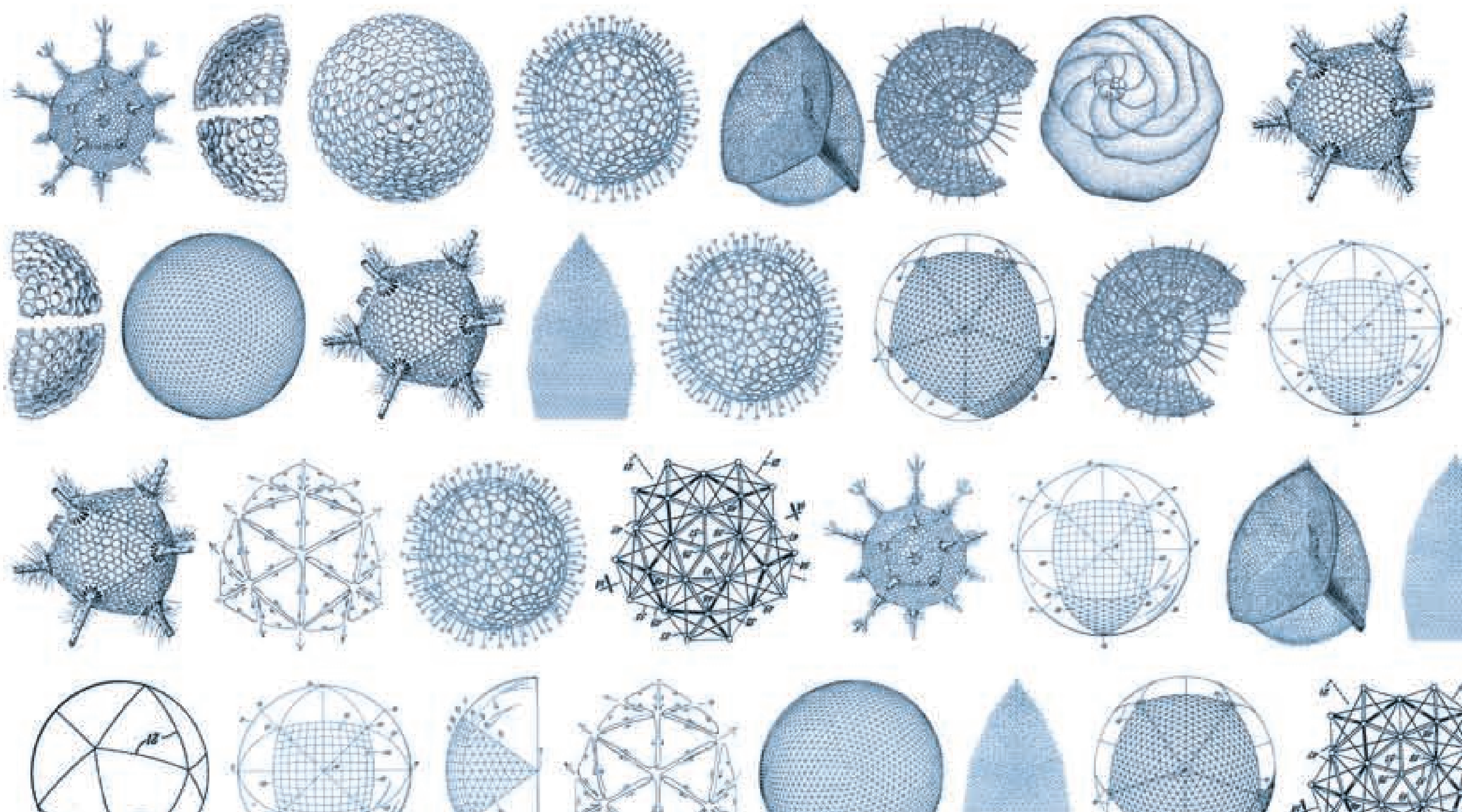
On Growth and Form

Organic Architecture and Beyond

Edited by Philip Beesley & Sarah Bonnemaison



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Preface

The essays in this book were originally written for the ACSA East Central Regional conference *On Growth and Form: the Engineering of Nature* held at the University of Waterloo in 2001. A selection of the papers presented at that gathering appear here. Each contributor revised and expanded their essay. We are grateful to Christine Macy for her generous editing of the essays, and we would also like to thank the Graham Foundation, Dalhousie University, the University of Waterloo, and Arriscraft Corporation, whose support made this project possible.

S. Bonnemaison and P. Beesley

Why Revisit D'Arcy Wentworth Thompson's *On Growth and Form?*

Sarah Bonnemaison and Philip Beesley

> Matter as such produces nothing, changes nothing, does nothing…[it] can never act as matter alone, but only as seats of energy and as centres of force. (Thompson 1942: 14).

In 1917, D'Arcy Wentworth Thompson published the result of his studies of morphology in *On Growth and Form*, arguing that the forms of plants and animals could be understood in terms of pure mathematics. The book became an immediate classic for its exploration of natural geometries in the dynamics of growth and physical processes. An extraordinary optimism is evident in this work, presenting a vision of the physical world as a symphony of harmonious forces. The book covers a vast range of morphological studies. He draws out the laws governing the dimension of organisms and their growth, the statics and dynamics at work in cells and tissues including the phenomena of geometrical packing, membranes under tension, symmetries, and cell division; as well as the engineering and geodesics of skeletons in simple organisms. Thompson conceived of form not as a given, but as a product of dynamic forces that are shaped by flows of energy and stages of growth. His eloquent writing and exquisite illustrations continue to inspire scientists, artists, and architects alike.

The authors who contributed to this volume re-visit Thompson's way of thinking and seeing the world, and apply it to their own work – in the realm of materials, construction, architectural form-finding and form-making. The array of design work featured here reveals an ongoing commitment to the vital pursuit of organicism, drawing upon contemporary art and science, and supported by a theoretical context for the work. In addition, critical readings provide alternatives to a traditional history of modern architecture that has celebrated the aesthetics of the machine. The essays invite the reader to bring together their own associations in applied and speculative paths of research

The essays present two diverging tendencies. Some are drawn to the patient craft and the technological optimism that is part of the search for design elegance. Key references here are Buckminster Fuller and Frei Otto's Institute for Lightweight Structures (IL). Other essays are drawn to the radical and unstable. In this vein, *Scientific American*'s 150th anniversary issue on "Key Technologies of the 21st Century" tempered their usual American confidence with a sense of mounting anxiety,

> The truth is that as technologies pile on technologies at an uneven pace, it becomes impossible to predict precisely what patterns will emerge. Can anyone today truly foresee what the world will be like if, for example, genetic

> engineering matures rapidly to its full potential? If organisms can be tailored to serve any function, even becoming a living spaceship, can anyone guess what a 21st-century factory will look like? (Rennie 1995: xiii)

The experiments in artificial intelligence and genetic development presented in our *On Growth and Form* speak of continuous, restless transformation. When artifice extends its reach into nature, popular commentary would have it that this can only invoke the tragic dimensions of Mary Shelley's Frankenstein. Yet the critical culture surrounding this work has shifted from passive anxiety about tampering with life, to a more poignant, integrated involvement in complex systems. As the American theorist Donna Haraway says, "we're inside of what we make, and it's inside of us … I am not interested in policing the boundaries between nature and culture – quite the opposite, I am edified by the traffic" (Haraway 1991: 6).

Key Reference Works

Many architects and designers have explored the interface between architecture and nature, and we might refer briefly to their work to place this volume in its intellectual context. In his *Patterns of Nature*, Peter Stevens revealed the geometric patterns present in nature. He juxtaposes the branching of trees with branching arteries and rivers; images of crystal grains and soap bubbles.

> To the casual observer, nature appears limitless in its ability to create and modify the shape of its creations. Upon closer examination, however, this myriad of forms is in fact constructed from a limited number of relatively simple shapes, determined by the combination of a number of constraints. The patterns and forms employed by nature are restricted by the constraints of physical space, the relations between area and volume, and the need to minimize resource consumption (Stevens 1974: flyleaf).

More recently, George Hersey's *The Monumental Impulse* and Norman Crowe's *Nature and the Idea of a Man-Made World* draw analogies between architectural forms and natural constructions – molecular, plant and animal. By pairing biological forms with architecture, Hersey establishes relations between physical structures and living organisms such as skeletons of birds and bridges, or winding DNA strands and a double spiral stair.

In the realm of computer-generated forms that mimic natural processes of evolution and transformation, John Frazer, author of *An Evolutionary Architecture*, is a key pioneer in the digitization of morphological transformations. Such work continues earlier studies into three-dimensional morphology by Haresh Lalvani – itself based on Buckminster Fuller's, Anne Tyng's and Louis Kahn's investigations into geometric transformations – and this line of study continues in the work of architects such as Greg Lynn.

A second group of architectural theorists have turned to vernacular construction with the conviction that such buildings and settlements express the interconnectedness between humans and the landscapes they live in. Bernard Rudofsky is perhaps the best known of these, for his book *Architecture without Architects*, but many other architects in the 1950s and 60s were working in the same vein, such as Aldo van Eyck, Maurice Smith, and later, Christopher Alexander. They believed that the best architecture resulted from deep-seated cultural practices attuned to the landscape from which they arose. Myth here provides the link between nature and design. As Aldo van Eyck pointed out, myth serves as the repository of meanings linking built works to the natural world in all its cosmological force. Christine Macy and Sarah Bonnemaison show the uses and misuses of myth in architecture and landscapes designed to express a notion of nature bound up with nation-building, in their book *Architecture and Nature*: *creating the American landscape*.

A third approach is the writing of the history of nature in architecture. Caroline van Eck, in her remarkable work *Organicism in Nineteenth Century Architecture*, convincingly argues that organicism was the prime theoretical referent for architects working long before the advent of modern architecture. Bruno Zevi and Peter Collins have argued that the organic ideal was a significant theme in twentieth century architectural theory, while more recent publications have traced the influence of organic thought in modernism, including Colin Porteous' *The New Eco-Architecture: alternatives from the Modern Movement*, and Sarah Menin and Flora Samuel's *Nature and Space: Aalto and Le Corbusier*. George Baird, in his *The Space of Appearance*, explores the impulse towards organicism among modernist architects and theorists such as Frank Lloyd Wright and Lewis Mumford, suggesting that a false dichotomy between abundance and scarcity allied the "organicist" project with consumerism. Detlef Mertins' essay "Bioconstructivisms" discerns conflicts within the modern tradition of organicism, positioning Thompson as a Platonic thinker in a transcendentalist tradition from the nineteenth century German zoologist Ernst Haeckel to Buckminster Fuller, and contrasting this lineage to other thinkers such as Frei Otto whose studies of structural systems emphasizes the differences, rather than the similarities between species. Mertins suggests that Otto's approach sidesteps essentialism, "to open up a world in which unique and complex structures result immanently from material exigencies, without being subject to any transcendent authority" (Mertins 2004: 368).

Essays Collected in this Book

The essays are organized into three sections. The first one, called "History and Criticism", covers the theoretical basis of organicism and examines canonical buildings through the lens of organicism. Ryszard Sliwka looks at the idea of natural order in architecture. He takes Ruskin's argument and brings it forward into the design practices of Le Corbusier and, more recently, Frank Gehry. Dörte Kuhlman traces the history of organicism and contextualizes modern architects within an intellectual milieu concerned about nature as an aesthetic idea. Kevin Nute interprets the organic forms of Louis Sullivan and Frank Lloyd Wright.

The 1960s and 70s were a period when determinism and behaviourism had the upper hand on environmental studies. This led to debates on the ethical and political dimensions of our relationship to nature. Buckminster Fuller, Pierre Teilhard de Chardin, and Frei Otto have each, in their own way, posed significant questions about our awareness that life on earth is a global phenomenon (Fuller 1969, Teilhard de Chardin 1959, Otto 1975-95). The three subsequent essays look at these influential figures and the impact they had on architecture. Christine Macy looks at the influence of philosopher Teilhard de Chardin on the back-to-the-land movement, new age philosophy and environmentalism. For example, living in geodesic domes was seen as a way to expand one's consciousness and "closing the loop" was a central ethical principle in early experiments in ecological living. Hadas Steiner turns her gaze to soap bubbles, noting their appeal to Frei Otto and others working on pneumatic structures. The fascination with inflatables, she argues, has to do with the way they express fluctuations in ambient conditions and the ease of construction in a do-it-yourself culture. Lastly, Sarah Bonnemaison interprets Fuller's geodesic pavilion at Expo '67 as an engineered expression of nature's geometric patterns. As a result, she suggests, the building resonated with a younger generation that saw – in its transparency, weather-responsive shutters and earth-like form – a strong ecological message. "Reading the Organic" is the second section of the book. The first essay, by Nat Chard, explores two methods of representing a landscape: strictly pictorial *anamorphism* and a *stereotomic* folding of the picture plane. He carefully analyses their use in habitat dioramas from natural history museums. Chard is particularly interested in the dioramas of James Perry Wilson, a renowned diorama artist, and in order to understand how Wilson distorts an image to register a normal view, he built a camera to capture, in one photograph, the full range of transformations Wilson made to his picture planes. The essay relates the technical findings of his camera and speculates on the way our body is implicated when we view a landscape. The essay by fabric artist Ann Richards is a meditation on her work. She considers the forces involved in creating her textiles to be aspects of growth in D'Arcy Thompson's sense – that is, the stresses shown by the phenomenon of their creation. Her work relies on textures and shapes formed by the forces intrinsic to the fabric, resulting from the specific properties of materials and yarn twists. Finally, Reinhold Martin's essay brings us to the hidden aspect of our relationship to nature, looking at our impulse for destruction. Martin argues that when we look at the relationship between architecture and science we cannot avoid its connection to war. War accelerates the scientific and technological advances that are only later brought into the building industry. He supports his argument with many examples that take us from architecture to science, to war, and back to architecture.

The third and last section of the book is called "Nature as Teacher". With the rise of computer-driven design, morphology has once again emerged as a significant theme in contemporary architectural theory. This set of essays addresses this emerging interest in morphology with an emphasis on tensioned systems and lightweight structures. The authors are architectural practitioners who draw from their study of D'Arcy Thompson. Thomas Seebohm's essay relates the development of his computer program to design tensegrity structures as a way to help us describe nature. His aim was to develop a software that would allow the design to go from a two-dimensional topology of struts and cables to the corresponding resulting three-dimensional structure when released. Seebohm draws out the poetry from abstract analytical concepts such as the role of prime numbers or the way tensegrity subsystems form larger wholes and reality. Manuel Báez argues that the coexistence of complexity and simplicity in nature challenges our imagination and he tries to address this apparent contradiction by building a series of installations. The forms are based on simple rules that eventually reveal the paradox of constrained and versatile freedom. Such research into geometries derived from nature, he argues, brings new energy to the study of architectural forms. Hajo Neis's essay reflects on Christopher Alexander's observations of natural processes in developing his "pattern language". These include the concepts of 'smooth unfolding', 'structure-preserving transformations', and 'formations of centers and fields of centers'. Neis shows the application of these processes in his own projects in Germany, the United States and Japan. Lastly, Edgar Stach describes his design project for an elephant enclosure in the Cologne zoo. Inspired by the balanced, flowing, weightless form of a cloud, he developed a structural concept for the roof that is realized with an iterative digital process of dynamic modeling and force-path calculation.

New Tools and Analytical Methods

D'Arcy Wentworth Thompson demonstrated new working methods for understanding the influence of physical forces in the environment, and the architectural projects in this book owe much to Thompson's research. They explore structural systems that use tension and 'tensegrity', in which forces animate the entire structure. Digital design tools now allow such complex interactions to be quantified and dynamically modeled, and digital prototyping and manufacturing play important roles in their realization. Instead of relying on centralized systems that resist environmental changes, new generations of buildings can accommodate shifting forces, distributing loads to better withstand undesirable deformation. Such buildings involve new methods of construction using chains of components and distributed structures.

Recent research confirms Thompson's empirical observations of biological form which showed that cell shapes are dictated by three-dimensional skeletons that mirror large-scale architectural space-frames. New developments in materials compatible with physiology, and miniature fabrication methods similar to those used for manufacturing computer chips have contributed to further this development in lightweight structural frameworks. Analytical tools that support visualization in space and time have led to miniaturization of established technologies such as magnetic resonance imaging (MRI) and positron emission tomography (an imaging by sequential sectional cuts, known as

PET), which permit the analysis of molecules and cells in living animals. The two-way street of evolutionary development involves molecular exchanges that can be detected with these tools. This ability to probe allows for the measurement of mechanical properties alongside observations of spatial and chemical dynamics. Adaptation to the environment through intimate linkages of natural forms and functions is now being described in mathematical detail. Molecular biology now asks critical questions about shape and structure at the scale of atoms, cells and organisms. A convergence of dynamic 'network' thinking from information technology has blurred the boundary between environment and organism. In turn, the natural world is being revealed in molecular detail as a dynamic ecology of interconnectedness.

Similarly, computer-aided design is capturing the geometric relationships that form the foundation of architecture, building upon now-established practices of form-finding and finite element analysis (which breaks down a continuous structure into many simple, linked elements in order to find optimal thicknesses and arrangements of supporting elements). New developments in parametric modeling permit control of design through models that can coordinate and update themselves. These systems can automatically update the entire model or drawing set based on changes as small as a joint or as large as the entire floor plan, offering flexible design of deeply nested relationships. In much the same way that mutations in nature generate biodiversity, individual variation in architectural components can be achieved economically. Parametric design practice employs 'dependency' networks akin to the complex process diagrams used to express relationships in natural systems, offering increasingly fine-tuned approaches to building component design. Using these tools, Architectural disciplines are poised to work with increasing effectiveness in responsive, interactive systems.

Whether through design practice or a critical perspective on design, the essays in this book ask what might we learn by revisiting Thompson's way of seeing the world, and apply the answers to their own work. The array of design work reveals an ongoing interest in the pursuit of organicism, and the critical interpretations of history provide alternatives to a traditional historiography of modern architecture that celebrates the aesthetics of the machine, by bringing to light some of the questions raised by the thorny relationship between nature and artifice that make our world. In their own way, these essays contribute to this important discussion.

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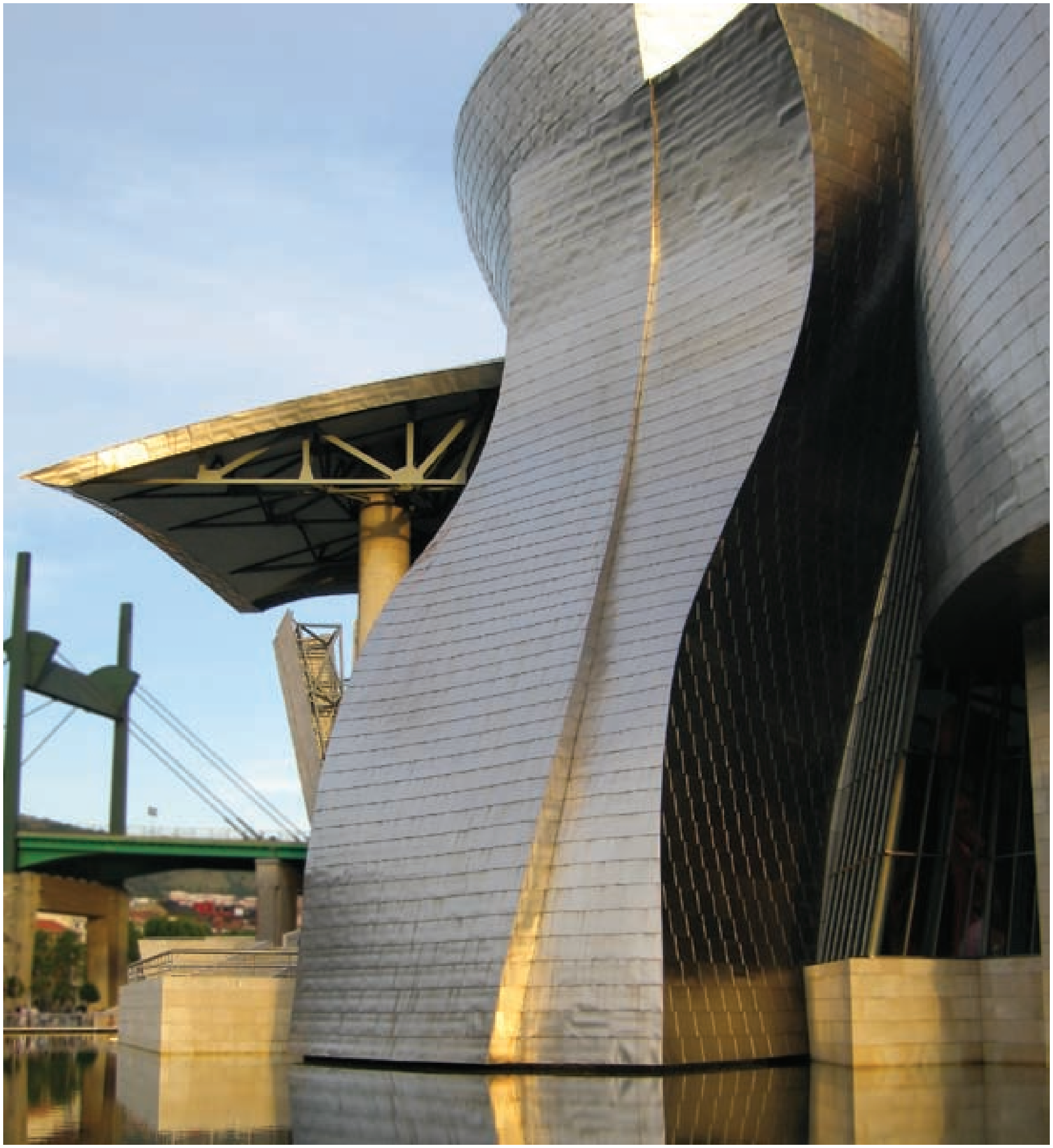
HISTORY AND CRITICISM



1: Frank Gehry, Guggenheim Museum, Bilbao, Spain, 1997. Photograph Shane Czypyha.

