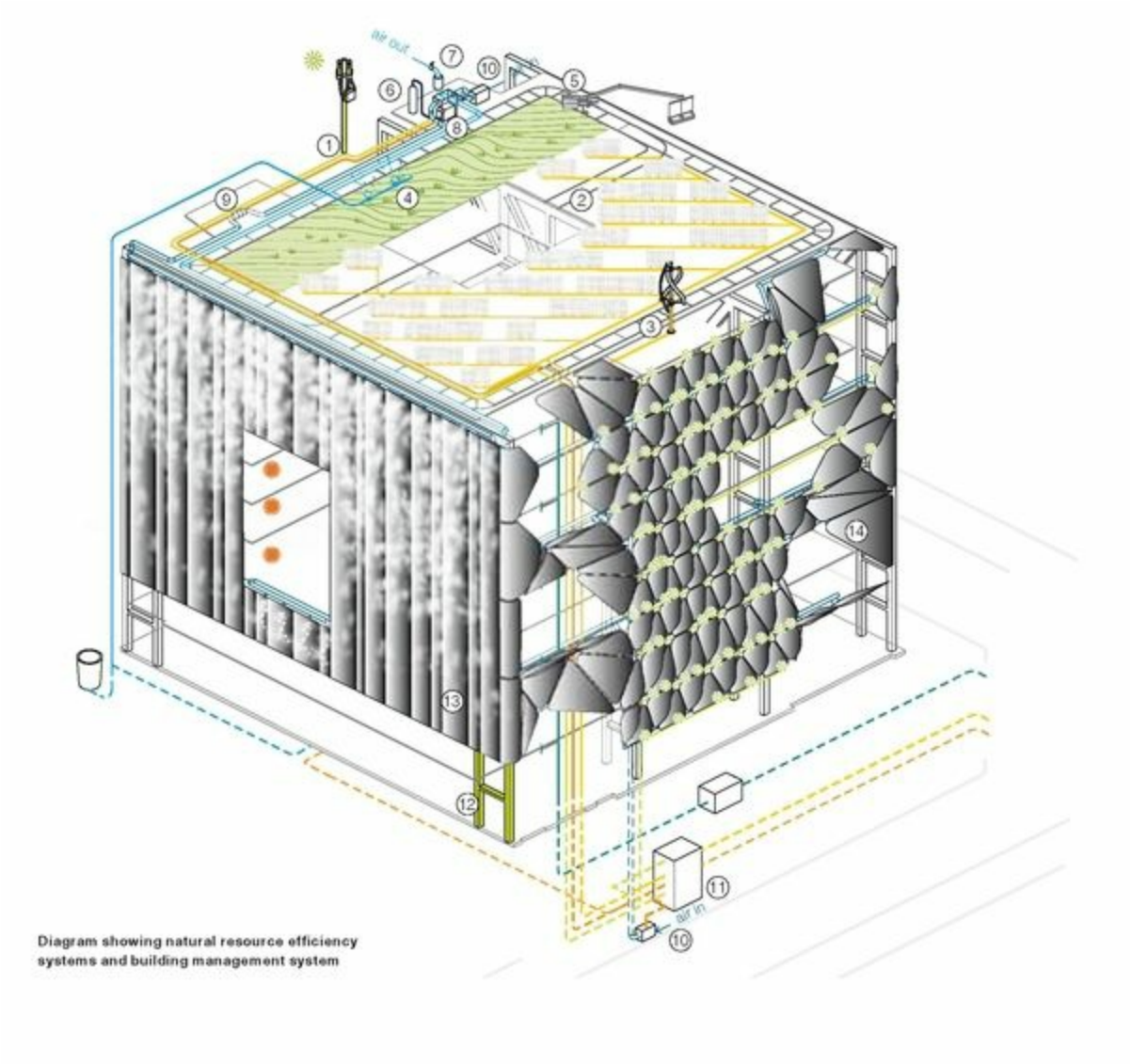
18.13 *Media-TIC*: an irregular steel lattice braces the structure.

18.14 *Media-TIC*: structural elements are coated with green luminescent paint.



18.15 *Media-TIC*: inflatable ETFE cushions can provide different degrees of shading and thermal insulation.

18.16a and b *Media-TIC*: the south-west façade is covered with nitrogen-filled air cushions.



18.17 *Media-TIC:* the building performs its own climate control with a distributed network of sensors.

The building relies on an Arduino-based network that connects over hundred sensors that measure heat and the sun's angle to the ETFE cushions, controlling their diaphragm or fog actuation, and making the building adapt to the sun's changing position by becoming more or less opaque, saving energy by reducing solar radiation. The building performs its own climate control with a distributed network of sensors, Arduino controller boards, and pumps that control the ETFE cushions (Figure 18.17). Additional energy savings are produced with presence sensors inside the building that control its artificial lighting. This distributed network decides effectively what happens within and on the building, and it is not some kind of central brain that gives instructions.