Geometries of Creation: Architecture and the Revision of Nature

Ryszard Sliwka

Cell and tissue, leaf and flower, are so many portions of matter, and it is in obedience to the laws of physics that their particles have been moved, moulded and conformed. They are no exceptions to the rule that God always geometrizes (Thompson 1992).

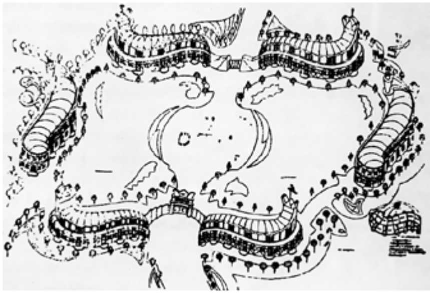
Since the time of Vitruvius, architecture has periodically identified its origins in nature. And since the Enlightenment, such narratives of origin have often turned into manifestos of aesthetic judgment and authenticity. In the modern era, the outright rejection of tradition has led modern architects to search ever more frantically for a substitute for the lost origins of the discipline, as justification and a source of regeneration.

D'Arcy Thompson's On Growth and Form, first published in 1917, plays an unusual role in these events through its relevance to two propositions about architecture. Certainly, Thompson's study of the underlying structures of nature had an influence on the modern architecture developed between the world wars. On the one hand, it extended a line of reasoning expounded in Abbé Laugier's 18th century discourse on the 'primitive hut', and on the other, it was related to 19th century attempts by theorists such as Ruskin to establish a unity between scientific, aesthetic and spiritual life, encompassing developments in science, biology and mathematics that fall loosely today under a paradigm of 'non linear science' or the 'new naturalism'[1] (Prigogine and Stingers 1984).

2: Charles Eisen, The primitive hut, 1752 (Laugier 1755: frontispiece)

These two lines of thought, broadly described as 'rational-empirical' and 'organic,' seem to operate as distinct cultural typologies in modern architecture. A recent discussion with a professional colleague about Frank Gehry's Guggenheim Museum in Bilbao, Spain made this distinction apparent (Fig.1). My colleague, like other critics who have felt the museum to be capricious or whimsical, had strong reservations about the building. Its language of expression was too 'arbitrary'. In spite of its popular acclaim, Gehry's design flew in the face of the empirical imperative that has shaped much of our modern representational discourse; one that in architectural terms demands that architecture convey a sense of its utility and its inherent logic.

My colleague's use of the term arbitrary recalls the late 17th century distinction between arbitrary beauty and positive beauty, a distinction that led Claude Perrault to rearrange the traditional architectural orders into a more elegant system of mathematical relationships to express positive beauty (Perrault). Our discussion touched on a whole set of assumptions about the appropriate representation of architecture. For my friend, a simple lexicon of structural elements and pure geometries as exemplified in the work of Mies van der Rohe provided a more compelling aesthetic criteria than the machinations of Gehry's buildings. The reasons for this may relate to earlier attempts to derive principles of architecture from the evolutionary processes of nature, notably by Abbé Laugier in his Essai sur l'Architecture (1752). Laugier's essay, motivated by the desire to save architecture from the "capricious whim of artists," sought out principles founded on "simple nature and nature's process." His dictum that "it is only by approaching the simplicity of the first model, that fundamental mistakes are avoided and true perfection achieved" (Laugier 1977: 12). However, Charles Eisen's engraving of the Primitive Hut that accompanied the essay (Fig. 2) suggests that Laugier's version of nature was modeled on Vitruvian classical precedents.



3: Herman Finsterlin, Expressionist town plan, 1923. Editions Crès, Paris.

Order and the Imperfection of Nature

A contemporary iteration of this position explains in part the reaction to Gehry's building. Laugier's assertion that "the parts that are essential are the cause of beauty" (Laugier 1977:12), is critical to an understanding of modern architecture, one which is confirmed in D'Arcy Thompson's observation that the structures and organisms of nature are shaped by the laws of physics. Thompson's explorations into the underlying structures of nature, in his classic On Growth and Form, influenced the debates crucial to the birth of early modernism. His analogies between bones and engineered structures showed how stress diagrams of engineered works mirrored the way bone reinforced itself when under load. Thompson's book described how a limited set of constructional principles and proportional geometries shaped the form of organic structures in the natural world. It was tempting to discern a teleological rationale in the formation of organisms and structures that was independent of human conventions, that was subject to implacable universal laws. Thompson however, was never so doctrinaire and sought a more complex balance between ideas of final cause and the interactive processes of nature. Nevertheless, the suggestion that architecture might similarly abandon its traditional conventions and evolve more successfully, through alignment with natural processes, toward an evolutionary perfection proved compelling (Maxwell 1978: 8; Portoghesi 2000: 162).

In the light of this discussion, it is easy to see how the formal complexities of Bilbao might engender accusations of 'arbitrariness.' Such a reaction to Gehry's work was probably no different from the unease that Le Corbusier felt towards the expressionist work of Hans Poelzig in the 1920s. He compared Poelzig's architecture to the ruins of Rome, but saved his most vociferous outburst for an Expressionist town plan by Herman Finsterlin from the same period,

> In the depths of our being, larva, toads and beasts which haunt the memories of the primordial world reemerge today [...] we see them as a new crisis of the spirit which followed the war: frightening dreams of Hermann Finsterlin from Bavaria with their viscous ejaculations recalling underwater horrors, or those viscera, or impure acts of beasts (Jencks 2000: 126) (Fig. 3).

For Le Corbusier (at least at this stage of his career), the conditions of modernity were a distinct improvement on the processes of nature. The evolutionary ideals embodied in his Purist paintings, his architecture, and his advocacy of machine culture led to his assertion that,

> there is nothing in nature that, as seen objectively by our eyes, approaches the pure perfection of the humblest machine (the moon is not round: the tree trunk is not straight; only very occasionally are the waters smooth as a mirror; the rainbow is a fragment; living beings with very few exceptions, do not conform to the simple geometrical shapes, etc.) The machine appears to us the goddess of beauty... Gods! Geometry and the gods sit side by side (Le Corbusier 1987:112).

For Le Corbusier's rationalism is further reinforced by metaphysical assumptions underlying the Platonic concept of measure. Only through such abstraction might architecture disclose its transcendental nature. Nature, he seems to suggest, cannot live up to the intellectual beauty underlying the material realm. The Purist vocabulary he employed in painting and in architecture is based on a set of objet-types — forms derived from industrial objects and a 'purified' Cubist repertoire of still-life props, developed out of a 'Darwinian' process of evolution, aligned with functionalism and the world of industrial production (Fig.4). Their poetic qualities express a sober utility that was shared by both industry and the avant-garde at this time, as ideas of progress aligned with notions of efficiency and economy.

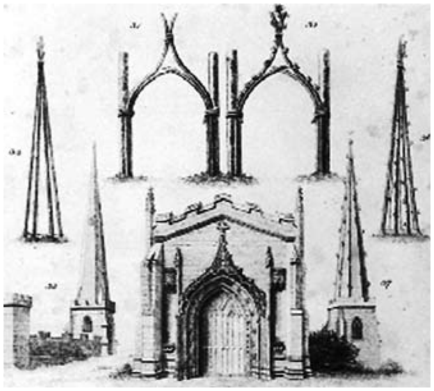
4: Le Corbusier, Purist objet-types, Fondation Le Corbusier, Paris.

Nature and the Imperfection of Order

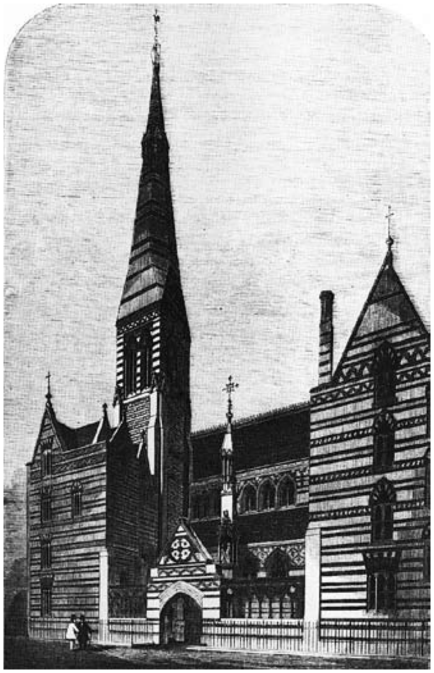
There is another aspect to D'Arcy Thompson's work that links it with an earlier tradition of natural theology and more recent developments in science, biology and mathematics. This is an alternative cultural typology also found in modern architecture, and one with similar claims to authenticity through alignment with the principles of nature. Its source is the writings of John Ruskin, perhaps the most influential advocate of the Gothic revival in the nineteenth century and the most significant precursor of Thompson's work.

Ruskin's religious beliefs were shaken by scientific evidence that undermined a literal reading of the Genesis story. For him, the study of nature risked a precipitous descent into meaninglessness, leading to his lament that "the clink of the geologists' hammers seemed to ring reproachfully at the end of every Biblical cadence" (Wiley 1966: 87). However, just as one branch of science — geology — was disputing the accuracy of the first book of the Bible, Ruskin hoped that another branch of science — biology — might point to God's authorship of His second book, the book of Nature. Ruskin imagined that the forms of modern Gothic could be discovered in leaves and living plants.

He was not the first to imagine such a link. In the late 18th century, the prominent Scottish geologist James Hall put forward a theory of Gothic as an imitation of nature, proposing a Gothic genealogy for the primitive hut. He built a wicker cathedral in his garden, showing how willow bark peeled away from timbers in a perfect imitation of the pointed arch (Fig. 5). Ruskin's belief in a scientific natural theology was less functionally



5: "Gothic primitive hut". (Hall 1813)



6: William Butterfield, All Saints Church, London, 1859 (Builder 1853)

driven. In his *Seven Lamps of Architecture*, he asserts that God has stamped the familiar shapes of the everyday world with the character of beauty, a revelation that was understood by Gothic artists who reproduced the "non-functional beauties of natural proportion and natural forms" (Fuller 1988: 61). He sought an open ornamental figuration with a sense of movement and energy, expressed in a vital contrast of force and counter force.

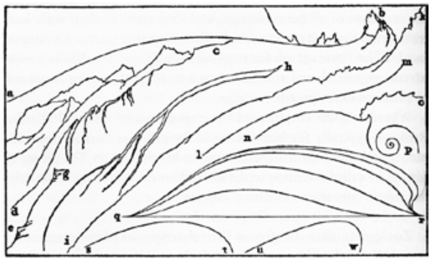
For Ruskin, the hands of the builder gave life to a building. Gothic buildings conveyed this life, they were "organized creatures" that communicated depth and emotion. They assumed grotesque, savage, changeful or naturalistic attributes. They were even sexualized as manly, feminine, or with elements of both. Yet such psychological characterizations were secondary to a more essential expression — that of a natural landscape. In Ruskin's own drawings of mountain landscapes, the stones seem to quiver with a 'magnificent animality.'[2] Gothic buildings could be seen as assonant fragments of this natural world. Something of this Ruskinian imagination is reflected in Gehry's observations on his own work and his speculation that the beginnings of architecture come from "zoomorphic yearnings and skeletal images". (Van Bruggen 1998: 42).

Ruskin proposed that a wall might use stones of different textures to emulate geological strata, an idea that was taken up by the architect William Butterfield in his design for All Saints, Margaret Street (1853) (Fig.6). However, few buildings in the modern gothic style came up to Ruskin's exacting standards. One that almost achieved this status was Deane and Woodward's Natural Science Museum at Oxford (1860), with its curved iron framework as dramatic as the dinosaur specimens it enclosed (Fig.7).[3]

As far as proportional systems went, Ruskin's well-known dissection of the flower *Alisma Plantago* led him to propose principles of proportion that extended to include the curvature of the leaves themselves, beautiful because they "approach the infinity of God". For Ruskin, such curves of intense and exceptional beauty were inherent not only to fine ornament but to natural forms such as the profile of mountains, the slopes of glaciers, and the convolutions of organic forms such as shells, fish, or willow leaves (Fuller 1988: 61) (Fig. 8). His style of writing, though at times verbose, might be described today in cognitive and empathic terms in a way that communicates how architecture can be transcribed within us to give it a semblance of life. The orientation to natural theology in Ruskin's work anticipates the nonlinear paradigmatic formulations of the 'new science' in which some scientists such as Gregory Bateson have rehabilitated the idea that mind, proportion and beauty are evidenced in nature, although they do not assume that it inevitably leads to a belief in God (Bateson 1973: 13).[4]

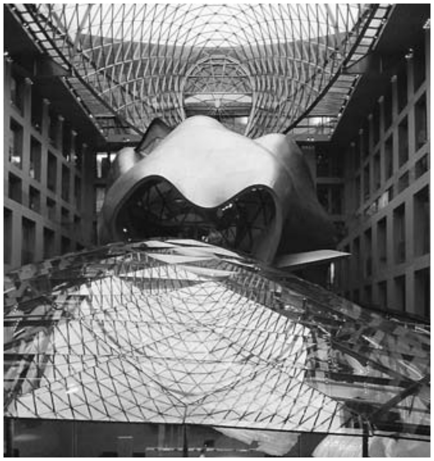
Ruskin's investigations of nature also prefigure recent studies on how intricacy and complexity arise from simplicity. His insights into the scaling behaviours and self-similarities in the natural and pre-modern world were largely ignored until the mathematician Benoit Mandelbrot identified a new family of shapes known as fractals. In Mandelbrot's opinion, this fractal geometry comes very close to a scientific identification of those shapes that, in natural theology have been described as 'the signature of God.' Shapes within nature that could not be described by traditional geometry, shapes we have

7: Ironwork. Thomas Deane and Benjamin Woodward, Museum of Natural History, Oxford University, 1860. (Karl Harrison, Oxford University)



8: John Ruskin, Study of curves. (Ruskin 1902: vol. 1).

9: Frank Gehry, Fish sculpture, Vila Olimpica, Barcelona, 1992. Photograph Ryszard Sliwka.



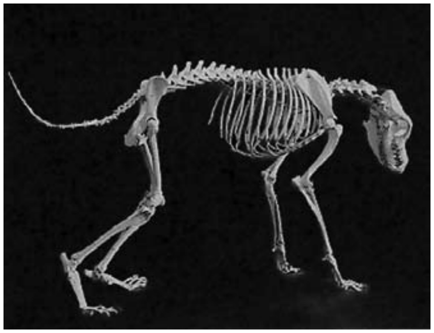
10: Frank Gehry, DG Bank, Berlin, 2000. Photograph Ryszard Sliwka.

described as "grainy, hydra-like, in between, pimply, pocky, ramified, seaweedy, strange, tangled, tortuous, wiggly, wrinkled, etc" can now be delineated rigorously (Mandelbrot 1980). Such work allows one to reconsider the supposedly 'arbitrary' nature of Gehry's Bilbao Museum and other contemporary architects such as Santiago Calatrava, to relocate them in discussions of 'Growth and Form.'

Ruskin's viewpoint is antithetical to the 'mechanistic science' associated with early modernism. Indeed the early modernists largely ignored him. One aspect of his interest in forms that communicate a sense of energy and movement was developed in early modernism however. Within the Cubist, Futurist and Constructivist movements, or the photography of Etienne-Jules Marey, the idea is reiterated through the use of fragmented overlapping forms. More recently, Gehry has attempted to capture movement in the same fractured multifaceted way. In a surprising analogy with Ruskin's metaphorical descriptions of buildings as 'organised creatures,' Gehry's fish and snake lamps, his fish sculpture at Barcelona's Vila Olimpica (1990-91) (Fig.9), or his structure in the DG Bank Building in Berlin (Fig.10), oscillate between figuration and abstraction. They allow us to speak again of buildings as 'savage', grotesque' or 'changeful.' At the DG Bank, Gehry offers a reconciliation of two typologies within one building; the carefully composed Cartesian geometries of the exterior are offset within by a horse-head shaped conference space that 'charges' the courtyard. At Bilbao, these animating energies are brought to the exterior where the shimmering titanium 'skin' metaphorically evokes a fluid continuous motion that animates the building. Gehry's desire to register a fleeting moment of time in matter imbues the prosaic with a sense of magic. This search for the 'pregnant moment,' that underlies the formal expression of the Bilbao museum, is communicated through a sailing metaphor. He relates how the moment of instability a sail has under changing wind directions, the slight ripple known as the luff, poised between fullness and collapse, becomes a leitmotif in the development of his work (Van Bruggen 1998: 57; Sliwka 2000: 54). At Bilbao, the conveyance of this energy and movement, replaces the role played by ornament in Ruskin's modern Gothic .

Ruskin's dissection of *Alisma Plantago* is at the heart of his discourse on Gothic architecture. Searching for the "authoritative principle" underlying "the inner anatomy which regulates growth and form," he drew from his empirical observation in the field. His studies into the origins of the Alps contributed to the birth of a new branch of research — described in his book Modern Painters as the problem of "growth and form," the phrase used later by D'Arcy Thompson to describe the process referred to by natural scientists as "morphogenesis." Thompson's pioneering text is a more systematic study of Ruskin's observations, which confirms that movement 'impresses' form on structure, and develops more complete and complex structures from elementary components of a "very simple kind".

This aspect of Thompson's work has an interesting connection to the architecture of Santiago Calatrava, and has been described extensively by Alexander Tzonis and Liane LeFaivre in their discussion of that architect. Thompson understood that organisms evolve their structural forms in response to forces, moving matter to fortify the organism where required — strengthening structure at critical points by reinforcing it or dispensing with unnecessary material (Tzonis and LaFaivre:127). His illustration of a bison skeleton for example, shows these phenomena clearly. By comparison, the simple post and beam structures of the primitive hut have no place in this view of nature. Their uniformity of cross-section, inefficient allocation of material, and poor distribution of loads do not reflect actual stresses within the material. Yet the orientation of architects such as Gehry and Calatrava towards more intricate, 'organic' and dynamic forms is a more complex matter. Calatrava uses as a key reference in his work a dog skeleton (Fig.11) — an image that connects him to Thompson's concept of morphology. Not surprisingly, his work is known for its use of non-orthogonal, differentiated members, which are aligned to direct forces to earth along the shortest routes. Like Thompson's organisms that adapt to forces, Calatrava's sections thicken and taper in response to dynamic loads. In this sense, they confirm the memory of that movement in their form. Like Thompson, Calatrava presents us with a morphological reading of structure which "is not only interested in the forms of material things but their dynamic aspect, interpreted in terms of force and the operations of energy" (Thompson 1992: 19). In organisms, Thompson observed,



11: Santiago Calatrava, Model of dog skeleton. (Sharp 1996: 7)

> it is not merely the nature of motions of the living substance which we must interpret in terms of force (according to kinetics), but also the confirmation of the organism itself, whose permanence or equilibrium is explained by the interaction or balance of forces, as described in statics (Tzonis and LeFaivre: 134).

Both Gehry and Calatrava want to express a dynamic sense of the interaction of forces in their buildings, although they differ in their approach to this goal. For both architects, the quotidian act of construction can be tied to the 19th century architectural debates that culminate in Thompson's work and a growing body of work in many disciplines, on emergent properties and self organizing systems that can be described as the 'new naturalism.'

Tzonis suggests that Calatrava's notion of the 'pregnant moment' is bound to an engineering concept of the "critical point" — a point beyond which, if a certain design variable is exceeded, "the interatomic bonds of a member will be broken and the structure will disintegrate" (Tzonis and LeFaivre: 152-153). This theme occurs in the Stadelhofen station, where the structures tilt and return in a dynamic play of forces. It is developed subsequently at different scales in the supports of the galleria at BCE Place, Toronto (Fig.13), or the project for St. John the Divine in New York. Calatrava's referential tree sketch for BCE Place (Fig.12) connects us in spirit to the origins of Gothic architecture as envisaged by Hall in the late eighteenth century, and links in an interesting way to the investigations of Ruskin.[5] Ruskin's drawing of a tree structure examines the law of ramification as well as illustrating the "delicate curve" between the borders of the foliage and the rhythmic traits of the development process (Fig.14). Such branching, which occurs in Calatrava's tree-like formations, "represents the metamorphosis that at a certain point of its growth doubles in nature" (Portoghesi 2000: 50). This law of self-similarity in the structure of a tree (or its fractal nature) had been observed almost a century before Mandelbrot defined it in mathematical terms.

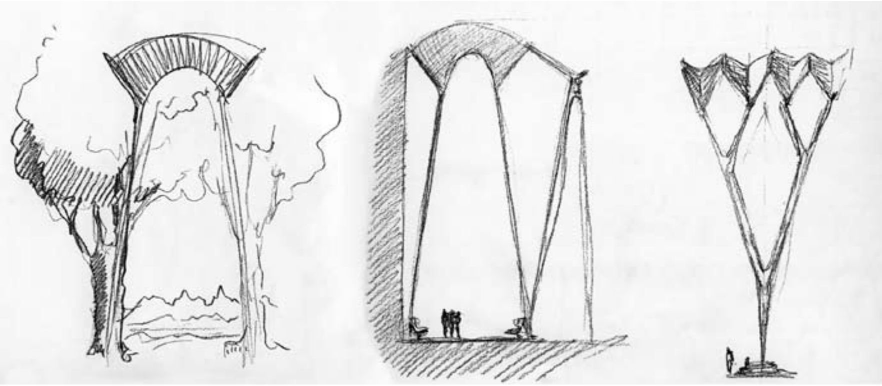
With his project for the south transept of the unfinished neo-gothic church of St. John the Divine, there is yet another curious return to origins (Fig.15). Throughout the body of the church, supported on a skeletal system of inclined structural members, Calatrava has proposed a bio-shelter beneath a glazed roof.[6] The Christian symbol of the 'tree of life' is physically embodied in the new structure, complete with actual foliage of the attic bio-shelter, which will help cool the interior.

Human Agency and the Engineering of Nature

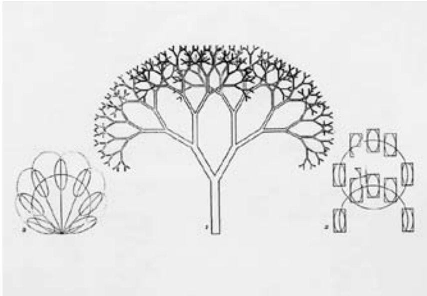
If we extend the discussion of architectural analogies with nature to the question of intentionality, we return to Ruskin's insistence that the registration of the hand of the worker in the building's form contributes to the life of the building. This notion finds an interesting resonance in Frank Gehry's work. First, his early projects rely on an aesthetic of unfinished-ness, an intentional roughness of detail and use of cheap mass-produced materials. The attitude is reminiscent of Le Corbusier's use of rough and inexpensive *beton brut* in projects such as the Unité d'Habitation at Marseilles. For Le Corbusier, the faults of the material were like wrinkles on the human face, adding character.

Secondly, like Ruskin's gothic carver, Gehry's design process involves a constant response to 'material' rather than the imposition of a preconceived idea. He values the tactility of modeling and the spontaneous energy of freehand drawing as means of registering the expressive intentions of a design. His Guggenheim Museum in Bilbao, although heavily dependent on digital curved surface modeling software, was developed from such gestural and sensual investigations in sketch and model form. Once the sculpted forms were finalized, an exact digital model described the building in mathematically defined curves and surfaces. This ability to precisely register an architect's gestural intentions in digital models and construction techniques has profound implications for architectural practice — involving the architect, like his medieval forbears, far more directly in fabrication, construction and the interactive relationship between builder and material. It also has significant implications on the economics of assembling buildings.

William Mitchell, in a discussion of the technical innovations pioneered in Gehry's practice, argues that developments in computer aided manufacturing and assembly have made the production of buildings that use non-Euclidean geometries increasingly competitive. Simple boxes are still cheaper to build, but they will soon have to compete with digital prototyping and fabrication technologies that make it easier to build curves. According to Mitchell, the new digitally controlled CAD/CAM machinery also allows for mass customization which is "particularly attractive in the fabrication of construction components, since buildings are mostly one-off rather than mass-market products, and it is often difficult to get sufficiently long production runs to achieve major economies

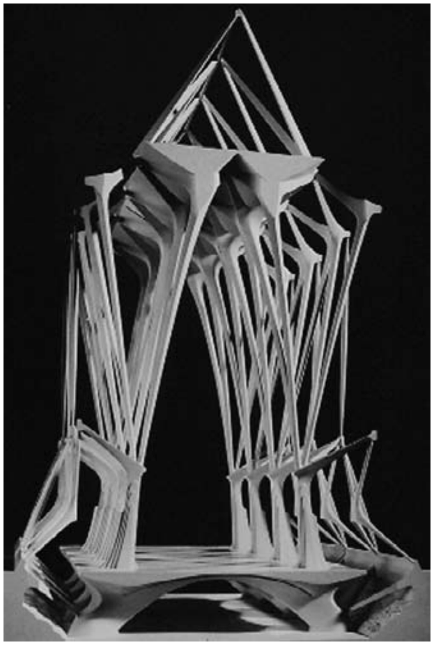


12: Santiago Calatrava, Tree sketch for BCE Place, Toronto. (Blaser 1990: 68-69)



14: J. Elmslie, Tree structure (Ruskin 1897: vol. 5, pl.56)

13: Santiago Calatrava, Galleria at BCE Place, Toronto, 1992. (Daniel Sliwka)



15: Santiago Calatrava, Proposal for completion of the Cathedral of St John the Divine, New York City, 1991. (Tzonis 2001: 89) of scale" (Mitchell 2001: 360). Because of these innovations, steel frames can be formed economically into complex shapes. This technique was used at Bilbao and more recently in Gehry's renovation to the Art Gallery of Ontario in Toronto, where the construction photograph shows a striking resemblance to Thompson's bison skeleton[7] (Fig.16).

Computer controlled multi-axis milling machines can fabricate three-dimensional solids, a technology "extensively used in the automobile industry for full-scale prototyping of metal parts. In architecture, it has the potential to reinvigorate the tradition of non-planar cut stonework, substituting high-speed, precise mechanical action for the chisels of masons" (Mitchell 2001: 360-1).[8] The on-going construction of Antonio Gaudi's Sagrada Familia in Barcelona uses this technology, which was also employed to shape the cut-limestone exterior of Gehry's American Center in Paris (1988-94).

Mitchell argues for the likelihood that the digital era strategies and techniques developed by Gehry's office will become mainstream to the point that "simplicity and regularity hardly matter anymore [...] (and that if) designers want to emphasize these qualities, they must now do so on their grounds" (Mitchell 2001: 359). The question remains — on what grounds, other than economy, would architects consider an alternative to rationalism? Part of the answer might lie in our modes of perception, which may in fact be closer to the 'new naturalism' described by the psychologist J.J. Gibson as 'topological' (Gibson 1976; Casey 1993). This way of experiencing space differs from the more familiar Cartesian schema, and may relate to a more kinesthetic sense of engagement in the world. Once we are comfortably 'habituated' in a Cartesian environment, we tend to close out the larger world of nature. Gehry's experimentations, and to some extent those of Calatrava, exert a complex dialectic between formal Cartesian geometries and topographies of chance that assert a collusion with wilderness; the constant perceptual shifts in their architecture, displace any notion of a habitual centering schema.

Conclusion

Cultural typologies offer metaphors of reality. At the beginning of the 21st century, science and models of architectural rationalism are no longer arrogant enough to claim absolute objectivity. The extraordinary complexity of the world may even be disturbing to the modern intellect accustomed to a concrete reality, and seduced by a mastery of technology. But as our minds become progressively tuned to ecological and global concerns, Ruskin and Thompson's evocation of architecture and nature recall an even older image of the world as a living creature, re-awakened from its sleep. The kinesthetic engagement of this world alluded to in the work of Gehry, Calatrava and others, liberates us, if only briefly, from sclerotic vision that defines most urban development. Their projects operate as "assonant fragments" in this environment, creating points of contact with nature and the work of our hands (Portoghesi: 70). In Gregory Bateson's words, they remind us "there is at least an impulse still in the human breast to sanctify the total natural world of which we are" (Bateson 1980: 27; Fuller 1988: 224).

16: Frank Gehry, Art Gallery of Ontario, Toronto, 2007. Photograph Ryszard Sliwka.

Notes

[1]The term is adapted from Ilya Prigogine who used it to describe a new synthesis in science, embracing Western tradition (characterized by its tendency towards experimentation and quantitative theories) together with oriental concepts centered round the idea of a spontaneously ordered world.

[2] Ruskin used this term to describe the work of certain painters he admired (Fuller 1988: 94).

[3] Ruskin seemed ambivalent in his attitude to the translation of Gothic into iron in the realization of the central court of this building. Moreover, he had reservations about the carving executed by the sculptor O'Shea. For a more extensive discussion of Ruskin's views, see Michael W. Brooks in *John Ruskin and Victorian Architecture*, published by Thames and Hudson, 1989, pp.131-134

[4] In the Platonic model, it is tempting to lose the idea of immanence of God within nature.

> Bateson argued that if you project the idea of God beyond creation and set him against it, if you come to see yourself in the role of a god, in relation to nature, then you will logically and naturally see yourself as outside and against the things around you. Bateson has suggested that perhaps our own minds see things the wrong way round; nature may not be the product of an ordering creative mind [...] but our ordering and creative minds are certainly the products of nature; it is therefore not surprising that there should be innumerable correspondences between the two (Fuller 1988: 141-2, 227-8).

[5] In a curious parallel to the discussion of arbitrariness and architecture, I once showed the Heritage Square portion of Calatrava's BCE Place to a New York architect who had studied with James Freed, a partner in Pei, Cobb and Freed, and a disciple of Mies van der Rohe. Freed had constructed his own homage to Mies in the form of the elegant CIBC Bank Tower in Toronto, situated across from the TD Banking Hall designed by his mentor. My colleague admired Freed's building immensely but decried Calatrava's work as structural pornography.

[6] The term 'bio-shelter' has been defined by biologists Nancy Jack and John Todd as a "solar-age workhorse that integrates architecture and food production, water purification, and recycling of wastes, and blends structure, living systems, and solar and electronic technologies to support human culture within a sustainable ecology" (McQuaid 1993: 30).

[7] The capacity to custom-engineer each steel section individually for the Experience Music Project represents a technical advance over the earlier system of layered standard steel sections that support the titanium skin of the Guggenheim Bilbao.

[8] Mitchell also argues that on-site assembly of computer-fabricated elements is more complex than conventional standardized pieces, but the use of a three-dimensional digital model is a valuable aid that can drive laser positioning devices and other electronic construction devices.

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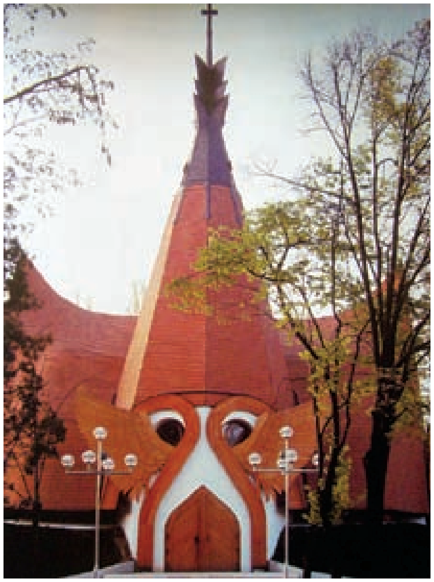
1: Nox, Spuybroek, H2O Pavilion, 1994-97.

Old and New Organicism in Architecture: The Metamorphoses of an Aesthetic Idea

Dörte Kuhlmann

Despite their authors´ claims of producing something radically new, many of the design methods applied by the current architectural avant-garde can be traced back to one of the oldest and most influential ideas in architectural history: the concept of organicism in its various guises. Aristotle's definition of art as the imitation of nature provided the unquestionable premise for two millennia of classicism. The basic idea of organicism, to take nature as model, is one of the most oldest and most fundamental aesthetic concepts in western art and architecture theory. Since the Renaissance it has shown an uninterrupted continuity, influencing architecture on both the conceptual as well as on the metaphorical level. As late as 1747, Charles Batteaux still reduced the fine arts to a single principle, that of *ars imitatur naturam*. Not only classical, but also modern architects, attempted to imitate natural forms or processes in design. While the influence of classical philosophers waned during and after the Enlightenment, the appeals to the authority of nature only intensified. Thus, the study of organicism concerns a very basic question in the history of architectural theory as well as in the current discourse.



2: Imre Makovecz, Lutheran Church, Siófok, Hungary, 1986. Dörte Kuhlmann.

Even though modern architects rejected naturalist ornaments, they still found in nature "the eternal example for every human creation," to quote Walter Gropius. Not only for Frank Lloyd Wright but also for his arch-enemy Le Corbusier, Mother Nature was the "great and eternal teacher" (Le Corbusier 1980: 176). Yet the lessons they learned from their eternal *alma mater* were radically different. Even post-structurally oriented theorists, such as Greg Lynn and Daniel Libeskind, often make references to nature and to the natural sciences, although their work can be seen as a re-interpretation if not a challenge of the organic paradigm.

Below, we will consider different ways the Aristotelian principle of *ars imitatur naturam* has been applied in architectural theory and design. Starting with the literal, not to say Platonic, imitation of the forms of natural beings, we move to the direction of increasing abstraction, touching the issue of anthropomorphic proportion, the doctrine of form and function being interdependent, the implications of ecological thinking for architectural theory, the influence of chaos sciences, and finally, the very concept of organic unity.

Nature as a Source for Form

Like the current avant-garde, architects of the past turned to contemporary debates in philosophy and natural sciences in order to develop new design strategies. In architecture, the notions of organicism led to the rather Platonic imitation of natural forms. Callimachus, the alleged inventor of the Corinthian order, is credited for designing a bronze chimney in the form of a palm tree in the Erechtheion. The application of plant and animal shapes to ornaments constitutes perhaps the most obvious case of architecture imitating nature, but the principle was not always limited to small details. Claude-Nicholas Ledoux designed a phallic-shaped brothel and Jean-Jacques Lequeu a dairy in the form of a cow. Later, Rudolf Steiner married Callimachus and Ledoux in his design for the heating plant in Dornach; Herb Greene built his vacation house in a shape evocative of a buffalo or a "prairie chicken," and Imre Makovecz gave the dormers in his buildings eyelashes. (Fig. 2)

In most cases, such a design approach is based more on semiotic than aesthetic concerns. The champions of *l'architecture parlante*, for example, reached for a universally understandable language of architecture. Makovecz, on the other hand, has attempted to get to the essence of architecture by investigating the biomorphic etymologies of Hungarian words related to buildings. Other architects have sometimes adopted natural forms for structural purposes. Henrik Petrus Berlage, inspired by Ernst Häckel's *Art Forms in Nature*, used one of his jelly fish images to design a lamp. However, the more recent designs of Frank Gehry, Future Systems, Renzo Piano and others also show strong affinities to the structures of natural organisms. Santiago Calatrava and Nicholas Grimshaw for instance, design expressive skeletons which fold and bend like body parts, as can be seen in Calatrava's garage door that folds like an eyelid. Even more explicit may be the shape of the H2O Pavillon by Nox and Oosterhuis architects, which evokes a stranded whale while its interior seems to address the fluidity of a virtual, liquid 'Deleuzian' space. The computer-generated designs of Greg Lynn, Lars Spuybroek and Jeff Kipnis follow a "blob grammar," which resembles the amorphous forms and viscous transformations of natural organisms one sees in floating jellyfish.

Organic versus 'Mechanical' Form

In more abstract terms, organic forms have often been opposed to geometric forms. Yet organic and geometrical shapes were not always seen as oppositions. Louis Sullivan for example, started with a simple square intersected by diagonal and orthogonal axes to create delicately floral motifs. In his "Essay on Inspiration," he describes the fusion of geometric and organic forms as a design principle of nature, finding in it a transcendental, religious dimension. Influenced by Emanuel Swedenborg, he recognizes the 'feminine' principle in floral, organic forms which emerge from the underlying geometric 'masculine' form. The idea that life is generated from such oppositions and that the universe rests on a dualist foundation is a fundamental idea in his architecture (Sullivan 1979: 188).

Interestingly enough, Sullivan saw no contradiction between ornament and function, despite his reputation as a forerunner of modernist theory; rather, he considered ornament as a necessary element. The opposition of geometric versus amorphous forms, which was not an issue for Sullivan, bitterly divided later theorists. One problem concerned the definition of organic form. Claude Bragdon saw two fundamental possibilities, designed

3: Peter Eisenman, Biocenter of the Johann Wolfgang Goethe-University, Frankfurt am Main, Germany, 1987. Archive Institute of Architecture Theory, Vienna University of Technology.

vs. organic architecture, and recognized this duality as a basic principle of life. Designed architecture is conceptual and artificial, created by talent and influenced by taste, whereas organic architecture is unconscious, free and imaginative. However, he had to concede that the two kinds of architecture could not always be clearly separated (Sharp 1988: 17). In a similar vein, Walter Curt Behrendt talked in the thirties about the opposition between organic and mechanical order (Behrendt 1937: 11f).

Numerous attempts to limit organic theory to the formal phenomenon alone could not survive closer scrutiny and in practice led to an incoherent set of divergent variations. Bruno Zevi felt that organic architecture should never be understood as the application of forms derived from or inspired by plants and animals nor as the more metaphorical representation of nature. Again and again in his *Towards an Organic Architecture*, he disavows the use of biomorphic imagery which in his mind reduces aesthetic pleasure to physiological or sexual sensations (Zevi 1950).

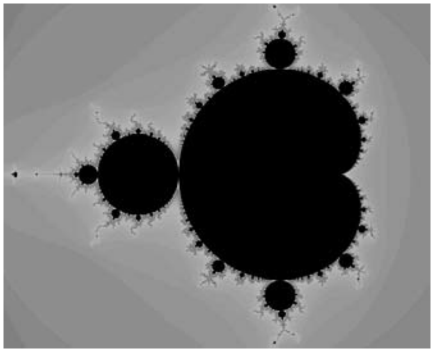
A new solution to the age-old dilemma of organic vs. mechanical form was offered in the seventies by the popularization of fractal geometry. This branch of mathematics was popularized by Benoit Mandelbrot, who promoted it as a geometry of nature. Frustrated with the inadequacy of mathematics to model certain natural phenomena, Mandelbrot found that the apparent disorder of nature reveals, on closer inspection, repetitions of certain structures (Mandelbrot 1982). He was able to provide equations that reproduced the irregular, fragmented patterns of natural phenomena, through the use of iterative processes: branches of trees made from innumerable smaller branchlets, a convoluted coastal landscape comprised of countless smaller involutions, the shape of a feather created out of myriad smaller 'feathers' at ever smaller scales. Mandelbrot traces this observation back to Eugene Delacroix who in his turn refers to Swedenborg's claim "that the lungs are composed of a number of little lungs, the liver of little livers, the spleen of little spleens" and so forth (Mandelbrot 1994).

Organic Proportionality

Still, it has been more common in western architecture to make use of the proportions of natural beings than their forms. Vitruvius advocated basing the proportions of a building on those of a perfect man, establishing a tradition that inspired numerous reconstructions and revisions, the most famous one in modern architecture being Le Corbusier's *Modulor* of 1948, which overlaid the image of a man on the Fibonacci series, found in the shell of the spiral nautilus and which formed the basis of the golden section.[1]

Yet in the 18th century, British empiricists had argued against the idea that architecture should imitate the proportions of natural organisms. In *A Philosophical Enquiry into the Origin of Our Ideas of the Sublime and Beautiful*, Edmund Burke argued that proportion is not the cause of beauty in vegetables, nor can the notion of architectural proportion be derived from the Vitruvian man. His major arguments against the Vitruvian doctrine ran as follows:

> Men are very rarely seen in this strained posture; it is not natural to them; neither is it at all becoming. – the view of the human figure so disposed, does not naturally suggest the idea of a square, but rather of a cross; – several buildings are by no means of the form of that particular square, which are notwithstanding planned by the best architects, and produce an effect altogether as good. [Finally, Burke concluded,] no two things can have less resemblance or analogy, than a man, and a house or temple: do we need to observe, that their purposes are entirely different? (Burke 1812: 164ff and 183f)



4: Benoit Mandelbrot, Fractal structure, 1980. Archive Institute of Architecture Theory, Vienna University of Technology.

Form Follows Function

Burke's tacit assumption was that if the purposes of a man and a house are different, then their forms should be different as well. In this, he relies on another Aristotelian commonplace: that an entity is defined by its *telos* or goal. For Aristotle, *ars imitatur naturam* meant that artists should work like nature – not by imitating the appearance of natural organisms, but by letting their creations unfold their own natures. If Aristotle is correct, nature does nothing in vain, "God and nature create nothing that has not its use" (Aquinas 1963: II,4; Aristotle De Caelo 271a35; De Part.An.645a23-26; 639bl9).

The fundamental tenet of functionalism, that of designing "von innen nach aussen" agrees with Aristotelian essentialism (Häring 1965: 8 and13f). Mediated by Romantic and Transcendental thought, the Aristotelian principle of creation was reformulated in 1896 by Louis Sullivan,

> It is the pervading law of all things organic, and inorganic, of all things physical and metaphysical, of all things human and all things superhuman, of all true manifestations of the head, of the heart, of the soul, that the life is recognizable in its expression, that form ever follows function. This is the law (Sullivan 1979: 208).

The Aristotelian theory of organic form, as defined by Friedrich Schlegel and Samuel Taylor Coleridge (and restated by Frank Lloyd Wright, Hugo Häring, Le Corbusier and the functionalists), implies that the *unfolding* of the innermost essence of a being is the source of value and that any outside influences could only be harmful. Aristotle does not hesitate to reason, for example, that "if the movement of the soul is not of its essence, movement of the soul must be contrary to its nature" (Aristotle: *De P. An*. 407b1; cf. *Pol*. 1325b10). This line of organicism sponsored functionalism and led naturally to an interest in 'authorless' vernacular traditions as well as user-planning, both explored by many architects over the past decades. It also underlies more recent avant-garde concepts such as the "death of the author," which redefine the role of the architect and provide a philosophical foundation for contemporary design methods that use computer-generated forms and design algorithms.

The obvious difficulty in designing from the inside out is to determine what the essential nature of a building is. While Peter Eisenman's early houses or Greg Lynn's projects have occasionally been understood as proposing the building as an end in itself, most architects choose to see a house as a reflection, expression or extension of its inhabitant. In the *Nicomachean Ethics*, Aristotle maintained that "handicraft is he that made it," implying that the limits of an entity are not the limits of its immediate body but that houses and machines, for example, are parts of living beings, extensions of man (Aristotle: *E.N.* 1168a7 and Clark 1975: 62). Following this suggestion, a house should be read neither as 'dead matter' nor as a natural entity but as a natural secretion of a person in the same sense that a snail secretes its shell.

Ecology

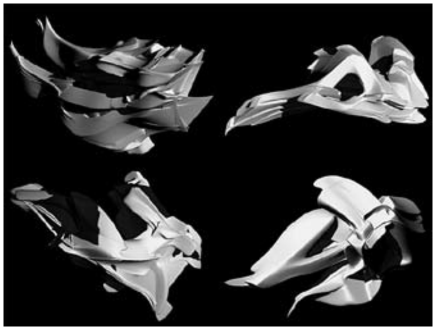
A building could be seen as issuing from its inhabitant, but it could also be seen as growing from the earth like a plant, much as national styles and art forms (according to Johann Gottfried Herder) arose from the soil of their time and place. In recent years, ecological architecture has become the focus of much research, provoked by the 1970s energy crises. However, while attempts to develop sustainable architectural systems with minimal energy use and minimal waste are certainly important, the theoretical implications of ecology also need to be addressed. One of the central issues concerns the individuation of organisms in ecological thought. Instead of conceiving of a plant or an animal as a separate entity as would have Carl Linneus, ecologists usually focus on populations and relate different elements in an ecosystem together. A squirrel could in fact not exist without the plants it eats; these would not grow except for certain minerals, water and air, etc. Logically applied, then, the ecological point of view entails the concept of an ecological superorganism, a concept proposed by Frederic Clements in 1916. It states that different ecosystems are organisms in their own right, with particular emergent properties that their constituent parts, animals and plants, do not have.