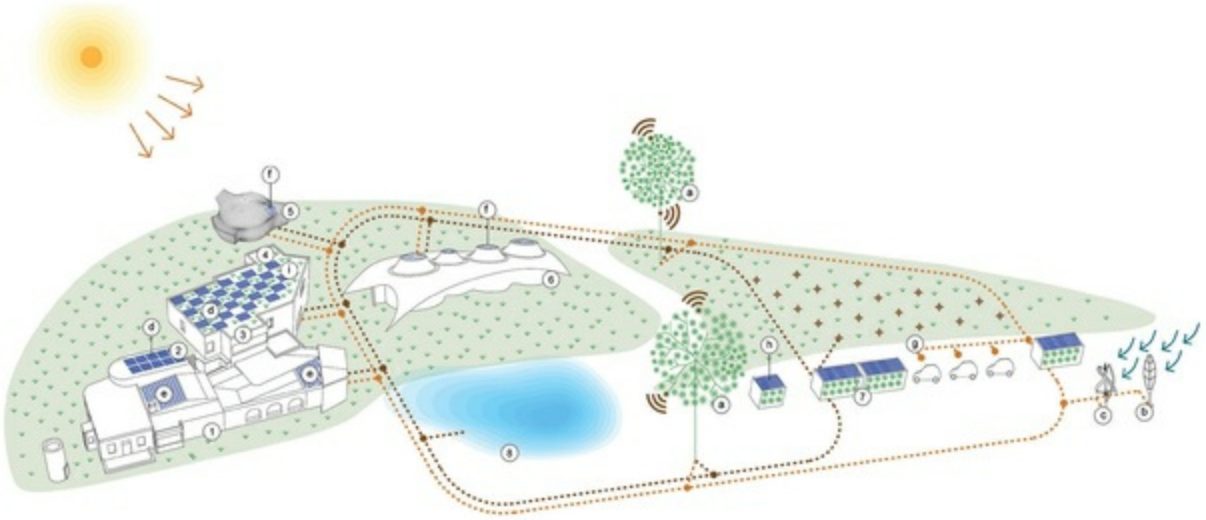
As *Media-TIC* is a workspace building with public access, its dynamic adaptation to environmental conditions can be observed by a relatively large number of people. It is a twenty-first-century performative symbol of energy sufficiency: it has a 20 percent CO_2 reduction due to the use of district cooling and clean energy; 10 percent CO_2 reduction due to the photovoltaic roof; 55 percent CO_2 reduction due to the dynamic ETFE skin; and 10 percent CO_2 reduction due to energy savings related to smart sensors. That's a 95 percent CO_2 reduction compared to a conventional building of a similar size. *Media-TIC* is close to being a net-zero building.

18.18 Masterplan for the *elBulli Foundation,* featuring spaces for the elBulli archive and the brainstorming of ideas, a thermal house, and various other buildings for experimentation.