The application of such considerations to architectural and urban design raises several questions. Just as no animal is self-sufficient but rather merely an element interacting with others in a larger ecosystem, neither are buildings self-sufficient or independent. In cities, buildings tap into the infrastructure of water pipes and sewers, electric lines and communications, and streets. This idea was given graphic expression in Peter Eisenman's Wexner Center for the Visual Arts in Cincinnati, where the grid of the building extends onto the sidewalks as inlaid brick in the concrete.

From Fractals to Catastrophies

Eisenman and his followers, however, are interested not in ecology but in mathematics and physics. In the eighties, Eisenman aspired to a 'tectonic literature' that will write itself, absolving him from the responsibility of authorship and the guilt of authority. To this effect, he proposed several design methods which attempted to dislocate the author from the work by replacing the designer's intentional choice with either aleatory systems or the impersonal determinism of an algorithm. A number of his projects, built and unrealized, were developed using scientific models: fractals in the Wexner Center in Columbus Ohio, 1989; the genome in the Biozentrum in Frankfurt, 1989 (Fig. 3); 'Boolean' cubes for the Carnegie Mellon Research Institute in Pittsburgh; the 'butterfly cusp' diagram of catastrophic events for the Rebstock Park Housing in Frankfurt, 1992; the Möbius strip for the Max Reinhardt Haus project for Berlin, 1993; and soliton wave studies for the Jörg Immendorff Haus in Dusseldorf, 1993.

The longest-standing of these was his interest in the 'scaling' aspect of fractal geometry. (Fig. 4) Borrowing the term from Mandelbrot, but ignoring the mathematician's intuition that "the fractal new geometric art shows surprising kinship to Great Master paintings or Beaux Arts architecture," Eisenman attempted to revive the avant-garde project by reading fractals as analogous to Jacques Derrida's deconstruction, and vice versa (Mandelbrot 1994). Eisenman believed that fractal geometry could overturn the 'metaphysics of scale' in Western architecture, because the self-similarity of fractals destroyed the possibility of originality, an originary trace, and a decidably 'real' scale (Eisenman 1986: 4). This interpretation must, however, be rejected. If self-similar recursivity questions origin, so too do self-sameness, reflexivity, resemblance, or similitude in general, and fractals have no monopoly on dislocating origins. Furthermore, in Eisenman's projects such as the Wexner Center or Frankfurt Biozentrum, self-similarity was limited to but a few privileged points, while in fractal geometry, every point has that property. Finally, Eisenman introduced neither self-similarity nor the principle of scaling to architectural design. Charles Jencks points out that Bruce Goff "virtually invented fractalian architecture before the fact" in his design for the studio of Joe Price, overlaying of triangles, hexagons, trihexes and lozenges (Jencks 1995: 44). In fact, the repetition of self-similar forms is found throughout architectural history, most evident in Gothic cathedrals and even in Greek and Egyptian temples.



5: Marcos Novak, Four 3-D Projections of a 4-D Object, 2001. Archive Institute of Architecture Theory, Vienna University of Technology.

Though scaling, folding and other mathematically inspired design algorithms fail to bear out authorial claims about their fractal, deconstructive, rhizomatic or scientific nature, they do make some progress towards realizing the ideal, proposed by both Hugo Häring and Stéphane Mallarmé (among countless others), of completely erasing the author and letting the work create itself in a natural, unmediated way (Jormakka 1994). Influenced by Hegelian philosophy, Mallarmé wrote to Henri Cazalis already in 1867,

> I am impersonal now: not the Stéphane you once knew, but one of the ways the Spiritual Universe has found to see Itself, unfold Itself through what used to be me (Mallarmé 1982: 87).

In some of Eisenman's designs, such as his *Romeo and Juliet* project of 1986, the designer almost disappears, just letting various discourses, including Shakespeare's play and the city of Verona, to intersect and unfold in new combinations.

While Eisenman's algorithmic designs have succeeded at times in displacing the author and disrupting the standard categories of architecture, his methods have been criticized by his own authority. Jacques Derrida accused Eisenman's scaling of being

> totalizing first because it is structured as a closed narrative entirely determined by origin and end – it does not respect textual openness and indeterminacy. Secondly, scaling is an anathema because it is the vehicle by which Eisenman seeks to replace one totality, traditional design, with a new and different totality (Derrida 1988: 114).

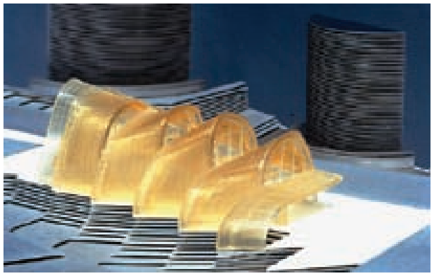
Chastened, Eisenman and his followers moved from Mandelbrot's fractal geometry and Derrida's deconstruction to René Thom's catastrophe theory paired up with the philosophical ideas of Gilles Deleuze. In its emphasis on unpredictable, locally emergent properties which result from feedback loops and irreducible, non-decomposable diffusion of decisive factors, catastrophe theory seemed the ideal response to Derrida's charge of totalization in the scaling method. Inspired by D'Arcy Wentworth Thompson, René Thom had developed catastrophe theory as a way of addressing biological morphogenesis mathematically. Catastrophe theory can supply a number of descriptions of morphological transformations – provided they can be approximated by dynamic systems with fixed points as their attractors – but mathematicians are divided over the means of deciding whether or not observable discontinuity on the level of phenomena can be interpreted as a mathematical jump in the space of the attractors. However, Peter Eisenman´s Max Reinhardt Haus project for Berlin (1993), which is partly based on these ideas, resembles the crystalline architecture of the Czech Cubist Pavel Janak.

The point has often been made that the architecture of Eisenman, Lynn, Chu, NOX, Marcos Novak (Fig. 5,6) and others bears a certain formal similarity, for example, to the *Merzbau* of Kurt Schwitters, to Czech Cubism, to Boccioni's futurism and to the chronophotographs of Etienne-Jules Marey (Fig. 7). One of the reasons why the designs of the new avant-garde look so much like experiments a hundred years ago might be that contemporary architects are still reading the same books, looking at the same pictures and engaging in the same issues as the artists of around 1900.

Although most applications of catastrophe theory (by Christopher Zeeman and others) have produced empirically false predictions, this does not necessarily invalidate it as an explanatory paradigm. However, the application of catastrophe theory in architecture is a different ball game altogether, since we are dealing not with descriptive but normative issues. Robin Evans once suggested that Peter Eisenman's houses were not so much *analogs* to language as they were three-dimensional models of Noam Chomsky's *theory* of language. Eisenman's work in the eighties can similarly be seen as attempts to petrify Jacques Derrida's beliefs about trace, *différance* and effacement in concrete, steel and glass (Evans 1985: 69). His more recent applications of the work of Deleuze or Thom are not essentially different – the question is why these theories about natural or social processes, which they purport to describe, should be reproduced in architecture?

Different reasons have been proposed by contemporary writers. Greg Lynn suggests that architects should use complex curved and folded planes because recent advances in computer modeling have made topological descriptions of such forms accessible to non-mathematicians (Jormakka 1994). Why the mere possibility of drafting certain forms with precision would justify those forms is, however, unclear – unless one subscribes to a variation of the classic principle of plenitude (i.e. the thesis that all true potentialities need to be actualized) or to some kind of organicist belief that everything is interconnected and hence every innovation must have consequences in every domain of life.

A different defense for the use of chaos theory in architectural design is provided by Charles Jencks, who claims that the task of architecture is to tie human beings into the cosmos by building close to nature, thereby representing "the basic cosmogenic truth" of self-organization, emergence and jumps to a higher level. Like Renaissance theorists, he insists that architecture must look to contemporary science for "disclosures of the Cosmic Code" and claims that Frank Gehry's design for the Guggenheim Museum at Bilbao reflects best the new paradigm. Only by looking "to the transcendent laws which science reveals," can architecture "get beyond the provincial concerns of the moment, beyond anthropomorphism and fashion" and "regain a power that all architecture has had" (Jencks 1995: 167ff). While ostensibly declaring avant-garde architecture to be as advanced and intellectually respectable as modern science, Jencks' New Age vision nevertheless relegates architecture to an inferior position, subordinate to natural science.



6: Greg Lynn, Project for a Hydrogen Pavilion, Austrian National Oil Corporation, Schwechat, Austria, 1996-99.

The Concept of Organic Unity

In architectural theory, the notion of *organic unity* was accepted on Aristotle's authority until the nineteenth century, when new interpretations were proposed on the basis of contemporary biology. Paraphrasing the biologist Georges Cuvier, the architect Eugène-Emmanuel Viollet-le-Duc wrote,

> Just as when seeing the leaf of a plant, one deduces from it the whole plant; from the bone of an animal, the whole animal; so from seeing a cross-section one deduces the architectural members; and from the members, the whole monument (Viollet-le-Duc 1875-82).

This argument was later repeated by Adolf Loos, who claimed that one could reconstruct an entire society from a single button.

Both Gottfried Semper and Viollet-le-Duc turned to biology to argue their position in the debate as to whether form follows function or vice versa. This debate began in the 1830s with the establishment of morphology and comparative anatomy. While Cuvier proposed the 'form follows function' theory, his rival Etienne Geoffroy Saint-Hilaire insisted one could not draw conclusions for the structure by looking at the function, arguing that no matter what their function, all organic forms could be reduced back to original types. In this conviction, he came close to Goethe's earlier theory of the *Urpflanze*, the original plant.

By the 1840s, biologists rejected both Cuvier's and Saint-Hilaire's position and questioned in general the validity of teleological interpretations of natural phenomena. Contrary to the theses of Viollet-le-Duc and Cuvier, a investigation of any organism immediately reveals an arbitrary number of parts, the shape, structure or function of which allow for no adequate explanation. Yet, despite the efforts of a century of Darwinism to present evolution as a process involving the random mutation of genes, with natural selection weeding out only those mutations that fatally affect populations, many organicist writers continue to view evolution as a teleological process of improvement in which organisms have achieved a perfect adaptation to their environment – permitting some ecologists to take it as axiomatic that all ecosystems are in perfect homeostasis, only upset by the thoughtless interventions of humankind. Such an idea of nature, as a perfectly functioning ecological complex, is not derived from empirical observation but rather from extra-scientific, usually theological, sources.

Be that as it may, the Aristotelian ideal of an organic whole has pervaded modern architecture, even the theories of architects who never used natural forms in their designs. Thus, Ludwig Hilberseimer for example, demanded that "all works, however different, must originate in a unified spirit" (Hilberseimer 1978: 99ff). Similarly, Ludwig Mies van der Rohe, defining a structure turns to the Aristotelian concept of organic wholes when he says, "by structure we have a philosophical idea. The structure is the whole, from top to bottom, to the last detail with the same ideas" (Carter 1961, 97).

In what is perhaps the most virulent formulation of organicism, the philosophy of G.W.F. Hegel, the concept is understood in terms of the interconnectedness or the essential fragmentary nature of everything. In his *Logic*, Hegel wrote,

> Everything that exists stands in correlation, and this correlation is the veritable nature of every existence. The existent thing in this way has no being of its own, but only in something else (Hegel 1975: 191 and Shusterman 1992: 72).

According to the British philosopher George Edward Moore, the Hegelian notion of an organic unity claims that "just as the whole would not be what it is but for the existence of its parts, so the parts would not be what they are but for the existence of the whole" (Moore 1959: 33 and Shusterman 1992: 72). The idea is that emergent properties belong to the parts as well as the whole. A severed hand, for example, cannot function at all in the way we expect of a hand. Things with different properties must be different things, so that a hand severed from its body detached is not the same thing as a hand still connected. Hence, parts of an organic whole (in the Hegelian sense) are inconceivable, except as parts of that whole.

Yet Moore rejected this view, because it confuses properties belonging to the whole with properties of one of its parts. Even more significantly, he viewed the Hegelian notion of an organic whole as self-contradictory, because it assumes that a part is distinguishable from the whole while simultaneously asserting that the part contains some aspects of that whole as part of itself. In other words, radical organicism postulates that any individual part we distinguish as an element in the whole cannot be so distinguished – the part *is*, it is not part of a whole.

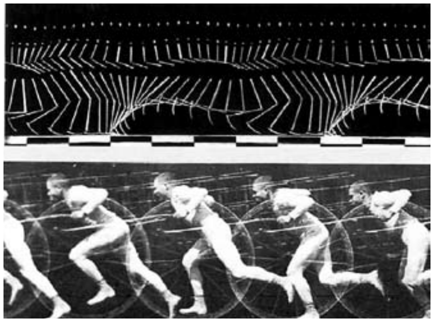
Obviously, Derrida's theories are a form of radical organicism, based on the universalization of Ferdinand de Saussure's diacritical linguistics or Friedrich Nietzsche's belief that

> in the actual world [...] everything is bound to and conditioned by everything else" and his conclusion that "no things remain but only dynamic quanta, in a relation of tension to all other dynamic quanta: their essence lies in their relation to all other quanta (Nietzsche 1968: § 559, 584, 635; Shusterman 1992: 72).

We have already seen that radical ecology makes similar claims for biological systems. In Derrida's hands, organic diacriticism leads, among other things, to the dissolution of the work of art as an independent entity, as defined by modernist criticism.

Hence, the very concept of an organic unity is self-contradictory. Yet, even poststructuralist writers accept the notion in their critical practice, for the assumption of unity is required of the concept of a work of art which in turn forms the basis of the interpretive activity (Dickie 1988: 164-165; Wimsatt and Beardsley 1971:1015; Danto 1992: 134). The concept of organic unity is therefore inexorably bound with the concept of a work of art – only if taken as a unity does a thing exist as a work of art (Jormakka 1994). In the same way, Mies van der Rohe compared different types of buildings to roses and potatoes, explaining that

> while both are based on the same natural principles, we ask of a rose only that it be a rose; we ask of a potato only that it be a potato. Philosophically speaking, only then do they exist (Neumeyer 1991: 299).



7: Étienne-Jules Marey: (top) Study of human movement, chronophotograph, 1886; (bottom) Man pushing a cart, chronophotograph, ca. 1891.

Conclusion

While attempts to base architectural design on the example of nature are typical of stylistic crises and indicative of a search for new, possibly objective foundations, the implications of organicism are not limited to particular styles or forms (van Eck 1994; Kuhlmann 1998; Kuhlmann and Jormakka 1997). Rather, they are general and fundamental enough to relate to contemporary issues at any time and pose radical questions. As the millennium draws to a close, the challenge of *ars imitatur naturam* focuses on the author and the object.

The objective of following 'nature' as revealed through the natural sciences or the 'nature' (essence) of the particular building, de-emphasizes the authorial self-expression of the architect and ultimately leads to the "death of the author," as announced by Roland Barthes. The notion of a building as a functional unity comparable to an organism necessitates a questioning, on the one hand, of what is a function, how it is historically and socially constituted, and what would qualify as a functional unit of study; and on the other, how body, function and building and the chiasmatic relationships between them may be articulated. If the argument sketched above is correct, the assumption of the building as an entity or an independent work has either to be given up or reformulated as deconstructive *différance*.

Notes

[1] In 1947, a year before Le Corbusier published his Modulor, Rudolf Wittkower published his studies on the architect Andrea Palladio, reducing all the different Palladian villas to a shared nine-square tartan grid. Wittkower claimed that the grid was "subconsciously rather than consciously perceptible to everyone who visits Palladio's villas and it is this that gives his buildings their convincing quality" (Wittkower 1983: 72). Despite major problems, Wittkower's brilliant essay soon became famous and inspired Colin Rowe to discover a similar nine-square grid in Le Corbusier's Villa Stein at Garches; since the sixties, the enthusiasts of generative grammars such as Georg Stiny and William Mitchell have used Wittkower's analysis as a foundation for generating more Palladian villas.

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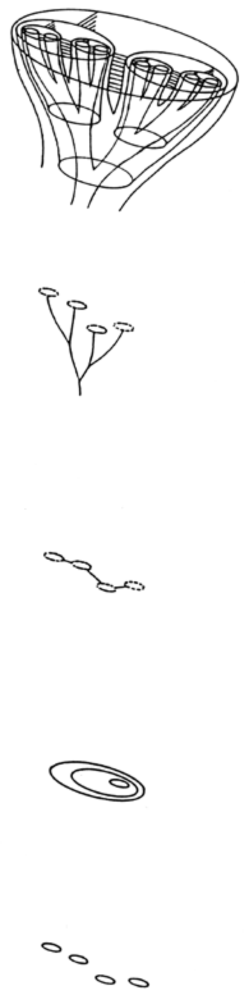
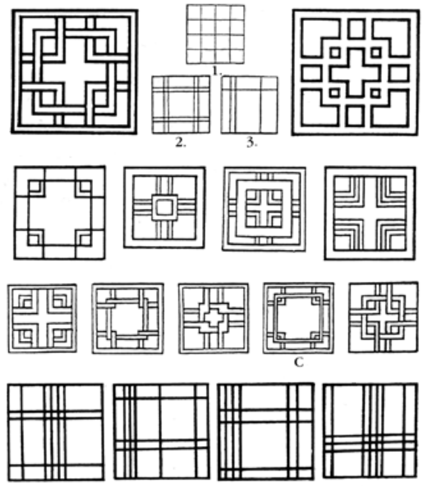


1: The four primary characteristics of biological order illustrated in a plant form. (Adapted from Riedl 1978, courtesy of Rupert Riedl.)

Functional versus Purposive in the Organic Forms of Louis Sullivan and Frank Lloyd Wright

Kevin Nute

Analogies between man-made artifacts and living organisms have been a persistent theme in Western thought since antiquity (Rousseau 1972). Historically these analogies have taken two primary forms: a rational appreciation of the fitness of living organisms for specific purposes, and an aesthetic appreciation of their purely formal quality of wholeness or coherence (De Zurko 1957).[1] Herein would appear to lie the origin of what was to be a critical difference between Louis Sullivan's interpretation of organic form and that of his erstwhile assistant, Frank Lloyd Wright.



2: Arthur Dow, Visually purposive organic 'line-ideas' based on interlocking rectangles, 1899.

Louis Sullivan and the Rational Appreciation of Functional Adaptation

In the case of Sullivan and Wright, the essential difference between their particular interpretations of organic form is more immediately traceable to the writings of the British sociologist Herbert Spencer and the German philosopher Immanuel Kant. Louis Sullivan's understanding of the organic form was strongly influenced by Spencer's explanation of its practical cause as progressive adaptation to specialized functions (Sullivan 1956: 254-5).

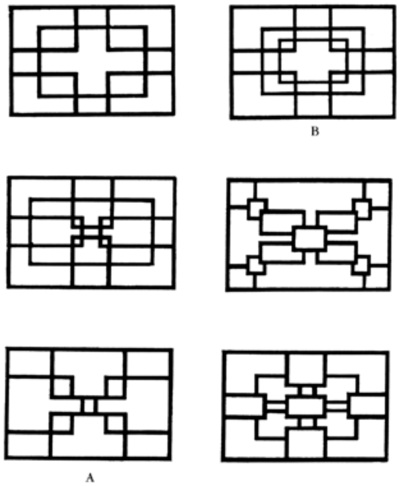
The notion of functional adaptation underlying Spencer's view of organic growth and evolution was summed up in his declaration, "a function to each organ and each organ to its own function, is the law of all organization. To do its work well, an apparatus must possess special fitness for that work; and this implies unfitness for any other work" (Spencer 1892: 121).

Apparently inspired by this functional explanation of organic development, Louis Sullivan later argued similarly in his *Kindergarten Chats*,

> If we call a building a form, then there should be a function, a purpose, a reason for each building, a definite explainable relation between the form, the development of each building, and the causes that bring it into that particular shape; and [...] the building, to be good architecture, must, first of all, clearly correspond with its function (Sullivan 1979: 46).

Sullivan's view of the organic form was thus essentially although by no means entirely–mechanistic. Which is to say, each of its parts was seen essentially as the 'effect' of a different functional 'cause,' an idea which Sullivan encapsulated in his much-abused motto "form follows function."

Crucially, however, functional adaptation only constituted half of Herbert Spencer's notion of organic development. Spencer had explained that at the same time as the various parts of the organism take on different functions, not only does the form of the



3: Arthur Dow, Organic line-ideas, 1899.

organism become progressively differentiated, but in the process, each part also becomes increasingly dependent on the others to perform the operations it has given up in order to concentrate on its own particular role:

> As it grows, its parts become unlike: it exhibits increase of structure. The unlike parts simultaneously assume activities of unlike kinds. These activities are not simply different, but their differences are so related as to make one another possible. The reciprocal aid thus given causes mutual dependence of the parts. (Spencer 1969: 21-22).

Although Sullivan seems to have been well aware of the quality of interdependence of parts characterizing the organic whole (Sullivan 1979: 47), his writings emphasized the differentiation of its parts due to functional adaptation, leading many who followed to the false conclusion that the appeal of the organic form stemmed primarily from a rational appreciation of the fitness of its various parts for specific purposes.

As Immanuel Kant had pointed out two centuries earlier in his *Critique of Judgement*, however, our appreciation of objects is by no means always based on an understanding of their functions. It can just as easily be purely formal. Kant argued that as long as a form appears generally 'purposive,' that is, ordered and apparently 'designed,' it is not necessary to know its precise function to appreciate it aesthetically as a form in its own right. Moreover, he suggested that the organic form was uniquely appealing in this respect, because its interdependent parts effectively exist *for the purpose* of sustaining each other and the whole, not only functionally but also formally, making it inherently 'purposive' and visually pleasing, irrespective of any knowledge of its actual functions (Kant 1892: 277, 280).

Sullivan, however, explained the appeal of the organic form as deriving from a rational understanding of the functional adaptation of its parts, arguing that the various functions of a building ought to be similarly directly 'legible':

> If a building is properly designed, one should be able with a little attention, to read through that building to the reason for that building [...] Consequently each part must clearly express its function [so] that the function can be read through the part (Sullivan 1979: 47).