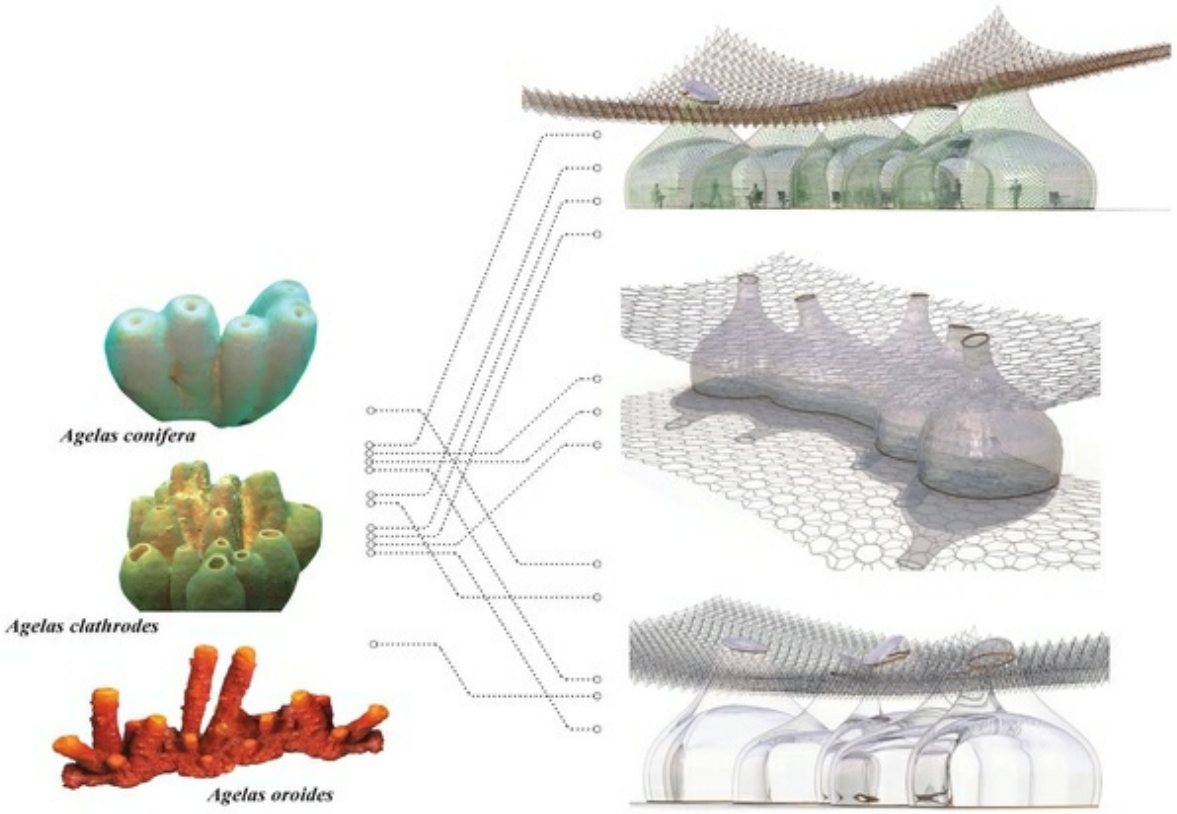
The Elbulli Foundation

We have recently completed the design for the *elBulli Foundation*, located in the Montjoi de Roses cove, in the Cap de Creus national park, in Girona. The Foundation will continue the activities of Ferrán Adrià's famous restaurant,[8] that closed in 2011. The project involves renovating the original building, part of which will be torn down, and building new facilities on a site with a 15-metre drop. The total built area will be close to 5,200 m^2, with new premises that would house galleries for exhibits, and an archive and a centre for research and training in avant-garde cuisine, and a residence for some members of the creative team (Figure 18.18). The new gastronomical complex will take advantage of natural ventilation and micro-eolic, photovoltaic, and geothermic energy (Figure 18.19).The project should be completed in 2016.

The *elBulli Foundation* is essentially a laboratory for cuisine culture on the Catalan coast. According to Ferran Adria, it will be a private, non-profit foundation for "all avant-garde gastronomy lovers, chefs, sommeliers, front-of-house professionals, gourmets, creative thinkers including writers and philosophers and people from the street, too." He wants it to be a think tank of gastronomic creativity, granting annual scholarships to chefs and front-of-house professionals who will work with the Foundation's creative team. It won't be a school. Adria seeks a synergy with other disciplines such as design, art and creative communication to pursue feedback, interaction, and projection beyond the world of gastronomy.



18.19 The *elBulli Foundation* will be a zero-emission pilot relying on wind, sun, wave and geothennal energy.



18.20 The organic particle architecture will interpret the concept of the network via sponges and of buildings as living coral structures.

The elBulli is a spirit, a way of seeing life. The Foundation is very much work in progress, full of experimentation. Ferran Adrià and Juli Soler, his associate, needed a space to think, create, and have ideas, with a view of the ocean. The elBulli restaurant was an assemblage of boxes but we saw something more mellow in the local topography; elBulli has a "techno-emotional" kitchen and we want its architecture to manifest its culture through a "techno-empathy."

Programmatically, the *elBulli Foundation* is an archive of the 15 years of activity and a creative center, one that will feature a cinema, for elBulli's ideology and experiences. We are converting the existing dining room into a historical archive about elBulli, and there will be five different "thinking spaces." The architecture of the Foundation will have stage spaces, each with green roofs, operating on the physical, digital, and interactive level. For the cinema/ brainstorming space we experimented with 19 different parametric prototypes. Our design concept makes it a "sister" of elBulli's kitchen – our organic, particle architecture will interpret the concept of the network via sponges and of buildings as living coral structures, for example (Figure 18.20).

Ferran Adrià and Juli Soler have asked us to include "experiences in special places" around the site. One of them, the Nido Experience, is a balcony made from the feathers of birds from Cap de Creus. There will be an observatory with a partially buried entrance. The observatory design is inspired by coral, bone, and limestone with holes to let in light or focus on special views of the sky. "Thinking spaces" distributed around the complex will feature translucent canopies and glass façades facing the sea. There is also a diving board-like structure called "The Trampoline."

The *elBulli Foundation* is located in a beautiful natural park whose biodiversity makes it a paradise. It will be a zero-emission pilot project in terms of sustainability, relying on wind, sun, wave, and geothermal energy –a self-sustaining smart grid to make a point of self-sufficiency. Our masterplan creates an eco-neighbourhood on the site which is nearly 14 hectares. We want to protect, conserve, and increase the biodiversity here. Our scheme includes a seascape on the site that deals with the creation of hydrogen from algae, as part of our collaboration with Tecnalia, one of the most important

companies in the Basque region. The firm performs advanced research and development of biomaterials among other things, and investigates the potential of algae as an alternative biomass to generate renewable energy, optimizing hydrogen technologies.

Particles Architecture

For us, architecture is articulated transversally by particle theory, from the visualization of landscape to the design and construction of the architectural project. Jorge Wagensberg, Professor of Physics at the University of Barcelona, says that the most important thing about particles is their relationships – the relations between the CO_2, ultraviolet light, photosynthesis, salinity, relative humidity, a natural park, geothermal qualities … Reality can be interpreted at the level of the particles that provide us with information, designing strategies for the interpretation of both the tectonic or material (territory, buildings, people) and the climatic or incorporeal (light, temperature, relative humidity, rain, wind, salt, CO_2, photosynthesis). Using 3D laser scanning technologies and sensors on site, the landscape is recorded as particles and not as geometric locations or simply as numerical data (Figure 18.21). The reproduction of this particles landscape maintains a direct link with the territory, which in turn enables the project to be understood not as a graft from outside, but, rather, as something that emerges from within. The natural environment for working with particles surpasses proprietary software and introduces environments that are more generic. They are managed through the use of free programming environments (processing), progressing from the exterior morphology of the project to the performance of its parts or internal composition. Work with particles allows not only formal development but also direct transposition from the 3D file to the construction. In this way, the *particles architecture* becomes part of a discourse that makes no distinction between objects and products, buildings and landscape, sea and mountain, but which understands reality, and therefore the architectural project, as

performing particles. That will be the change in architecture, the architecture of change: an empathetic understanding of a society in which human beings and nature speak a common language, that of particles architecture – an architecture that is alive.

18.21 It is all about particles.

Notes

1 Our commitment to ecologically advanced buildings is influenced by the sustainable values promoted by Jeremy Rifkin, American economist and author of *Biosphere Politics: A New Consciousness for a New Century* (New York: HarperCollins, 1992).

2 NURBS stands for Non-uniform rational B-spline, a mathematical model for generating and representing curves and surfaces in computer graphics, i.e. in 3D modeling software.

3 This is one of the six patents granted to Cloud 9 that were embedded in the design and construction of the house.

4 The *Media-TIC* building won the top prize at the 2011 World Architecture Festival.

5 *Media-TIC* won the European Award for Steel Structures in 2009.

6 We decided to invest 40 percent of the construction budget in the structure of the building, instead of the normal 25 percent or 30 percent.

7 We have patented the ETFE diaphragm and the ETFE fog.

8 Ferran Adrià is the world-famous master chef of elBulli, which has been called the best restaurant in the world. Accommodating only 8,000 people a year since Adrià took over as co-owner in 1990, elBulli is renowned for its 18-month waiting list for the June–December season, the only period when the restaurant is open. elBulli closed in 2011 to undergo a reinvention; it will be set in the same location as the *elBulli Foundation.*

Appendix

Biographies

BRANKO KOLAREVIC
Professor and Chair in Integrated Design
University of Calgary
Calgary, AB, Canada

Branko Kolarevic is a Professor at the University of Calgary Faculty of Environmental Design, where he also holds the Chair in Integrated Design. Prior to his appointment at the University of Calgary, he was the Irving Distinguished Visiting Professor at Ball State University in Indiana. He has taught architecture at several universities in North America, including University of Pennsylvania, and also in Asia, at the University of Hong Kong. He has lectured worldwide on the use of digital technologies in design and production and has authored, edited, or co-edited several books, including *Manufacturing Material Effects: Rethinking Design and Making in Architecture* (with Kevin Klinger), *Performative Architecture: Beyond Instrumentality* (with Ali Malkawi), and *Architecture in the Digital Age: Design and Manufacturing*. He is the past president of Canadian Architectural Certification Board (CACB) and past president of the Association for Computer Aided Design in Architecture (ACADIA). He is a recipient of the ACADIA 2007 Award for Innovative Research and several awards for teaching, at the University of Miami and the University of Hong Kong. He holds doctoral and master's degrees in design from Harvard University and a diploma engineer in architecture degree from the University of Belgrade.

evds.ucalgary.ca

VERA PARLAC
Assistant Professor
University of Calgary
Calgary, AB, Canada

Vera Parlac is an architect and educator focusing on integrative approach to design and practice. She is a registered architect in Pennsylvania, USA, and an assistant professor at the Faculty of Environmental Design at the University of Calgary. She received a diploma engineer in architecture degree from University of Belgrade and master's degree in architecture from University of California, Los Angeles (UCLA). Vera Parlac is one of the cofounders of the Laboratory for Integrative Design (LID), a design research laboratory where design is engaged as a broadly integrative endeavor by fluidly navigating across different disciplinary territories.

Vera's current design and research is focused on responsive material systems and informed by contemporary models in biology, material science research, and mechatronic systems. Her research centers on experiments with composite materials that embody behavior and have capacity to adapt under external and internal influences, testing a threshold between a composite material and an architectural assembly.