In fact, even if perfect adaptation to function were practically achievable in a building – which is doubtful, since no design program is ever really complete – it would almost certainly not be widely appreciated, since this would require a detailed knowledge of the internal functions of buildings unavailable to most ordinary observers.

To be fair, on other occasions Sullivan merely suggested that it was appropriate that the various parts of a built form should vary in form according to their differing functions, without insisting that these functions be directly readable by an observer (Sullivan 1896). In fact he specifically pointed out the danger of treating design as merely the formal expression of a program, I wish to warn you that a man might follow the program you have laid down, to the very last detail of details, and yet have, if that were his make-up, a very dry, a very pedantic, a very prosaic result. He might produce a completely logical result, so-called, and yet an utterly repellent one–a cold, vacuous negation of living architecture (Sullivan 1979: 48).

Unfortunately Sullivan's warning did not prevent others from later pursuing his "form follows function' motto into the dead-end of functional determinism. A notable exception, however, was his former assistant, Frank Lloyd Wright.

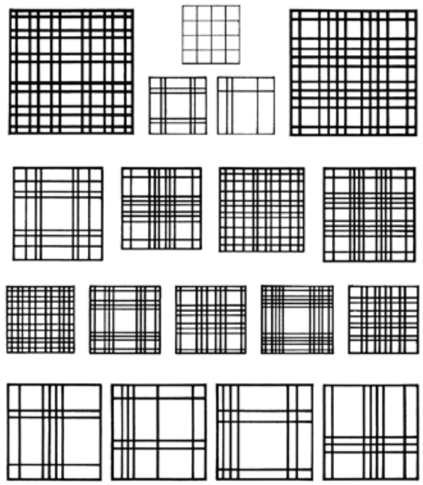
Frank Lloyd Wright and the Aesthetic Appreciation of Formal Purposiveness

While Frank Lloyd Wright would have been well aware of Louis Sullivan's explanation of the functional causes of the organic whole, early on he seems to have made a conscious decision to concentrate instead on recreating its formal qualities, characterized by an apparent purposiveness based on a balance of differentiation and interdependence of parts.

For Wright, the initial means of bringing this quality into his own work seems to have come in the form of a series of two-dimensional interlocking patterns illustrated in a turn-of-the-century design textbook written by Arthur Wesley Dow. The book *Composition*, published in 1899, was a graphic interpretation of the theories of Dow's former colleague at the Boston Museum of Fine Arts, Ernest Fenollosa, best known for his role in championing Japan's traditional arts in the face of Westernization at the close of the 19th century. In return, Japanese art had provided Fenollosa with the foundation of a radically new approach to art education, based upon the aesthetic organization of lines, tones, and colors into mutually interdependent 'organic' wholes. When this theory was graphically illustrated by Dow in his book *Composition*, it appears to have had a direct impact on Wright, who by the time of the book's appearance was already an admirer of Fenollosa's work (Nute 1991).[2]

In his introduction to *Composition*, Dow described how he was using primarily Japanese examples to illustrate what he and Fenollosa considered to be universal aesthetic principles (Dow 1899).[3] From his studies of Japanese art, Fenollosa had come to the conclusion that the quality of organic wholeness was essential to all the arts. Dow took this up as a central theme in *Composition*, where he illustrated the concept in the form of a series of simple two-dimensional patterns, or 'organic line-ideas,' which, while having no obvious practical purpose, displayed an aesthetically pleasing balance of differentiation and interdependence of parts characteristic of the organic whole (Fig. 2,3). As Dow explained,

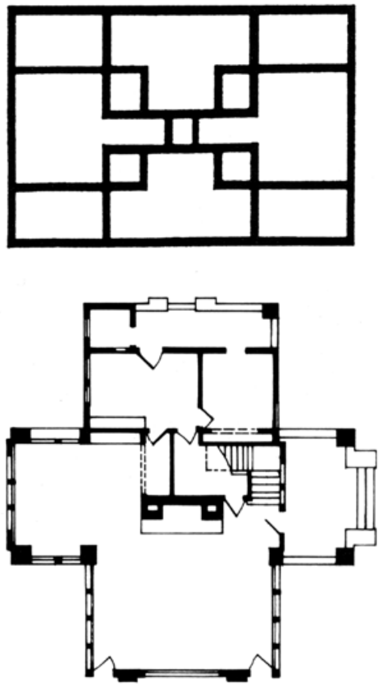
Every part of a work of art has something to say. If one part is made so prominent that others have no reason for being there, the art is gone. So in this case; if one line asserts itself to the detriment of the others, there is discord. There may be many or few lines, but each must have its part in the whole. In a word, wholeness is essential to beauty; it distinguishes Music from Noise (Dow 1899: 38).



4: The tartan grids underlying Dow's organic line-ideas.

In accordance with Fenollosa's ideas, Dow described all the visual arts, including painting, as 'space-arts,' concerned primarily with the aesthetic division of space – irrespective of the rational content they might convey. To this effect he declared, "the picture, the plan, and the pattern are alike in the sense that each is a group of synthetically related spaces" (Dow 1899: 24).

Wright appears to have taken a similar approach to these elements in his own work (Nute 1993: 86). He treated the plan drawing, for example, as an aesthetically pleasing organic whole in its own right, irrespective of its practical implications, having suggested "there is more beauty in a fine ground plan than in almost any of its ultimate consequences. In itself it will have the rhythms, masses and proportions of a good decoration if it is the organic plan for an organic building with individual style." (Gutheim 1969: 153). Such an aesthetic approach would certainly help to explain the unusual visual appeal of Wright's plan drawings, which was noted by his Chicago contemporary Thomas Tallmadge as early as the 1920s when he observed that "many of [Wright's] plans, like those for the Imperial Hotel in Tokyo, even when entirely divorced from their practical significance, are exquisite pictures in themselves (Tallmadge 1928: 228).

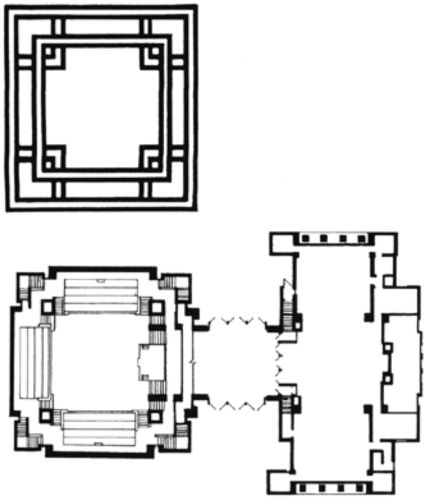


5: Line idea 'A' (from Fig. 4) and the plan of Wright's Charles Ross House, Lake Delavan, Wisconsin, 1902.

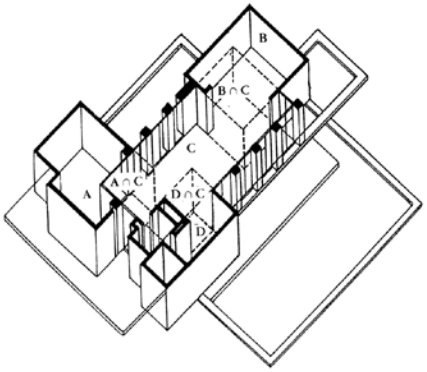
The appeal of Wright's plan drawings is clearly connected to their underlying order, although, as the British architect Richard MacCormac correctly sensed, it stems from something more subtle than a regular grid. His suggestion that Wright may have used irregular or 'tartan' grids as the basis for his early plans was a perceptive one (MacCormac 1968: 143-46). Rather than employing such grids directly, however, it seems that Wright may have begun by making use of some of Dow's organic 'line-ideas,' which were themselves based on syncopated grids (Fig. 3).

Dow had made a point of illustrating the rich variety of aesthetically pleasing patterns which could be generated from irregularly spaced grid lines – demonstrating how, as one gradually removed lines from a uniform grid, the degree of choice and with it the number of creative possibilities progressively increased (illustrations 1 through 3 in Fig. 2). Dow's symmetrical 'line-ideas' were all based on underlying patterns of either four or five interlocking rectangles, and significantly both of these configurations were to appear in Wright's plan designs in the years immediately following the publication of *Composition*.

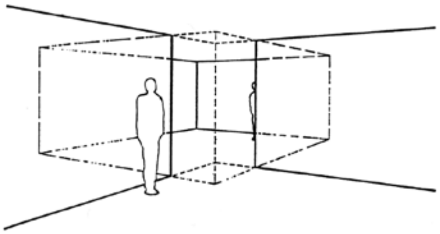
In 1902, for example, Wright completed the Charles Ross house in Wisconsin. Essentially a cruciform pattern of four overlapping rectangles, the core of this plan is close to Dow's line-idea 'A' (Fig. 3,5). In its original form, this pattern would clearly not have been practical as an architectural plan, since its internal spaces were not linked. Wright's stroke of genius appears to have been simply to remove the lines where the rectangles overlapped, creating what amounted to a single functionally differentiated space as the first floor of the house. Similarly, the five interlocking squares which form the plan of the main hall of Unity Temple could well have been inspired by Dow's line-idea 'C' (Figs. 2,6). In Dow's interlocking line-ideas then, it seems that Wright may have found the basis for his first genuinely 'organic' architectural plans and with it the interpenetrating spaces which came to characterize his mature work (Figs. 7,8).



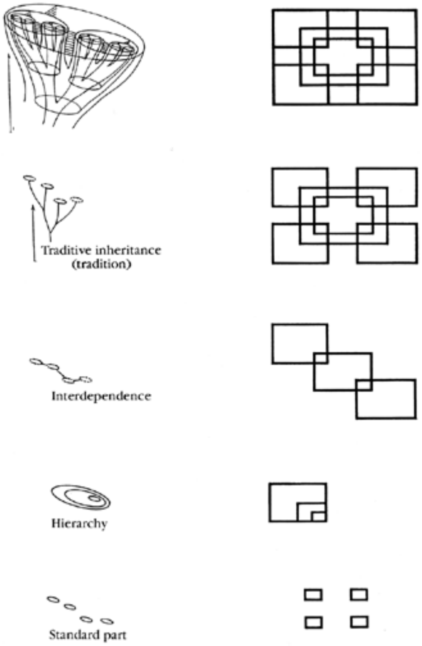
6: Dow's line-idea 'C' (from Fig. 3) and the plan of Wright's Unity Temple, Oak Park, Illinois, 1906.



7: Interlocking spaces in Wright's Life House project, 1938.



8: Interstitial space formed by the implied interpenetration of two incomplete forms.



9: The four primary characteristics of biological order reflected in one of Dow's organic line-ideas. (Images on the left from Riedl 1978, courtesy of Rupert Riedl.)

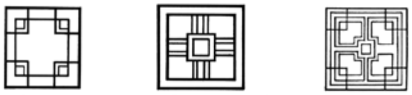
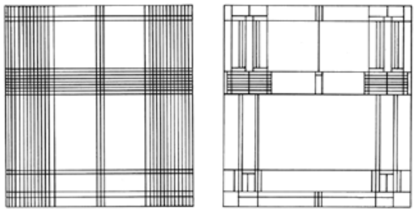
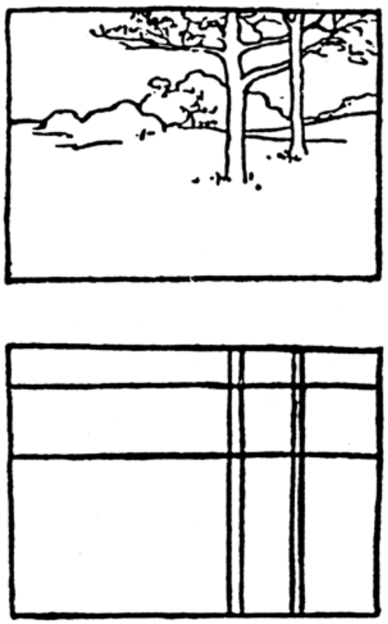


Fig. 10: The asymmetrical tartan grid underlying Wright's decorative window design for the Ward Willits House, Highland Park, Illinois, 1902.



11: Dow's line-ideas (from Fig. 3) underlying the decorative design in Wright's Storer House, Pasadena, California, 1923.



12: Arthur Dow, Landscape composition based on an underlying spatial framework, 1899.

The rectilinear nature of much of Wright's work has led many to question how it could be considered 'organic' or life-like. For Fenollosa, Dow and Wright, however, it was not geometry which made a form organic, but rather the mutually interdependent relationship between differentiated parts. Indeed, if Dow's line-ideas are analyzed according to modern scientific criteria, they are found to exhibit all four major characteristics of biological order (Fig. 9). This may help to explain why Wright also felt justified in describing his famously geometrical decorative designs as 'organic.' In fact several appear to have been similarly directly based on line-ideas published in *Composition* (Fig. 10,11).

The central theme of *Composition* echoed Ernest Fenollosa's belief in the essential unity of abstract design and pictorial art,

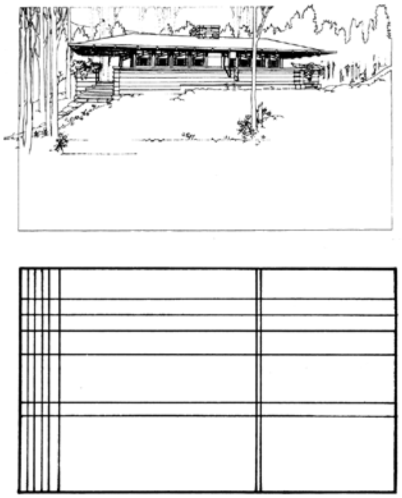
> The designer and picture-painter start in the same way. Each has before him a blank space on which he sketches out the main lines of his composition. This may be called his Line-idea, and on it hinges the excellence of the whole [...] A picture, then, may be said to be in its beginning actually a pattern of lines (Dow 1899: 24).

Dow cited the work of the Japanese woodblock artist Ando Hiroshige as a perfect example of this use of simple 'line-ideas' as underlying aesthetic frameworks for pictorial compositions, even suggesting that in this respect Hiroshige shared something in common with the best architects (Dow 1899: 27). Significantly, Wright described the woodblock print in virtually identical terms – as an abstract composition in its own right, irrespective of its content – suggesting "these prints are designs, patterns, in themselves beautiful as such; and, what other meanings they may have are merely incidental, interesting or curious by-products" (Wright 1912: 12).

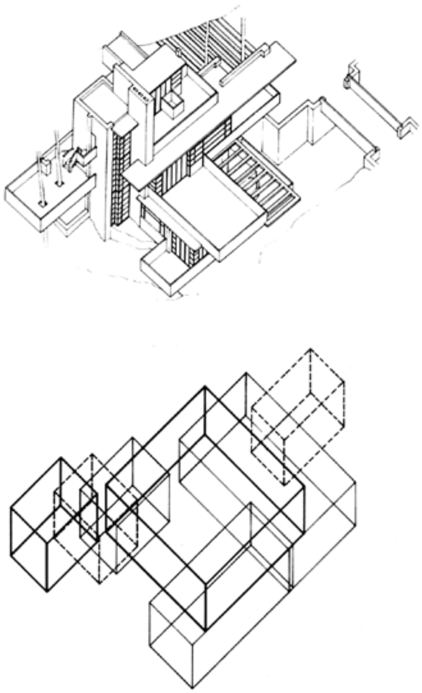
Dow also illustrated the use of geometric structures as the basis for pictorial compositions with several simple landscapes of his own design, each based upon a few irregularly spaced grid-lines (Fig. 12). Of which he wrote,

> Returning now to our premise that the picture and the abstract design may show the same structural beauty, let us see how the simple idea of combining straight lines, as so far considered, may be illustrated by Landscape. Looking out from a grove we have trees as vertical straight lines, cutting lines horizontal or nearly so. Leaving small forms out of account we have in these main lines an arrangement of rectangular spaces much like the gingham and other simple patterns (Dow 1899: 25).

This may it seems have inspired Wright to compose his own *architectural* pictures based on similar underlying frameworks, as for example his rendering of the Como Orchard project (Fig. 13). The presence of such a hidden structure would certainly help to explain the sense of order in Wright's renderings noted by Arthur Drexler, who described how "the eye travels across these pictures in a rhythm established by vertical lines made by features of the architecture" (Drexler 1962: 12).



13: The spatial structure underlying Wright's Wasmuth rendering of the Como Orchard Summer Colony project, Darby, Montana, 1909.



14, 15: Differentiation and interdependence of parts expressed in the interlocking forms of Wright's Edgar Kaufmann House, Bear Run, Pennsylvania, 1936.

Arthur Dow's 'organic' line-ideas, then, may well it seems have provided Frank Lloyd Wright with the crucial practical means of moving beyond his mentor's built expression of organic form. While functional differentiation of parts was a characteristic of Sullivan's work, it never came close to expressing the interdependence of those parts as emphatically as Wright's interpenetrating spaces would (Fig. 14,15).

Notes

[1] Socrates, for example, interpreted the beauty of living creatures in functional terms, "It is in relation to the same things that men's bodies look beautiful and good, namely in relation to those things for which they are useful" (Xenophon 1923: III, 5-6). Plato was one of the first to describe the purely formal quality of organic 'wholeness', "You will allow that every discourse ought to be constructed like a living organism having its own body and head and feet: it must have a middle and extremities which are framed in a manner agreeable to one another and to the whole" (Aristotle 1895: 177).

[2] Ernest Fenollosa was the cousin of Wright's first employer in Chicago, Joseph Lyman Silsbee, and on several occasions Wright wrote approvingly of Fenollosa's efforts to protect the teaching of traditional Japanese art in Japan (Nute 1991: 224-38).

[3] Dow explained,

> He [Fenollosa] had had exceptional opportunities for a critical knowledge of both Eastern and Western art, and as a result of his research and comparisons, guided by a brilliant mind's clear grasp of fundamental ideas, had gained a new conception of art itself. He believed Music to be, in a sense, the key to the other fine arts, since its essence is pure beauty; that space-art may be called 'visual music,' and may be criticised and studied from this point of view. Following this new conception, he had constructed an art-educational system radically different from those whose corner-stone is Realism. Its leading thought is the expression of Beauty, not Representation. I at once felt the truth and reasonableness of his position, and after much preparation in adapting these new methods to practical use, I began teaching a class in Boston, with Professor Fenollosa's co-operation. Here for the first time in this country, Japanese art materials were used for educational purposes (Dow 1899: 5).

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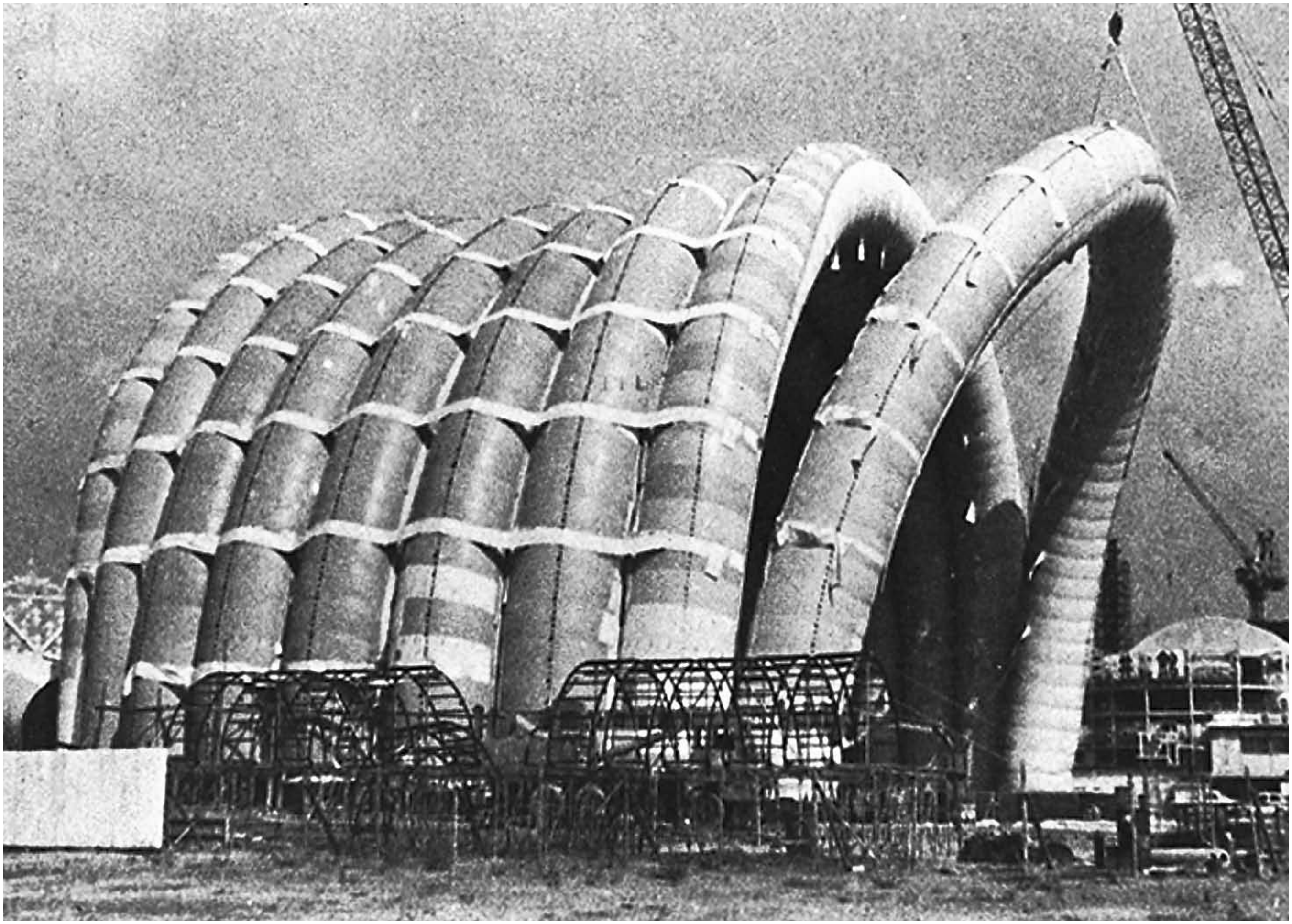
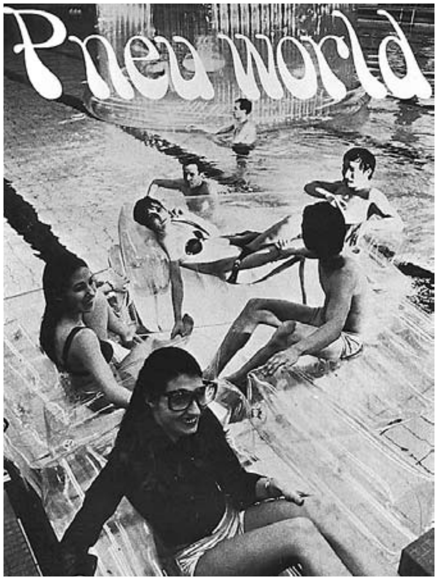


1: Yukata Murata with Mamora, Fuji Pavilion at Expo '70, Osaka. Y. Murata / Taiyo Kogyo Co.

The Forces of Matter

Hadas A. Steiner

> And to me too, who loves life, it seems that butterflies and soap-bubbles, and whatever is like them among men, know most about happiness.
>
> (Nietzsche, *Thus Spake Zarathustra*)



2: 'Pneu World,' cover of *Architectural Design*, June 1968.

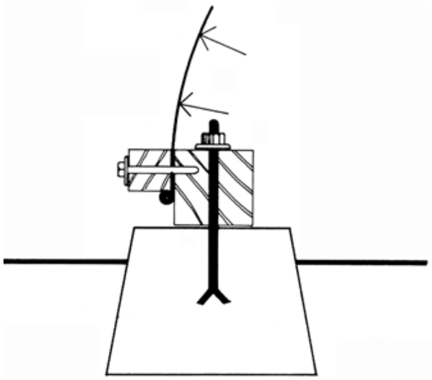
In the decades that followed the Second World War, soap bubbles drifted onto the pages of architectural texts. Bubbles had long symbolized the fleeting quality of material things in Vanitas paintings and supplied ideal models for scientific studies, from the dioptrical experiments of Robert Hooke and Isaac Newton to the microphysical ones of James Clerk Maxwell and Michael Faraday. The soap bubble was a unique structure because it always enclosed the maximum volume with the minimum surface area. After the paradigmatic research into long-lived soap films by Joseph Plateau in the mid-nineteenth century, the resilience of the fragile envelope preoccupied science (Plateau 1873). Mixing wonder with physics as they did, lasting bubbles made an excellent centerpiece for popular demonstrations of scientific principles. 'On the Forces of Matter,' the series of lectures delivered by Faraday himself "before a juvenile auditory" at the Royal Institution over the Christmas holidays (1859), included the soap bubble as demonstration of chemical cohesion. Faraday asked: "Why does it hold together in this manner? Why, because the water of which it is composed has an attraction of particle for particle – so great, indeed, that it gives to this bubble the very power of an India-rubber ball." Faraday's investigations into the structure of nature inspired others, including D'Arcy Wentworth Thompson's *On Growth and Form* (1917) that familiarized postwar architects with the utility of a form "so pure and simple that we come to look on it as wellnigh a mathematical abstraction" (350-351). It was on the strength of the soap film and its economy of materials that the technology of pneumatic structures hoped to draw.

The Science of Bubbles

The physics of the bubble demonstrated the properties of air-supported structures in the pneumatic literature. The 1947 handbook of the British Compressed Air Society traced pneumatics back to the magical technologies of Hero and Ctesibius in the 2nd century BC who used air pressure to make statues moan and to open temple doors mysteriously. The roots of pneumatics in such theatric architecture embedded it, as Vitruvius described, in a structural type that was notoriously subject to alteration and illusion. Within the architectural discipline, the technique had to wait until 1917 to be elevated from a source of animation to a principle of support. Spurred on by the need for quick construction during the first world war, Frederick William Lanchester patented a technique of supporting temporary enclosures with a continuous supply of low-pressure air. The development of components for use in WWII provided the necessary materials for the realization of pneumatic structures. After the success of the 'Radome,' an inflatable weather shield to protect military equipment, Walter Bird extended the practice of his firm, Birdair, to the civilian arena during the mid-50s. Despite their cost-effectiveness, however, pneumatic structures were rarely seen in the street.[1] When conventionally trained architects turned to inflatable design in the late fifties, the structures tended to be exiled to the arena of the Exposition where they efficiently provided coverage for large areas. [2] Due to their novelty and suggestion of transience, for many, inflatables would continue to exhibit a lack of rigidity that was disturbing even for use at temporary sites. Bubbles might have been perfect pneumatic forms in the abstract space of science, but on the ground there are all sorts of forces that destabilize the skin held in place by air.

In some quarters, though, the very nature of this shifting architecture was met with enthusiasm. "I believe that pneumatics are the most important discovery ever made in architecture," wrote Arthur Quarmby. The technique, he believed, had the potential to, "free the living environment from the constraints which have bound it since history began" (Quarmby 1974: 114). Pneumatic contraptions already had a prehistory within utopian thought as well as a presence in the alternate worlds of science fiction. The additional attributes of responsiveness and spontaneity were built into the transition from theory to practice. Not only did the inflatable structure document the fluctuation in ambient conditions, the construction process required a minimum of time and expertise. An inflatable was simple to put up and, crucially, easy to take down (Fig. 1). For those who wished to transform the environments in which people lived to accompany the cultural changes going on all around in the sixties, air-supported architecture had particular significance. In provocative practices, including those of Cedric Price and Archigram in London, or Coop Himmelblau, Hans Hollein and Haus-Rücker-Co in Vienna, pneumatics would play a visionary role. In Paris, where social unrest was pronounced, Utopie focused exclusively on inflatables. Reyner Banham characterized these groups, Archigram in particular, as 'Zoom Wave' newcomers, "stoned out of their minds with science-fiction images of an alternative architecture that would be perfectly possible tomorrow if only the Universe (and especially the Law of Gravity) were differently organized" (Banham 1966) (Fig. 2).

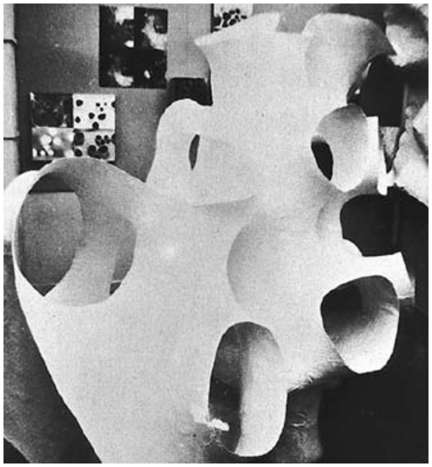
"The particular beauty of the soap bubble, solitary or in collocation," wrote Thompson, "depends on the absence (to all intents and purposes) of these alien forces [of gravity] from the field" (Thompson 1917: 350-1). Though by now, lightness of materials and truth in structure were routine aspirations in the architectural discipline, the tall, slender skeleton wrapped in glass was still an object as the public – and the architects – understood it, with a defined parameter and constant dimensions. "This sort of environment can never be the answer," stated an early Archigram collage with arrows pointing at generic high-rise blocks, "and it isn't even good technology." A method for overcoming the conventional limitations of building technology was exactly what the bubble suggested with its alternative to post and lintel construction. The air-supported envelope combined the intrinsic strength of materials used in tension with the structural efficiency of the shell, with no concern for bending or buckling In the inflatable, as in the bubble, material was pushed to its limits to enclose the maximum space with the minimum boundary and with no need for any rigid infrastructure of columns or beams. By removing the remaining supports, the pneumatic structure tended even more towards the limits of materiality. With the availability of components far lighter than those of the industrial revolution, the young architects aspired to an architecture as portable as a suitcase, or even as a suit.



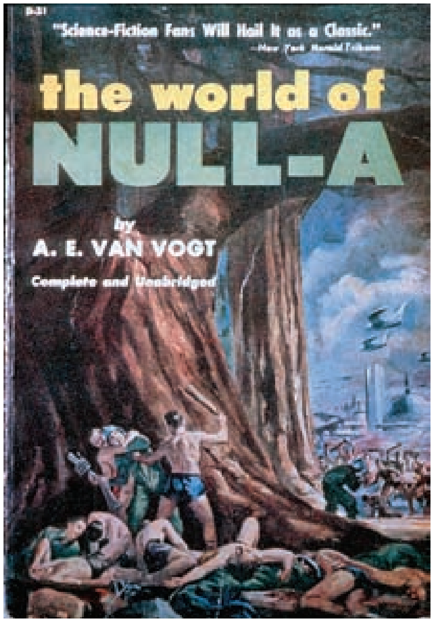
3: Clamped ground anchorage system. (Dent 1971: 109).

Broadly speaking, there are two types of air-stabilized architectures that are sometimes used as hybrids and often mixed with conventional building techniques. The less innovative and more common of these, the inflated structure, functions much like other building systems, using inflatable ribs or vertical supports. The inflated structure is easier to control than the other kind, a moody structure in which a membrane is supported mostly by air pressure. Due to the use of air as a structural component, the air-supported structure was in a constant process of actively enclosing – the fans continuously churned to maintain the pressure holding the skin and changes arose from variations in this artificial breath. In themselves, the buildings were also subject to ambient forces, sensitive and responding to "minute variations in climactic parameters and loading conditions" (Dent 1971: 21). Everything about air-supported structures spoke of continuous change. As it visibly and audibly adjusted to climactic conditions from within or without, the self-regulating skin strained against the pull of gravity. Far from exerting force on the ground, the air-supported structure, if not firmly anchored, floats away.

The problem of a building drifting and how it might be moored raised issues not addressed before, at least above sea level. Structures that threatened to abandon their foundations required an alternate notion of what constituted architectural soundness (Fig. 3). Buckminster Fuller had been advocating such a conceptual shift for some time, wanting contemporary architecture to be light on its feet. Fuller routinely denounced the lack of meaningful engagement with the properties of new building materials within the architectural community. His crusade to change the nature of building expanded on the contention that organic evolution was driven by the requirements of structure. Polyvinyl Chloride (PVC), for example, was an "inherently natural" material for Fuller because it was based on "complex structural behaviors permitted by Nature" (Meikle 1995: 215-6). Thus Thompson's legacy extended to the methodology behind the approach (Massey 1995: 44). Thompson had criticized the tendency to explain the natural world exclusively "by the teleological concept of end, of purpose or of 'design,'" explaining, "in Aristotle's parable, the house is there so that men may live in it; but it is also there because the builders have laid one stone upon another." (Thompson 1917: 4, 6). Objects, then, were not just finished forms, but diagrams of the forces that had molded them. Underlying Thompson's vision of nature was a conception that viewed change and motion, "the ephemeral and the accidental," as essential elements for understanding the world, "not



4: James Stirling, Richard Matthews and Michael Pine, *Bubble sculpture* from *This is Tomorrow* exhibition, Whitechapel Gallery, London, 1956. Michael Pine Collection. Photo David Wager.



5: Robert Schulz, Cover, ACE edition of *The World of Null-A*, 1953.

eternal or universal things" (Thompson 1917: 4). In turn, Fuller's extension of this natural philosophy to technological production sparked a trend of curious texts published after WWII linking design according to these principles to the improvement of the human condition.[3] As it had for Thompson and Fuller, the bubble retained its ideal status throughout this unsystematic chain of transmission. "In the soap film, the material achieves its 'moment of truth,'" wrote Michael Burt in *Spatial Arrangement and Polyhedra With Curved Surfaces*, a typical example of these texts. In less extreme form, the emphasis on development over formal results had influence the methodology of Siegfried Giedion, notably in his postwar tour de force, *Mechanization Takes Command* (1948), and the art historical approach of Ernst Gombrich (Massey 1995: 44).

The Art of Bubbles

This notion of process, natural and technological, captivated the attention of members of the Independent Group, the loose gathering of assorted artists at London's Institute of Contemporary Art (ICA) during the fifties. The debt to Thompson was overt in the (minimally attended) 'On Growth and Form' exhibition of 1951 organized by Richard Hamilton. The 'Parallel of Life and Art' exhibition of 1953, a collaborative effort by Peter and Alison Smithson, Eduardo Paolozzi and Nigel Henderson, demonstrated the structural similarity of biological and engineered things. The larger 'This is Tomorrow' exhibition held at the Whitechapel Gallery in 1956 featured, among twelve pavilions, one by James Stirling, Richard Matthews and Michael Pine (Fig. 4). This pavilion was dominated by a sculpture extrapolated from photographic studies of soap bubbles undertaken by the group.[4] The sculpture, in other words, assimilated the process of documenting the procedure of making bubbles.

An additional work on the reading list of Independent Group members further underscored the methodological agenda: Alfred Korzybski's *Science and Sanity* (1933), or rather the translation of this work into popular terms by A.E. van Vogt and his science fiction *World of Null-A* (1948) (Fig. 5). Korzybski critiqued the legacy of Aristotelian logic in language – the 'either-or' construction of day or night, land or water, life or death – arguing, like Thompson, in favor of a dynamic, process oriented model. The dynamic model was at the root of the rejection of the curatorial policy that had shaped the visual practice promoted by the ICA under the leadership of Herbert Read. It was against Read's agenda, modeled as it was on the ethos of the Purist manifesto, that the independence of the Independent Group was asserted: "But what strikes me," Ozenfant had written, "is not how ephemeral all this is, but particularly how prodigiously stable […] These vast 'constants.'" It was in Thompson's drive to study local relations rather than an ideal final cause that the Independent Group saw its reflection. In short, the struggle of ICA modernism with the 'everyday' values of the Independent Group was the struggle of the universal with the ephemeral, the teleological view of a world versus a world of constant change.

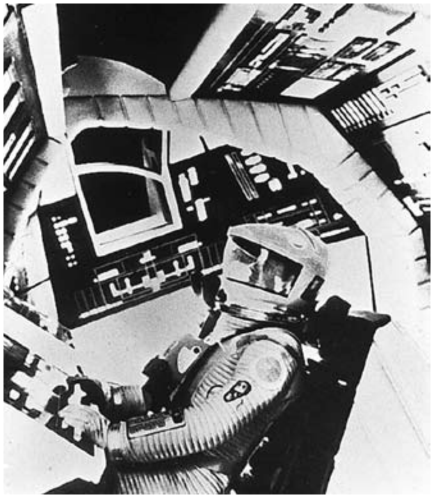
Reyner Banham, himself a part of this alternative scene, defined the Independent Group through his criticism, especially after its demise. Banham continued to privilege work that took changing environmental or social conditions as its premise throughout his career. By identifying practices that took on technologically adaptive structures as true extensions of the modernist project, particularly those on the London scene with which he was most familiar, Banham determined the emphasis of historical discourse. Those engaged in the development of technologically enabled ephemera were also those drawn to experiment with pneumatic structures. In this regard, Cedric Price was a role model (Fig. 6).

6: Adrian George, Cover of *Architectural Design*, October 1970.

Price began to integrate inflatables into his projects in the early sixties. As was not the case with most of his contemporaries, Price's involvement with the mechanical aspects of pneumatics was thorough: he collaborated with Frank Newby on handbooks for the British Standards Institution and for the Department of Environment,[5] lectured at the 'First International Colloquium on Pneumatic Structures' in Stuttgart in 1967 and delivered the keynote address at the 'National Conference of Air Structures in Education' held in an inflatable at Antioch College, Maryland in 1973. In keeping with his aversion to formal perfectionism, Price's survey of pneumatic structures was the only one of its kind to not include the idealism of the bubble analogy. The conscious avoidance of finitude would differentiate standard practice from the visionary use of pneumatics. The interest Price took in inflatables was consistent with his overall ambition to introduce temporality into the finished architectural product. In his own projects, Price capitalized on the capacity of pneumatic structures to adapt rapidly, which integrated what he called a "precise time factor into the process of enclosure" (Price 1984). This inclination also took the flip side of the bubble's structural properties into account: the possibility of sudden and dramatic collapse.[6] With the introduction of the element of time, the bubble as a paradigm of static form was abandoned in favor of a paradigm of a dynamic system. In the pneumatic enclosure, a resilience prone to transience tread the same territory as the desire for structural temporality confronted by the need for shelter.

In 1963, rigid domes, a form that often bore the shadow of the inflatable scaffolding used in construction, were appearing in the *Archigram* publication as 'bubbles'. Learning their lessons from Price, though, the Archigram group wanted to design environments where duration really mattered. By subjecting things more directly to the contingencies of time, the new generation hoped to contest what passed in the architectural discourse of the time under the guise of 'mobility.' The Smithsons had agitated for this cause and employed the term often in their polemics to promote their doctrine of modular extension. But the Smithsons' concept of mobility had little to do with weight or lifespan and made nothing in particular of new technology or materials. Architectural extensions into the landscape utilized conventional building materials such as steel and concrete and glass, materials that, over the course of the sixties, architects began to refer to as 'hardware.' Flexible membranes, on the other hand, were dubbed 'software'.

‘Virtual architectures’ yet to come are still rooted conceptually in this time when programs still came hardwired into computers as a package and it was difficult for the public, including architects, to distinguish between hard and soft technology. Amongst architects, ‘software’ became shorthand for any vehicle for change and adaptation, which lead to confusion in image and text over the domain of compliant technology and materials. Banham reified this fallacy in ‘The Triumph of Software’ (1968) when he contrasted the hardware imagery of *Space Odyssey 2001* (1968) with the inflatables of *Barbarella* (1967) (Fig. 7,8). Banham compared Kubrick’s constructions to a ‘Pompeii re-excavated’: “All that grey plastic and crackle-finish metal, and knobs and switches, all that […] yech […] *hardware*!” By contrast, he wrote, the bubbles of Barbarella were “responsive environments… curved, pliable, continuous, breathing, adaptable surfaces. Banham did acknowledge elsewhere that inflatables could only ever be a low-tech approximation of an actual cybernetic environment (Banham 1968).



7: Stanley Kubrick, *Space Odyssey 2001*, 1968. Warner Brothers.

8: Roger Vadim, *Barbarella*, 1967. Paramount Pictures.

Banham suggested that “taste that has been turned off by the regular rectangular format of official modern architecture” was “turned right on by the apparent do-it-yourself potentialities of low pressure inflatable technology” (Banham 1968). And, indeed, the conviction that rounded forms offered a way out of the dead end modernism had reached by the late fifties was reiterated in the technical literature on pneumatic architecture. In a deviation from his factual voice, Thomas Herzog explained in his handbook that “orthogonal forms with hard, cold, machine-produced surfaces” had dominated architecture, and that, “previous attempts to oppose this with a sensuous plastic world have meant a negation of the technical/structural dimension of architecture.” Pneumatic structures, Herzog contended, offered a synthesis through the use of forms that are “technically highly developed, using soft, flexible, movable, roundly spanned, “organic” shapes, which can be of great sensuous beauty” (Herzog 1976:7; see also Meikle 1995: 217-8). In short, pneumatics suggested a blend of the organic world and built form that would not negate the primary role of architecture.

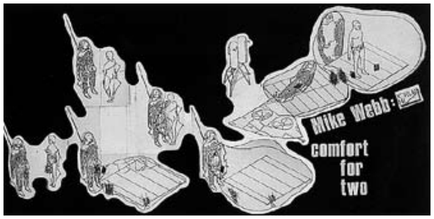
This ‘organic’, not to mention gendered, metaphor, implicated the biological world in the confusions of an architecture based on the bubble. In addition to the analogical rhetoric of curvaceous sensuality, Frei Otto’s classic study of tensile structures, first published in 1962, was more directly concerned with how pneumatic architecture structurally emulated plant and animal life. He wrote,

> We find [pneumatic principles] not only in fruits, air bubbles, and blood vessels, but also in the skin kept taut by muscle tissue and blood pressure, and largely supported, in addition, by a skeleton resistant to bending and compression. Animal and man exhibit the essential features of a lightweight structure […] Pneumatic structures, developed along lines dictated by purely technical considerations, are meeting the justified and growing demand that technology abandon its abstract, antiorganic-mathematical conception, though not its scientific basis, in favor of a conception nearer to organic life (Otto 1967: 10).

When Otto drew a detail of the layers of a pneumatic spacesuit, he included human skin as part of the outfit. Otto's biologically based pneumatics reduced the structural scale of the inflatable principle down to that of the organism.

The Architecture of Bubbles

As the Archigram group progressively departed from its mega-city 'hardware' of 1964, other proposals for domestic 'software' wrapped architecture closer and closer around the body; in Otto's terms, the organic principles of the body were being applied to enclose it. But while a spacesuit was still a suit, Mike Webb's proposal for the 'Suitaloon' (1968) blurred the boundaries between different kinds of bodily enclosures, of buildings and clothes, of inside and outside (Fig. 9). That was the point of the 'Suitaloon': when you wanted to be home, your suit inflated to enclose you. Webb combined what Price had called the 'time factor' and the capacity to integrate change with structure to overcome the 'either-or' dichotomies of permanence and instability, hard and soft, technological and natural–as Archigram perceived them. With the possibilities of lightweight materials, the *Suitaloon* was an enclosure that was fully transportable, exploited the speed of expansion and deflation, constituted and reconstituted itself at will, like a lung. It was a house that was only as durable as clothing and only as natural as a second skin.



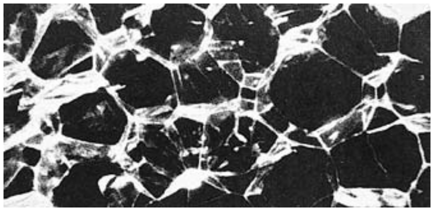
9: Mike Webb, *Suitaloon*, 1968. Archigram Archives.