Prior to her appointment in Calgary, she taught design and other subjects at several universities in North America, most recently at Temple University, and in Asia, in Hong Kong. Vera has worked in architectural firms in Philadelphia, Toronto, Boston, Miami, and Los Angeles, including Carlos Zapata Design Studio and Kieran Timberlake Associates.

evds.ucalgary.ca

MICHELLE ADDINGTON
Hines Professor of Sustainable Architectural Design
Yale University
New Haven, CT, USA

Michelle Addington is a Hines Professor of Sustainable Architectural Design. Prior to teaching at Yale, Ms. Addington taught at Harvard University for ten years and before that at Temple University and Philadelphia University. Her background includes work at NASA/Goddard Space Flight Center, where she developed structural data for composite materials and designed components for unmanned spacecraft. Ms. Addington then spent a decade as a process design and power plant engineer as well as a manufacturing supervisor at DuPont, and after studying architecture, she was an architectural associate at a firm based in Philadelphia. She researches discrete systems and technology transfer, and she serves as an adviser on energy and sustainability for many organizations, including the Department of Energy and the AIA. Her chapters and articles on energy, environmental systems, lighting, and materials have appeared in many books and journals, and she recently coauthored *Smart Materials and Technologies for the Architecture and Design Professions*. She received a BSME from Tulane University, a BArch from Temple University, and an MDesS and a DDes from Harvard University.

architecture.yale.edu

PHILIP BEESLEY
Professor & Director, Living Architecture Systems Group
University of Waterloo
Cambridge, ON, Canada

Philip Beesley (MRAIC, OAA, RCA) is a Professor in the School of Architecture at the University of Waterloo. A practitioner of architecture and digital media art, he was educated in visual art at Queen's University, in technology at Humber College, and in architecture at the University of Toronto. At Waterloo he serves as the Director for the Living Architecture Systems Group, and as the Director for Riverside Architectural Press. His Toronto-based practice Beesley Pucher Seifert is an interdisciplinary design firm that combines public buildings with international art installations. The studio's methods incorporate industrial design, digital prototyping, and mechatronics engineering. Beesley frequently collaborates with artists, scientists, and engineers. Recent projects include a series of hybrid fabrics developed with Atelier Iris van Herpen, and curiosity-based machine learning environments developed with Rob Gorbet and Dana Kulic of the Adaptive Systems Group.

Philip Beesley's work is widely cited in the rapidly expanding technology of responsive architecture. He has authored and edited ten books and appeared on the cover of *Artificial Life* (MIT), *LEONARDO*, *Architectural Design* journals, and a series of TED talks. His work was selected to represent Canada at the 2010 Venice Biennale for Architecture, and his distinctions include the Prix de Rome in Architecture, ACADIA Award for Research, VIDA 11.0, FEIDAD, Architizer A+, and two Governor General's Awards.

philipbeesleyarchitect.com

RODOLPHE EL-KHOURY
Professor and Dean
University of Miami
Coral Gables, FL, USA

Rodolphe el-Khoury is Professor and Dean of the School of Architecture at the University of Miami and partner in the design firm Khoury Levit Fong (KLF). el-Khoury is the author of numerous critically acclaimed books in architectural history and theory and has received international recognition for his design work as principal at Office dA, ReK Productions, and currently at KLF; el-Khoury is invested in architectural applications for advanced information technology aiming for enhanced responsiveness and sustainability in buildings and cities.

arc.miami.edu

MICHAEL FOX
Associate Professor, Cal Poly Pomona
Principal, FoxLin Inc.
Los Angeles, CA, USA

Michael Fox is a founding partner of FoxLin. He is also the author of the book

Interactive Architecture by Princeton Architectural Press and the upcoming book entitled *IA: Adaptive World*. In 1998, Fox founded the Kinetic Design Group at MIT as a sponsored research group to investigate interactive architecture. His practice, teaching, and research are centered on interactive architecture. Michael has lectured internationally on the subject matter of interactive, behavioral, and kinetic architecture. He has won numerous awards in architectural ideas competitions and his masters' thesis at MIT received the outstanding thesis award for his work on computation and design processes. Fox's work has been featured in numerous international periodicals and books, and has been exhibited worldwide most recently at the 2013 Venice Biennale. His work has been funded by NASA, the Annenberg Foundation, the Graham Foundation, and others. Fox is an Associate Professor of Architecture at Cal Poly Pomona and has taught on the subject matter of interactive, behavioral, and kinetic architecture at MIT, The Hong Kong Polytechnic University, the Art Center College of Design in Pasadena, and Southern California Institute of Architecture (SCI-Arc) in Los Angeles as well as numerous international workshops.