The inflated suit introduced the internalized world of the autonomous bubble for one, occasionally two, as domestic space. This excursion to the interior of the bubble provided a glimpse at technology adapting to the biological exigencies of life, becoming, as Moholy-Nagy predicted, "as much a part of life as metabolism" (Moholy-Nagy 1961: 64). The images of a meditative David Greene wearing Infogonk spectacles, a prototype of a virtual reality headset, inside the trial *Suitaloon* at the Milan Triennale of 1968 demonstrate this well (Fig. 10). The goggles completed the introversion by providing a view – architecture for the inside of the head – that was entirely perceptual. Such self-containment conflicted with the communal nexus of the stem and web that had been entrenched in the discourse since the fifties. "I have nothing against discontinuous domes," Philip Johnson quipped, "but for goodness sake, let's not call it architecture" (Johnson 1960: 191).

10: David Greene inside the trial *Suitaloon* at the Milan Triennale of1968. Archigram Archives.

The 'Suitaloon' had been provided with a plug to connect it with other like envelopes to circumvent enforced isolation; in the handbooks, meticulous attention was paid to how bubbles clung together in groups. The automatic adjustments made by the whole each time a bubble joined the collocation displaced the emphasis from the reclusive realm of the individual bubble to the interaction of these self-contained units in a responsive system. The inter-connections of the system, 120 degree angles at which bubbles converge, the curvature of their shared walls, provided insight into how to overcome the exclusivity of interiority and exteriority. More than the ordered cluster of bubbles, an agglomeration made up of a multitude of bubble sizes and shapes compressed into multi-angular bodies, as in a foam, is a better example of what emerges when the competing ambient forces of technology and society are at work (Fig. 11). Bubbles, even under conditions of duress, still enclose the largest volume with the minimal surface area. In 'Seaside Bubbles' (1966) one sees Ron Herron's "archigramesque" version of individual units collocating as a society (Fig. 12).

The desire to do away with formal concerns would continue to produce interconnected, complex, chaotic distortions of the bubble. The confusions over the domain of acquiescent materials and compliant technology would also linger on in the following generations of so-called virtual architectures. Thus the abstract perfection encapsulated by the suspended form under ideal conditions and the capacity to adapt optimally to environmental change on the jobsite remained a pervasive tension of the translation from bubble to building.



11: Agglomeration of different bubble shapes, or foam. Frei Otto, *Tensile Structures*.

Notes

[1] The spherical forms lent themselves to Picturesque scatter in non-urban situations. Simple inflatables proliferated during the fifties – by 1957, there were about 50 manufacturers in the US making portable air structures: Birdair, Schjeldall, Irving, US Rubber, Goodyear, Texair, Stromeyer, Krupp, Seattle Tent & Awning, and CID Air Structures, to name a few.

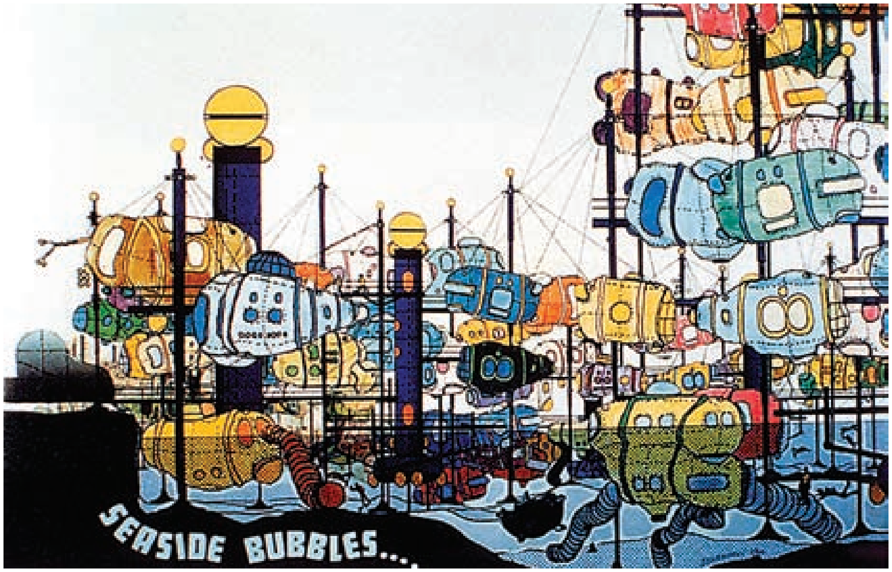
[2] Dent lists the Boston Arts Center Theater (Woods Hole, MA 1959), by Carl Koch and Margaret Ross with Paul Weidhinger of Birdair, as the first pneumatic construction designed by architects (Dent 1971: 39-40). Victor Lundy's hybrid pneumatic exhibition hall for the US Atomic Energy Commission (Santiago, Chile, 1960), with Walter Bird, was noted for its innovation at the architectural level (Dent 1971: 41-44; Reyner Banham 1969: 270-274). The Irving Air Chute Company exhibited a two room inflatable air house – two inflatable domes connected by a tube – at the International Home Exposition in New York City, June 1957. Pneumatics were extensively used at Expo 67, Montreal and Expo 70, Osaka.

[3] The archetypal example was Matila Ghyka's *The Geometry of Art and Life* (New York: Sheed and Ward, 1946) which had a cult following. The text made connections between geometrical form as found in nature, art and mysticism.

[4] "Pine", the catalogue quotes, "recalls the photographs as 'great fun to do' and then cites from a letter that he wrote to Jacquelyn Baas on the 20th of August, 1988: "An enlarger was focused through an aspirin bottle containing soapy water onto photosensitive paper on the wall. This was all set up using a red filter, and when we had a good bubble image, the red filter was removed for about four seconds, and the paper immediately developed. The problem with this was the tendency of the bubbles to burst during the four seconds of exposure. However, we got enough prints for our purpose." Pine and Stirling discounted any influence of Hamilton's 'On Growth and Form' (Whitham 1990: 143).

[5] *Air Structure Research Report*, Department of the Environment, London: HMSO, 1971, and *Air Supported Structures: Draft for Development*, London: British Standards Institution, 1976.

[6] Arthur Quarmby tells a precautionary tale of his three dramatic mishaps with inflatables (Quarmby 1974:98-100). As Banham put it, "an airdome is not the sort of thing that the kids, or a distracted Pumpkin-eater could run in and out of when the fit took them – believe me, fighting your way out of an airdome can be worse than trying to get out of a collapsed rain-soaked tent if you make the wrong first move" (Banham 1965: 59).



12: Ron Herron, *Seaside Bubbles*, 1966. Herron Archives.

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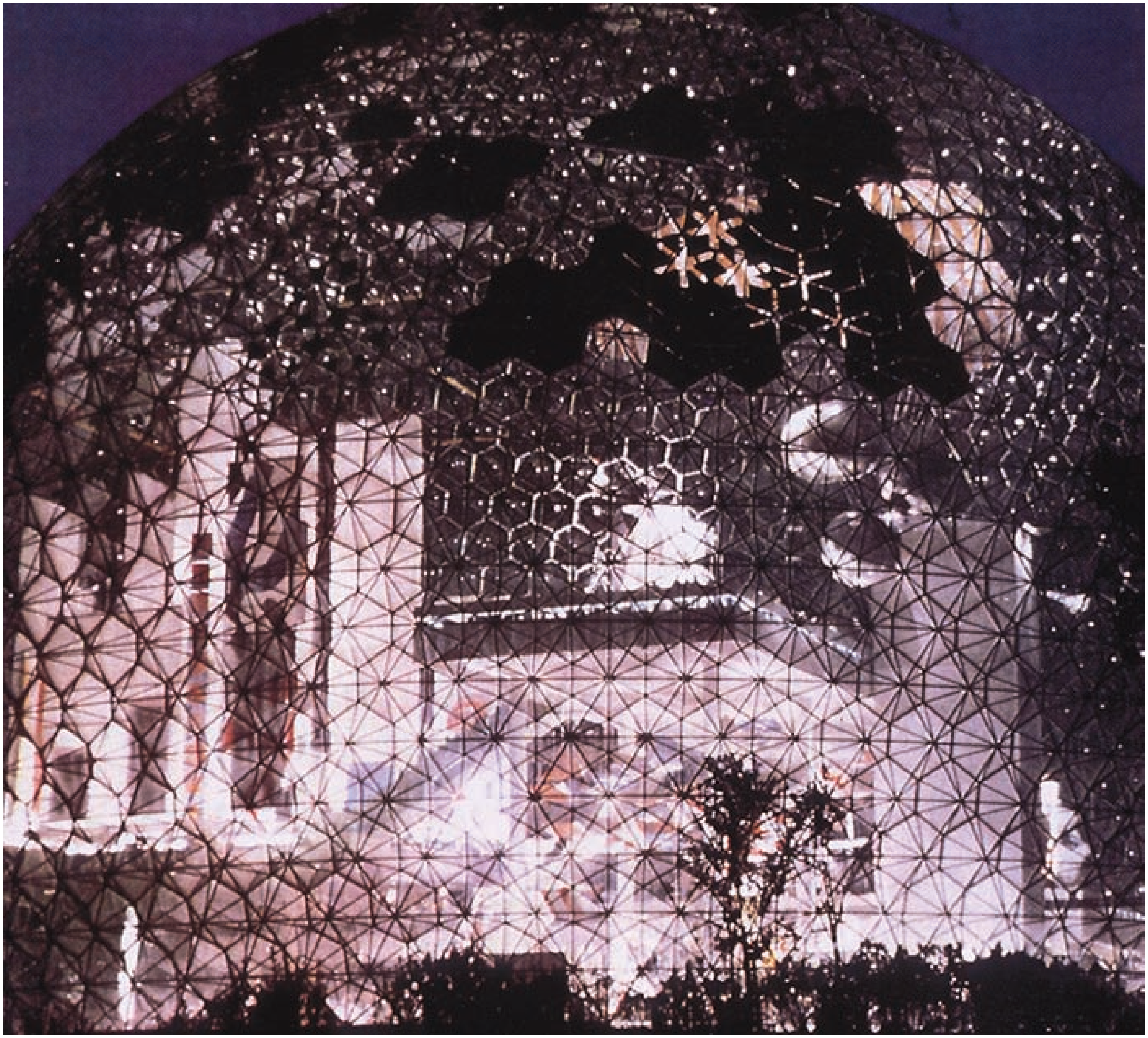


1: Buckminister Fuller, U.S. Pavilion, Montréal, 1967. Armour Landry, Ville de Montréal – Gestion de documents et archives.

The Skin of the "Sky Bubble" at Expo '67

Sarah Bonnemaison

At the end of his book *Travels in Hyperreality*, Umberto Eco visits the United States pavilion designed by Buckminster Fuller at the Montreal Exposition of 1967, and he meditates on a strange spherical building known as the "skybreak bubble" (Fig. 1).

> Inside, it was visually open, but the objects and interior structures were still enclosed in a dome of light. Mystical and technical, past and future, open and closed, this dome communicated the possibility of privacy without eliminating the rest of the world, and suggested, even achieved an image of power and expansion. [...] The dome was aesthetically the strongest element of the pavilion, and it was full of nuance, open to different interpretations (Eco 1990: 301).

While the space race between the Americans and the Soviets was a military competition for primacy in the skies (subject of a major exhibit in both pavilions), as a side effect it was fostering a new consciousness about the Earth and humanity's role on it. One aspect of the new consciousness resonated particularly well in the context of this Expo entitled *Man and His World*: the relationship between architecture and nature.

Why is the architecture of the dome interesting for this particular relationship to nature? Fuller's work drew from a nineteenth century view of nature that valued the regularity of platonic shapes because they seemed to express a natural order. But he also looked forward to a view of nature as a large interconnected system, which in turn has led to concepts we use today like 'ecology', 'sustainability' and 'embodied energy'. Fuller's ideas about world resources and his geodesic domes in particular, played a key role in the late 60s in the emerging ecological imagination and changing notions of the environment and many of these people, for better or for worse, are contributing to green buildings today.

The media were drawn to Fuller's photogenic building and his cryptic (if compelling) run-on sentences, and they disseminated his catchy phrases like "skybreak bubble" for the Expo dome. But in a more nuance vein, one can also explore how Fuller use of the 'laws' and 'principles' of nature in developing his architecture, and place it within a larger body of work, in both art and biology, of people who were excited about overlaps between the two. New techniques of seeing converged with new technologies of building and a close reading of the 'skin' of Fuller's bubble will allow us to explore the meaning of this tension between the science of looking at nature and the art of looking at science (Fig. 2).

When Eco described Fuller's dome as adding "something new", something "ambiguous" that was "open to different interpretations", he was in effect describing what he elsewhere called an *open work* of art. He used the idea of an open work to explain and justify the apparently radical difference in character between the avant-garde and traditional art

2 Buckminister Fuller, U.S. Pavilion, Montréal, 1967. Archives Nationales du Québec.

forms. Artists like Alexander Calder and Jackson Pollock held in common a decision to leave the arrangement of some of the constituents of their work to the public or to chance, thus giving not a single definitive order but a multiplicity of possible orders. The notion of open work as it was developed by Eco holds promise as a theoretical handle to understand the fluid relationship between natural sciences art and architecture in the late 1960s (Eco 1989). In other words, putting this architecture in a context of artists and scientists sharing a similar research agenda.

From the start, we can say that the deliberate and systematic ambiguity of the dome, as well as its ability to convey a high degree of meaning, makes the pavilion rich with metaphors. It can be read as a pop art bubble, the globe of the Earth, the Garden of Eden, a living organism or a breathing skin. Let us start our interpretation of the dome with the metaphor of the living, breathing skin as an exploration between art and architecture.

A Breathing Layer

What if the membrane that enveloped the dome was in fact a responsive breathing layer? Describing the acrylic skin of his "geodesic skybreak bubble," Fuller says,

> anyone looking at the geodesic dome in Montreal saw a very beautiful piece of mechanics. It did all kinds of things to your intuition. You saw there were curtains that could articulate by photosynthesis [light sensors] and so forth, could let light in and out. It is possible, as in our own human skin, all of our pores, all of the cells organize, so that some are photo-sensitive and some are sound-sensitive, and they're heat-sensitive, and it would be perfectly possible to create a geodesic of a very high frequency where each of these pores could be circular tangencies, of the same size. One could be a screen, other breathing air, others letting light in, and the whole thing could articulate just as sensitively as a human being's skin (Krauss and Lichtenstein 1999: 428).

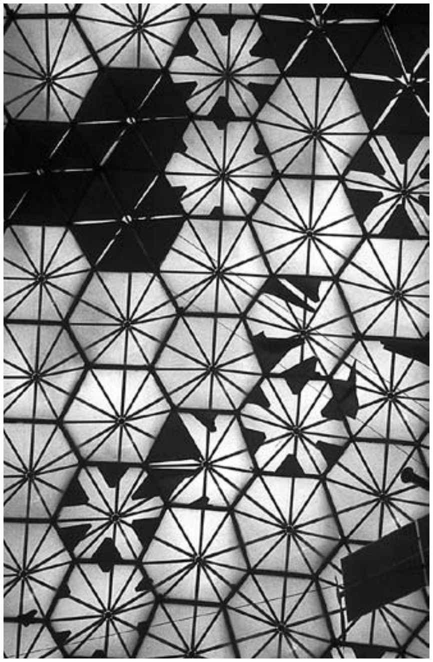
There is a dialectical movement between nature and technology in this sentence: sunlight is set in relation to artificial "curtains," and organic "pores" are set in relation to the mechanics of "photo-, sound-, and heat-sensitive" cells. Like the membrane of a cell, the skin of an organism, or the biosphere of the Earth, Fuller's thick and mesh-like matrix that enclosed the human activity inside was permeable to light and air; in the words of a German reviewer, "the sun, the moon, the landscape and the sky remain perfectly visible." And it is not static, but highly dynamic.

Fuller's first exploration with a spatial and climatic skin which regulated the exchange with the environment was in his *Garden of Eden* project (1955). This dome placed two revolving geodesics, each with glass on only one side, inside each other, so they could open to the outside (Krauss and Lichtenstein 1999: 421). But the dome in Montreal took the skin metaphor further: its openings designated for climate control are broken down into repetitive components like the pores of the skin. To maintain control over temperature with such a huge amount of glazing, Fuller designed small automated shutters in each cell that would modulate the sun's rays, selectively opening and closing as the sun moved across the sky (Fig. 3).

> A system of light sensors [...] raised and lowered shades in many of the clear panels in response to the amount and direction of the incoming sunlight. [...] 250 small electric motors connected to a central computer [...] would open or close the individual triangular panels in response to weather conditions (Sieden 1989: 86).

Since each shade opens or closes individually, the patterns they create are infinitely varied. It is an architecture operating in four dimensions, the skin of the dome moves as if it were alive. This animated architectural skin pushes to an extreme the idea of an open work. Like the kinetic mechanical sculptures of Jean Tinguely, or the delicately balanced steel mobiles of Calder, Fuller's dome leaves the arrangement of some of its constituents to chance or to the whims of nature, giving not a single definitive order but a multiplicity of possible orders. Movement is not implied, it is realized, making the work of architecture a "field of open possibilities" (Eco 1989: 86).

If we accept that we can experience the dome as an open work in movement, then we can say that at every performance the dome offers us a complete and satisfying version of the work, but at the same time makes it incomplete for us, because it cannot simultaneously give all the other solutions which the architecture may allow for. The ever-changing pattern created by the shutters is a display of intrinsic mobility, it suggests the infinite permutations we associate with ripples on water or the vibrating shadows of leaves under the trees. As we walk around the exhibits in the Expo dome, the movement of its shades opening and closing is combined with the movement of the visitor. Its skin moving in slow motion and the choreography of visitors through its space enter into a dance that describes a new relationship between utilization of architecture and contemplation.



3: Buckminister Fuller, automated shutters, U.S. Pavilion, Montréal, 1967. The Estate of Buckminister Fuller.

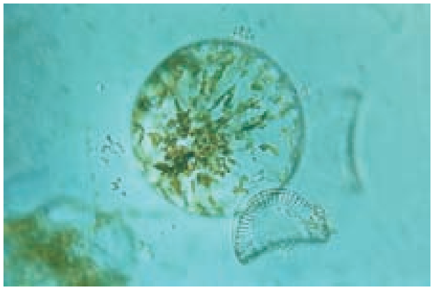
Natural Geometries

The press was fascinated with the fusion of architecture and nature. It is a "real, breathing if not living skin, composed of nearly 2,000 car-proportioned acrylic hexagons that throb and change color and keep the sun out or let it in", said the viewer of the *New York Times*. In The Nation, "the skin is equipped with vents that permits the bubble to 'breath' like an animal" (Galantay 1967: 562). The relationship nature and design was indeed a fascinating one. The university was another place where scientists and artists worked together to find order in the environment. The artist György Kepes for example, from his position as artist-in-residence at the Massachusetts Institute of Technology, edited a series of influential books under the rubric *Vision and Value* in the 1950s. They were in-depth explorations into the relationships natural sciences and the visual arts. He writes,

> Structures can be understood and qualities felt in a single, balanced perception of order, in an experience which has characteristics of scientific and artistic

> activity both. This balance is also possible on complex levels; one and the same set of created symbols can evoke an intense emotional response to the richness of its patterns and convey an idea of logical structure. (Kepes 1956: 22)

The key idea here is one of looking for patterns in images created by a joint effort between a scientific mode of inquiry and an artistic one. Research on patterns continued by Peter Stevens that resulted in his book *Patterns in Nature*, published in 1974.



4: Living cell. Institute of Lightweight Structures Archives.

The supporting structure of the dome can be seen as an expanded structural mesh. Siegfried Giedion would see in this mesh the idea of *Durchdringung*, a crucial component of modernity. The Eiffel tower was one such example where "instead of a massive tower, an open framework condescended into minimal dimensions." He says, "the landscape enters through continuously changing snippets" (Heynen 1999: 32). The mesh is based on regular repetitive geometries. For Fuller, the geometries used in the dome were directly related to the natural world, and his work was a divination which reveals the underlying order of nature. Like the chemist who believes there are exactly 92 elements to create everything on the planet because of the rules that direct the placement of electrons and protons, Fuller believed there exists a system that pre-exists nature itself, and that system is based on geometrical relationships. Oscar Wilde said "nature has been found to mirror art" (Ritterbush 1968: 40).

Form Reveals a Pattern of Integrity

The link between science and art at that time, lay not only in the fascination with patterns and order but with *form*. For example, historian of science Philip Ritterbush tells us that whatever was spherical was seen to be alive.

> Early morphologists saw the sphere as a first principle of life, and they searched for it not only where it was to be found (in animals like sea urchins, microscopic diatoms, and radiolaria), but in globular corpuscles such as cells, where its absence had to be explained. […] The sphere was the most ideal of the forms of transcendental morphology and according to that system of beliefs, its shape served to distinguish living nature from crystal growth. […] The attractiveness of the circle and sphere to the early *Naturphilosophen* probably reflected their rotational symmetry. In being rotated around their centers, they are carried unendingly into themselves (Ritterbush 1968: 27).

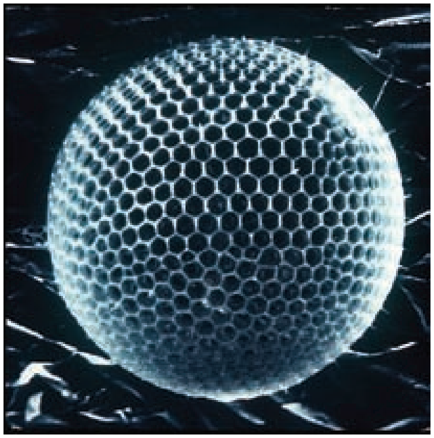
The closed geometry of the sphere gives a sense of being finite and a unity that was seen as a major attribute of natural forms (Fig. 4).

Today, our attraction to the irregular forms of blob architecture would reject radial symmetry as non-natural. But in the late 1960s radial symmetry seemed neither final nor limiting to the artists who populated the emerging landscape of the open work. Fuller is attracted to rotational symmetry because it allows for a strict and repetitive geometry of similar sections. In fact, Ritterbush argues,

> Symmetry is a property which figures in almost all serious efforts to explain esthetic responses and often is used as a synonym for harmony or proportion, but it is also susceptible to rigorous mathematical treatment and is in a strict sense a geometric concept (Ritterbush 1968: 46).