cpp.edu/~arcfoxlin.com

USMAN HAQUE
Director
Haque Design + Research
London, UK

Usman Haque is founding partner of Umbrellium and Thingful.net, a search engine for the Internet of Things. Earlier, he launched the Internet of Things data infrastructure and community platform Pachube.com, which was

acquired by LogMeIn in 2011. Trained as an architect, he has created responsive environments, interactive installations, digital interface devices, and dozens of mass-participation initiatives throughout the world. His skills include the design and engineering of both physical spaces and the software and systems that bring them to life. As well as directing the work of Haque Design + Research he was until 2005 a teacher in the Interactive Architecture Workshop at the Bartlett School of Architecture, London. He received the 2008 Design of the Year Award (interactive) from the Design Museum, UK, a 2009 World Technology Award (art), the Japan Media Arts Festival Excellence prize, and the Asia Digital Art Award Grand Prize.

umbrellium.co.uk

EDWIN B. (TED) HATHAWAY
CEO
Oldcastle BuildingEnvelope®
Santa Monica, CA, USA

Edwin B. (Ted) Hathaway is CEO of Oldcastle BuildingEnvelope® (formerly Oldcastle Glass®). Ted joined Oldcastle, Inc. in 1987 as Vice President Development where he championed the formation of Oldcastle BuildingEnvelope® with the 1990 acquisition of HGP Industries, an architectural glass fabricator. Over the next decade, 25 bolt-on acquisitions advanced the business to North American leadership in fabricated glass products for commercial construction. Ted was promoted to Chief Operating Officer in 1998 and to CEO in 2000. Subsequently, he positioned the company as an integrated supplier of architectural glass and aluminum glazing systems. Today, Oldcastle BuildingEnvelope® is the leading supplier of products

specified to close the building envelope and has over 50 locations in 26 states and 4 Canadian provinces, and employs more than 4,500 people. In 2009, Oldcastle BuildingEnvelope® partnered with Columbia University's Graduate School of Architecture, Planning, and Preservation (GSAPP) to create the Columbia Building Intelligence Project (C-BIP). C-BIP's goal is to study and explore the inherent inefficiencies that exist within the design and construction process. Ted is a member of the Board of Trustees for the New York-based Museum of Arts and Design and the Design Futures Council Executive Board. He was recently named to the Board of Directors of the American Red Cross Greater New York Region.

oldcastlebe.com

CHUCK HOBERMAN
Principal
Hoberman Associates
New York, NY, USA

Chuck Hoberman is an inventor, internationally known for his "transformable structures." Through his products, patents, and structures, Hoberman demonstrates how objects can be foldable, retractable, or shape-shifting. Such capabilities lead to functional benefits: portability, instantaneous opening, and intelligent responsiveness to the built environment. Hoberman is the founder of Hoberman Associates, a multidisciplinary practice with clients ranging across sectors including consumer products, deployable shelters, and space structures. Examples of his commissioned work include the transforming LED screen that served as the primary stage element for the U2 360° world tour and the Hoberman Arch in Salt Lake City, installed as the centerpiece for the

Winter Olympic Games (2002). Other noteworthy commissions include a retractable dome for the World's Fair in Hanover, Germany (2000); the Expanding Hypar (1997) at the California Museum of Science and Industry; the Expanding Sphere (1992) at the Liberty Science Center, Jersey City, New Jersey; and the Expanding Geodesic Dome (1997) at the Centre Georges Pompidou in Paris. Hoberman's work has been exhibited several times at the Museum of Modern Art in New York. He won numerous awards including the Chrysler Award for Innovation and Design in 1997. Hoberman is a Visiting Scholar at Harvard University's Wyss Institute for Biologically Inspired Engineering.

hoberman.com

ROBERT KRONENBURG
Roscoe Chair of Architecture
University of Liverpool
Liverpool, UK

Robert Kronenburg (PhD, RIBA) is an architect and holds the Roscoe Chair of Architecture at Liverpool School of Architecture, University of Liverpool, UK, where he was head of school from 2004 to 2009. His research engages with innovative forms of architectural design, film, and popular music. His sole author books include *Houses in Motion*, *Spirit of the Machine*, *Portable Architecture*, *Flexible: Architecture that Responds to Change*, *Live Architecture: Venues, Stages and Arenas for Popular Music,* and he is co-editor of the *Transportable Environments* book series. He is a past Fulbright fellow and has been a visiting fellow at St. Johns College, Oxford University. He curated the major exhibition *Portable Architecture* (1998) held at the RIBA,

London, and was curatorial advisor on the Vitra Design Museum's exhibition *Living in Motion* (2002–2006). His research has received support from the Building Centre Trust, the Graham Foundation, the UK Arts and Humanities Research Council, the Daiwa Foundation, the Leverhulme Trust, and the Paul Mellon Centre for Studies in British Art. His latest book *Architecture in Motion: The History and Development of the Portable Building* was published by Routledge in 2013.

www.liv.ac.uk/architecture/staff/robert-kronenburg

DAVID LEATHERBARROW
Professor of Architecture
University of Pennsylvania
Philadelphia, PA, USA

David Leatherbarrow is Professor of Architecture at the University of Pennsylvania, where he also serves as Chairman of the Graduate Group in Architecture. He teaches architectural design, as well as the history and theory of architecture, gardens, and cities. His recent books include: *Architecture Oriented Otherwise*; *Topographical Stories: studies in landscape and architecture*; *Surface Architecture*, in collaboration with Mohsen Mostafavi; and *Uncommon Ground: architecture, technology and topography*. Before that were: *The Roots of Architectural Invention: site, enclosure and materials*, and *On Weathering: the life of buildings in time*, again with Mostafavi. His research has focused on selected topics in the history and theory of architecture, also landscape architecture, and, most recently, the impact of contemporary technology on architecture.

design.upenn.edu/architecture

ILONA LÉNÁRD
Creative Director and Visual Artist
ONL [Oosterhuis_Lénárd]
Rotterdam, Netherlands

Ilona Lénárd is an independent visual artist and realizes large scale urban art projects in cooperation with architect Kas Oosterhuis. During their stay at Theo van Doesburg's studio in Meudon near Paris, Kas Oosterhuis and Ilona Lénárd opted for a fusion of architecture and art. From the very start of a project they work on the same scale and think about the same budget in a parallel and interactive processing. Their recent sculptural buildings, the saltwater pavilion at Neeltje Jans, the garbage transfer station Elhorst/Vloedbelt in Zenderen, and the music sculpture in Oldemarkt, show where their uncompromising urge for new concepts can lead. Kas Oosterhuis and Ilona Lénárd like to describe their work as building bodies, as intelligent sculptures, and as bodies generating real-time behavior.

onl.eu

CAROL MOUKHEIBER

Assistant Professor
University of Toronto
Toronto, ON, Canada

Carol Moukheiber is an Assistant Professor at the Daniels Faculty of Architecture, Landscape, and Design at the University of Toronto and Partner in the architecture practice Studio NMinusOne (n-1). She is the Director of RAD, which is probing the impact of emerging technologies on the physical environment. Her work with NMinusOne traverses various scales. Ideas manifest themselves in conceptual scenarios, competitions, commissioned built work, and experimental physical prototypes. The work tackles issues of physiological and psychological engagement or reciprocity between body and environment as mediated through architectural techniques of organization, technological enhancement, material calibration, and intangible effects. Zones of exploration include the domestic environment; responsive or embedded systems; and speculative urban strategies. The firm's work has been acquired by the San Francisco Museum of Modern Art and has been published widely in academic and mainstream media including *The New York Times Magazine*, *Praxis Journal of Architecture*, and *Domus*. The studio is the recipient of the Architectural League of New York, Emerging Voices 2012 award. She is the co-author of *The Living, Breathing, Thinking Responsive Buildings of the Future* and co-editor of *Wild Wild Urbanism, Redesigning California.*

daniels.utoronto.ca

KAS OOSTERHUIS
Professor and Director, Hyperbody
Delft Technical University

Delft, Netherlands

Kas Oosterhuis is an internationally recognized architect, educator, and researcher based in the Netherlands. He teaches digital design methods at the Delft Technical University and leads a staff of 12 researchers at Hyperbody, the knowledge center for Nonstandard and Interactive Architecture at the TU Delft. In his most recent book *Towards a New Kind of Building: a Designers' Guide to Nonstandard Architecture* Oosterhuis focuses on the change in conception and realization of design due to digital design and production methods and engages the new modes of architectural practice that embrace the shift from standard to nonstandard structures and from static to dynamic buildings. He is Director of the protoSPACE Laboratory and member of the Dutch Building Information Council (BIR). Kas Oosterhuis has lectured worldwide at numerous universities, academies, and international conferences. He has initiated two GSM conferences at the TU in Delft on the subjects of multiplayer game design, file to factory design and build methods, and open source communication in the evolutionary development of the 3D reference model. His design projects have received numerous awards including the 2006 Dutch Design Award for Public Space, 2008 Autodesk BIM Experience Award, 2006 National Steel Award, 2006 Glass Award.

hyperbody.nl

ENRIC RUIZ-GELI
Founder and Principal Architect
Cloud 9
Barcelona, Spain

Enric Ruiz-Geli is the founder and principal architect of award-winning Cloud 9 Studio in Barcelona. This cutting edge experimental practice is now well known worldwide for such works as *Villa Nurbs*, Empuriabrava; *New York Aquarium*; *Hotel Forest,* Barcelona; *The Millenium Project*, Valladolid; *elBulliFoundation*, Cap de Creus, Roses. The practice has made a unique commitment to research and experimentation in fundamentally novel approaches to technology, fabrication, and construction to realize these groundbreaking projects and create patents as masterpieces of digital fabrication. Acknowledged for his revolutionary approach to innovation in architecture, Ruiz-Geli's numerous awards include WAF Award for World's Best Building of the Year 2011 with *Media-TIC*, a net-zero building with a very competitive cost of construction.

Enric has lectured all over the world. Since 2010 he has been teaching as Unit Master of Diploma Unit 18 at Architectural Association School of Architecture in London. He is Co-Chairman of Third Industrial Revolution Architects Roundtable since 2009, working with Jeremy Rifkin on Global Green Growth, and is a member of the Science Committee of Tecnalia since 2011 and HP Experts Committee since 2012.

His works have been exhibited and published internationally by *The Wall Street Journal*, *The New York Times*, *Financial Times*, *Actar*, *Arquitectura Viva*, *Quaderns*, *Domus*, *Wired*, amongst others, and are in the collections of MoMA (New York), FRAC Centre (Orleans), and Centre Pompidou (Paris).

ruiz-geli.com

BRIAN R.SINCLAIR
Professor of Architecture and Environmental Design
University of Calgary

Calgary, AB, Canada

Brian R. Sinclair is Professor of Architecture and Environmental Design, and former Dean, in the University of Calgary's Faculty of Environmental Design. He has served as Presidential Advisor on Design and Sustainability, a demanding and creative role unique in the landscape of higher education. Brian is president of sinclairstudio inc., a Canadian-based multi-disciplinary design and research corporation engaged in a broad array of global projects. Prior to his deanship, Sinclair was Chair of the Architecture school at Ball State University. Brian holds postgraduate degrees in architecture and psychology. An educator and practitioner, Sinclair's expertise and engagement spans from science to art. Professional memberships include American Institute of Architects, Union of Mongolian Architects, Society of Nepalese Architects, Council for Tall Buildings + Urban Habitat, and Fellowships in Royal Architectural Institute of Canada and International Institute for Advanced Studies. International boards include Architectural Research Centers Consortium and Toda Institute for Global Peace and Policy. His doctoral degree (University of Missouri) focused on an innovative holistic design and planning framework to improve quality of life for some of world's poorest people. Scholarship includes professional practice, design methods, open building, agile architecture, strategic planning, integrated design, environmental psychology, international development, systems & sustainability, and the collision of science + spirit. His newest book (2009, CaGBC) is entitled *Context, Culture and the Pursuit of Sustainability.*

evds.ucalgary.ca

TRISTAN D'ESTREE STERK

Founder / CEO
Formsolver, ORAMBRA
Chicago, IL, USA

The Office for Robotic Architectural Media & The Bureau for Responsive Architecture (ORAMBRA) is a small technology office that develops new construction systems and components for buildings that alter the ways in which buildings perform, act, and operate. In particular the office is recognized for developing structural shape change technologies that alter the way in which buildings use energy. The office's mission is to develop the knowledge, systems, and state-of-the-art products that support tomorrow's building construction sector while enabling people to craft more responsive connections between construction systems, design, users, and the natural environment.

Formsolver (2014) is the first commercially available product offered by ORAMBRA. It is a cutting edge shape and material optimization design tool and the first of a new generation of design tools set to change the practice of architecture.

Tristan was awarded an AIA Chicago award of design excellence for unbuilt work (2011), and AIA Chicago Dubin Family award for Young Architect of the Year (2012).

formsolver.com orambra.com

SKYLAR TIBBITS
Research Scientist
Massachusetts Institute of Technology
Cambridge, MA, USA

Skylar Tibbits is the director of the Self-Assembly Lab in MIT's Department of Architecture, which focuses on self-assembly and programmable material technologies for novel manufacturing, products, and construction processes.

Skylar also teaches graduate and undergraduate design studios and co-teaches How to Make (Almost) Anything, a seminar at MIT's Media Lab. Skylar was recently awarded a 2014 Inaugural WIRED Fellowship, a 2014 Gifted Citizen award, a Fast Company Innovation by Design Award in 2013, a 2013 Architectural League Prize, The Next Idea Award at Ars Electronica 2013, the Visionary Innovation Award at the Manufacturing Leadership Summit, a 2012 TED Senior Fellowship and was named a Revolutionary Mind in SEED Magazine's 2008 Design Issue. Previously, he has worked at a number of renowned design offices including: Zaha Hadid Architects, Asymptote Architecture, and Point b Design. He has designed and built large-scale installations at galleries around the world, has been published extensively in outlets such as the *New York Times*, *Wired*, *Nature*, *Fast Company* as well as various peer-reviewed journals and books.

Skylar has a professional degree in architecture and minor in experimental computation from Philadelphia University. Continuing his education at MIT, he received a Master of Science in Design Computation and a Master of Science in Computer Science. He is also the founder and principal of a multidisciplinary design practice, SJET LLC.

selfassemblylab.net

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