Both architect and engineers have been fascinated by the little creatures of the sea called radiolarians (Fig. 5). These demonstrate complex spherical regularities. *The Institute for Lightweight Structures* under the direction of Frei Otto, for example, devoted years to the study of diatoms, radiolaria and other microscopic creatures that demonstrate regular patterns in their shell structure. D'Arcy Thompson's description of radiolaria remains one of the clearest,

> In its typical form, the radiolarian body consists of a spherical mass of protoplasm, around which, and separated from it by some sort of porous 'capsule,' lies a frothy protoplasm, bubbled up into a multitude of alveoli or vacuoles, filled with a fluid which can scarcely differ much from sea-water (Thompson 1961: 155).
>
> The 'froth' is made of equal size cells and "the resulting polygonal meshwork [is] beautifully regular." In addition, the outermost layer of the body of certain types were seen to have a "built up of a mass of 'vesicles,' forming a sort of stiff froth" and other have a siliceous skeleton. In short, we are dealing with a stiff network of continuous linear elements which resemble a spherical basket or "the finest imaginable Chinese ivory ball (Thompson 1961: 156).

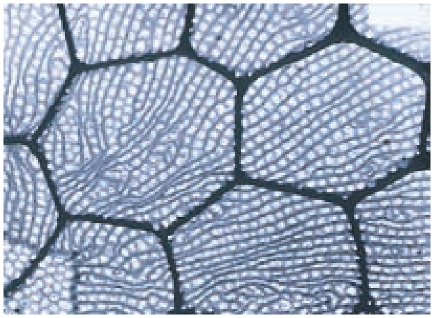


5: Radiolaria. Institute of Lightweight Structures Archives.

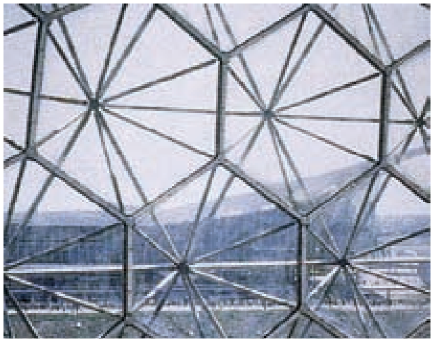
But most importantly to us here, Thompson says that "the whole arrangement will follow, or tend to follow, the rules of *areae minimae* – the partition-walls meeting at co-equal angles, three by three in an edge, and their edges meeting four by four in a corner." These basket-like structures can withstand enormous hydrostatic forces at the bottom of the sea with their three dimensional mesh for a skin. As structural demand increases, the radiolarian expands its mesh-work not as a stiffer crust on the outer surface, but by adding "successive levels, producing a system of concentric spheres." In other words, it increases its strength *not* by adding mass of silica in its walls and edges, but by creating a system of manifold surfaces and interfaces. The basket-like shell of the radiolarian is its breathing layer. It is made of a series of concentric layers creating an expanded mesh.

When we look at the cross section of Fuller's dome, we can also see a series of concentric layers. The outermost layer is made of triangular units assembled as a weave of interconnected diamonds. A second, inner layer made of hexagonal units forms a smaller sphere within the first. The two layers are joined by a filigree network of steel rods which form tetrahedrons, keeping an even distance between the two layers. The result, seen from outside or inside, is a faceted sphere. This sandwich arrangement is created by three different patterns of metal lace: triangular, hexagonal, and three dimensional tetrahedrons (Fig. 6,7).

"The sphere," Fuller liked to say, "encloses most space with least surface and is strongest against *internal* pressure; the tetrahedron encloses least space with most surface and is stiffest against *external* pressure" (Krauss and Lichtenstein 1999: 401). All three patterns maintain the rotational symmetry of the whole. In this rigid matrix, only the outlines and edges are solid and the rest is a void. As with the radiolaria, the structure of the geodesic dome gets stronger as more elements are used in triangulation. And in both instances, as the frequency of triangulation increases, each element can be more delicate. Here lies a fundamental principle in the search for lightness in construction: voids make a structure strong and light. In fact, as Robert Le Ricolais has shown, the void is a major structural principle.



6: Flow of hardening fluid. Institute of Lightweight Structures Archives.



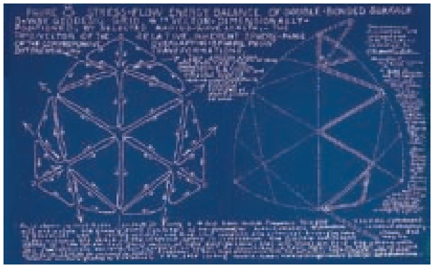
7: Buckminister Fuller, detail of the geodesic dome, U.S. Pavilion, Montréal, 1967. Rosengarten Collection.

Polarity

"In a fountain," says Joachim Krausse, "there is a moment of transition between the deceleration during the ascent and the acceleration of the descent. Fuller called this principle polarized. [...] The sphere is rounded in the equilibrium of the whole that results from many local forces" (McHale 1956: 401). For scientists, polarity is "an ordering relationship that involves a system of coordinates with directional information." So, we might ask, how do forces flow through the triangles which are the basis of the geometrical lattice? According to Fuller, "in networks, energy always tries to take the quickest most direct route across. [...] Energy automatically triangulates" (McHale 1956: 260-319). Since the idea is to bring the forces acting on the skin the most efficient way to the ground, these forces follow the lines of the steel struts, creating a regular pattern of energy vectors. But these energy vectors do not simply all flow downward as they would in the ribs of a Renaissance dome.

While Brunelleschi made the separation of tension and compression explicit in his design for the Duomo in Florence, with ribs acting in compression and iron chains encircling the dome working in tension, in Fuller's dome, the three dimensional skin works both in tension and in compression. Like a curved truss multiplied along a rotational symmetry, each small member making up the truss can work either in tension or in compression. Thus, we no longer see Fuller's reticulated structure simply as a matrix, but as a multitude of short vectors which direct the flow of forces along a web of steel struts. If we hold on to the image of these rivers of force flowing up and down the reticulated structure, we can see the skin of the dome as a sort of x-ray image. The image shows a skin with network of capillaries in which flows the tensile and compressive forces. If these forces are prevented to flow smoothly, if there is a tear in the fabric mesh, a sudden obstruction in the system made of hundreds of tetrahedrons, the building would collapse. In other words, the flow of forces represents the life force of the dome.

In his manuscript sketch entitled *Noah's Ark 2*, Fuller analyses the flow of stresses in a geodesic grid. He shows how they form a figure eight, balancing the forces in this "double-bonded surface," as he writes on the top of the drawing. Each triangle of the figure eight is decomposed into three arrows representing a vector of force. Together, the vectors transform the entire frame into a series of small rivers finding their way around the hexagonal pattern (Fig. 8). Seen as a whole, this game of polarities, of on and off, of plus and minus, feeds back onto itself. And because geodesics are spherical, "Fuller defines the system as a *closed* configuration of vectors – a patterning of forces that returns upon itself in all directions" (McHale 1956: 260-319). The figure eight, describing vectoral forces, ultimately envelops the sphere like a reticulated mesh. And like water shedding from a roof, the weight of the structure flows into the foundations and into the Earth.



8: Buckminister Fuller, drawing of the flow of stress energy in the structure. The Estate of Buckminister Fuller.

When the dome was completed, stress tests were performed in order to find out how the structure was behaving under wind loads. Using strain gauges, the weight at the foundations was calculated. It turned out to be less than the weight of the components used to build the entire structure. How was that possible? The enclosed space of the dome was so large, it had created an internal climate which resulted in a pressure differential from the outside. As a result, the dome was behaving like a hot air balloon, tending to lift the entire structure off its foundations. As Fuller imagines this process leading to its ultimate conclusion, as we see in his *Cloud Nines* project, the circle draws to a close as it rises into the air and the geodesic dome becomes a geodesic sphere. The dome of Expo 67, with the unity of form of a living organism, surrounded by the flowing forces through its reticulated structure, and clad with a 'living' skin was perhaps the clearest architectural expression of that relationship to nature and yet it remains open to interpretation.

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1: Buckminster Fuller, Moon rising over the U.S. Pavilion, Montréal, 1967. The Estate of Buckminster Fuller.

The Geodesic Dome as a Metaphor for Expanding Consciousness

Christine Macy

It is well-known that Buckminster Fuller's geodesic domes were a ubiquitous feature of the 'countercultural' society or, as it is often called, the 'hippie' culture of the 1960s in North America. Fuller's ideas, and his geodesic domes in particular, represented simultaneously a global, communal and personal ethos to many in the youth of that generation (Fig.1).

This paper is a reflection on why the geodesic dome was so popular in the counterculture era. The geodesic dome of course, was seen by many people in the 1960s as a representation of the planet Earth – not only by its inventor, Buckminster Fuller, but by many others in the era of the space program and the budding ecology movement. It was also interpreted as an egalitarian architecture, both person-centered and community-centered, and as an ecological way of building which enclosed the most space with the least materials. The geodesic dome is an intriguing object of study precisely because it was read in so many ways.

I will look at one particular view of the dome – the idea that it is an architectural form which represents expanding consciousness. The very earliest geodesic domes that Fuller realized were his *geoscopes* – computer-controlled and electronically lit models of the Earth on geodesic armatures that Fuller hoped would help people become more aware of their activities on the planet. He believed that these models of the planet would engender a heightened awareness of humanity's uses of the Earth's resources.

While Fuller was perfecting his geoscopes, the Jesuit theologian Pierre Teilhard de Chardin was gaining world-wide recognition for his idea that humanity had an instrumental role to play in the evolution of the planet. Teilhard envisioned the Earth enveloped by a conscious web of human thought, and he theorized that this structure, which he called the *noosphere*, could direct the evolution of the planet. In the intersection of these two historically simultaneous arguments – one which aims to visualize and orchestrate the use of the Earth's resources, and the other which argues for a conscious planetary evolution – I see the beginning of the counter-culture's transformation of the geodesic dome into an icon of "expanding consciousness."

2: Buckminster Fuller, 'World Town Plan', 1927. The Estate of Buckminster Fuller.

Spheres of Consciousness

In his *The Metamorphoses of the Circle*, Georges Poulet traces the long history between radial geometries and ideas of consciousness in Western culture (Poulet 1966). Representing God in the Middle Ages and a human-centered universe in the Renaissance, by the end of the eighteenth century the sphere is understood to have a dual orientation: outward to the world and inward to the self. By the twentieth century, the circle in Western culture is a symbol of self in relation to the surrounding world.

This insight will become central to how the domes of Buckminster Fuller are interpreted by the counterculture of the 1960s: in a *personal* way (in which the spherical shape expresses the "mind-expanding" self) and in a *cosmopolitan* way, in which the undivided and encircling sphere expresses community, gathering, and sharing.

Both of these qualities of the spherical dome work not only at the scale of the *oikos*, or household, but at the scale of the Earth itself, as the household of humanity. It is the implications of sphericality at the scale of the Earth that fascinated Teilhard. "One of the most fundamental characteristics of the cosmic structure," says Teilhard, "is the roundness of the Earth (Teilhard 1959: 239). Without the involution of matter upon itself... there would never have been the biosphere. [...] In [its] advent and development, life...[is] not only accidentally, but structurally, bound up with the contours and destiny of the terrestrial mass" (Teilhard 1959: 273). The spherical shape of the Earth itself forms the basis of Teilhard's view that life – spread out in a centripetal extension over the surface of the globe – reaches a "critical point" with the appearance of humanity.

> With the spread of people around the globe, life begins a centrifugal movement, seeing itself "in the mirror" for the first time.
>
> Man discovers that he is nothing else than evolution become conscious of itself. [...] Having reached the peak, we can now turn round and, looking downwards, take in the pattern of the whole. And what is more serious still is that we have become aware that, in the great game that is being played, we are the players as well as being the cards and the stakes(Teilhard 1959: 231, 230).
>
> If there is a future for mankind, it can only be imagined in terms of a harmonious conciliation of what is free with what is planned and totalized. Points involved are: the distribution of the resources of the globe; the control of the trek towards unpopulated areas; the optimum use of the powers set free by mechanization; the physiology of nations and races; geo-economy, geo-politics, geo-demography; the organization of research developing into a reasoned organization of the Earth. [...] We need and are irresistibly being led to create [...] a science of human energetics (Teilhard 1959: 283).

We are struck here by the similarity of Teilhard's ideas and Buckminster Fuller's (Fig. 2). While Fuller never wrote expressly about Teilhard's ideas, we cannot help but notice the parallel between Teilhard's call for a "science of human energetics" and Fuller's life-long project for the same thing. Exploring briefly Fuller's geoscope, we can see it as an instrument to visualize and thus to plan precisely those "points" that Teilhard sees as essential to the "future for mankind."

On a sphere constructed with geodesic geometry, Fuller wanted to create a dynamic map of the Earth, one that would perfectly mirror the real-time flows of people and materials around its surface. All knowledge about human uses of the Earth's resources would be visible at a glance – in Fuller's words, "all the inventory of human trends, known needs and fundamental characteristics" (Fuller 1969: 111).[1] The geoscope would present this data with an ever-changing pattern of lights, coordinated by a bank of computers into which he has fed his Inventory (Fig. 3).

If we look at Fuller's animated model of a globe through the lens of Teilhard's thought, the circle thickens. The lacy web of Fuller's animated geoscope gives a visual form to Teilhard's *noosphere*. These images show the electronic array of world resources as they move on the unfolded pattern of his geoscope. According to Teilhard, "the banal fact of the Earths' roundness" was bound to cause an intensification of human thought and 'psychosocial activity' – "confined to spreading out over the surface of a sphere, idea will encounter idea, and the result will be an organized web of thought" that envelopes the Earth. If we were to see the Earth from outside for the first time, says Teilhard, "the first characterization of our planet would be, not the blue of the sky or the green of the forests, but the phosphorescence of thought" (Teilhard, 183). If the hydrosphere, biosphere, and atmosphere are consecutive layers of the Earth that in themselves are the result of the "vitalization of matter" that we call evolution, the noosphere, from the Greek work *nous* or thought, is "yet another membrane in the majestic assembly of telluric layers." (Teilhard 1959: 182). Beginning with advances in the technology of transportation, and extended vastly through the machinery of European colonization, human thought now encounters itself in all directions. And with the development of radio, television, satellite communications and modern transport, "each individual finds himself [...] simultaneously present, over land and sea, in every corner of the Earth" (Teilhard 1959: 239).

3: Buckminster Fuller , Geoscope, Cornell University, 1952. The Estate of Buckminster Fuller.

For Teilhard, this is not about the dominion of capitalism, or the hegemony of Western instrumentalism. It is a spiritual manifestation of the Earth's evolution. With the spread of humanity over the surface of the Earth, he says "we have the beginning of a new age. The Earth 'gets a new skin.' Better still, it finds its soul" (Teilhard 1959: 183). Fuller echoes Teilhard when he writes:

> You and I
> Are essential functions
> of Universe
> We are exquisite syntropy (Sieden 1989: 418).

Recalling the tongues of fire that lit on the heads of the first evangelicals, Teilhard says "a glow ripples outward from the first spark of conscious reflection. The point of ignition grows larger. The fire spreads in ever widening circles till finally the whole planet is covered with incandescence" (Teilhard 1959: 182). While Teilhard never gives a visual representation of the noosphere, Fuller does. Speaking in 1962 of his geoscope project, Fuller suggests that,

> Its interior and exterior surfaces could be [...] dotted with ten million small variable intensity light bulbs and the lights controllably connected up with an electronic computer [...] At 200 feet minimum distance away from the viewer, the light bulbs' sizes and distance apart would become indistinguishable, as do the size and distances between the points in a fine half tone print. Patterns

> introduced into the bulb matrix at various light intensities, through the computer, would create an omni-directional, spherical picture analogous to that of a premium television tube – but a television tube whose picture could be seen all over its surface both from the inside and the outside (Wigley 1997: 17).

Fuller developed this visualization into the World Game. Medard Gabel, the co-ordinator of Fuller's World Game project, says what he sees while playing the Game, "once we started displaying the electrical energy grid and the transportation channels, it became apparent that the world looks like a biological organism"(Aigner 1970: 66). An illuminated icon, it does, as Fuller suggested, possess the mesmerizing qualities of a television set, but the image is compelling because it is about ourselves. Fuller's Geoscope gives a visual form to human self-awareness of life on Earth. It is an elaborate, constantly evolving mirror of our uses and abuses of the planet, our ecological conscience projected on the surface of a sphere. The metaphysical dimension of the geodesic dome has to do not only with the fact that it is spherical, but with the consciousness of the Earth represented in the Geoscope idea (Fig. 4).

4: Buckminster Fuller, 'Energy Slaves' modeled in World Game Seminar, 1972. The Estate of Buckminster Fuller.

Self-sufficiency

Teilhard's writings recast Fuller's technological utopia in spiritual terms. In the remythologizing of western society that occurs in the 1960s, the idea that people are personally responsible for the health of the Earth spurs new initiatives for realizing on a local scale Fuller's "whole world thinking"(Vattimo 1992: 32). We turn next to the Fuller acolytes that want to spread the message of "treading lightly on the Earth" – the many hundreds of thousands of hippies, communal activists, disaffected youth, back-to-the-landers, and emerging ecologists that contribute to what Theodore Roszak has called "the making of the counterculture"(Roszak 1969).

The Domes Multiply

As Fuller's ideas were taken up by the counter-cultural communes, domes sprouted across the North American landscape. The dome seemed to represent a different way to live, one that could be practiced both on the ground, and also symbolically in a new kind of architecture. Their spherical shape reinforced the idea that each person is the center of their own reality. Like a circle, the dome has only one center, and one cannot escape its pull. The "me" generation embraced this insight and its architectural expression. In the words of dome-builder John Premis, "A dome encloses you like an eggshell or a pair of cupped hands – gently, tenderly. In a dome there is an inward focus. You feel that you are at the center of things. There is no way you can be shoved into a corner!" (Premis 1973). Two contributors to *Domebook One,* Alan and Heath, describe how they feel in their 'dome home',

> Living in a spherical single unit house makes us wholer people. We feel more whole and have our whole trip around us. We stay more in touch with each other

> and our friends and also this wholeness has a healthy effect on our possessions, our wants and desires. Feeling whole and centered is crucially important, and domes can surely contribute to this. [...] Even our conversations are more centered because we sit in a circle and stay in closer touch with each other. All vibrations – sound, light, heat and all our awareness – begin in the center and radiate outward and rebound back and forth from the center. Consequently, chanting is mind-expanding and all-encompassing (Kahn et al. 1970).

The spherical dome, then, seems to be an architectural expression of the New Age axiom asserted by Stewart Brand in his *Whole Earth Catalog* of 1968, "We are as Gods," and unintentionally lampooned by the actress Shirley MacLaine when she stated, "I am God. I am God. I am God" (Heelas 1996: 1). This is a shift in countercultural priorities, from more collectively-oriented political and environmental actions (like the communes) to a new sense of personal power and responsibility. At one level, this can be seen as a retreat from the progressive thinking of the 1930s that counterculturalists admired, when social change was understood to be the result of mass political action in the public sphere. Yet at another level, it can be understood as a change in tactics. The goal is still universal (that is, global change), but the departure point is the self (Fig. 5).

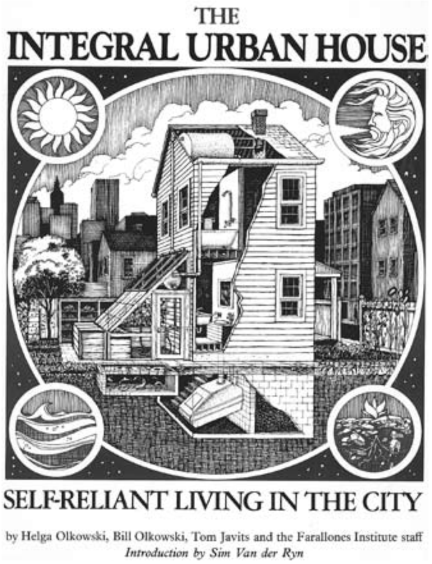
5: Dome with butterfly, 1970s. Photograph Jack Fulton.

In his book *The Spirit of the Sixties*, James Farrell has astutely described this perspective as a form of 'personalism'. Finding common roots between the anti-nuclear activism of the Catholic Workers, the civil rights movement, the anti-establishment activism of the Students for a Democratic Society, and the 'communitarian subjectivism' of the counterculture, he argues that all of the major political movements of 1960s America shared a belief that political action emerged from a personal commitment and individual action (Farrell 1997). In his introduction in the first issue of the *Whole Earth Catalog,* Stewart Brand is quite explicit in that regard,

> A realm of intimate, personal power is developing – the power of individuals to conduct their own education, find their own inspiration, shape their own environment, and share the adventure with whoever is interested. Tools that aid this process are sought and promoted by the *Whole Earth Catalog* (Rheingold 1994).

It must be said here that Teilhard's understanding of the noosphere is also at its core based on a *personal* action, as he sees it as a manifestation of Christ.

While Fuller relied on 'systems' thinking, his ideas are taken up most fully within this framework of 'personal' activism. The principles that underlie his World Game and his pragmatic, do-it-yourself approach helped to engender a whole generation of ecological architecture, work that has not yet begun to be criticized or analyzed within the architectural mainstream. From this perspective, Fuller's ideas did not reach an endpoint in the thousands of dome homes built in the communes – rather, we argue, the ecological metaphors of the geodesic dome were taken up in a much more fundamental and long-lasting way in the concept of the closed ecological system. And indeed, we see that Fuller's concerns with the energy flows in a closed system, his interest in using technology to optimize these flows, and his idea that waste is a resource, have all affected the alternative architecture from the late 1960s to today.



6: Gordon Ashby and Bill Wells, Front cover, Integral Urban House, 1979. Reprinted with permission by Sierra Club Books.

The Integral Urban House

In Berkeley in 1978, a new kind of urban dwelling was created on the flatlands of the eastern edge of the San Francisco Bay. Dubbed the 'integral urban house' by its creators, Mike and Helga Olkowski and the Farallones Institute, this house presented itself as a self-contained 'life support system' that was meant to serve as a model for ecological living in an urban environment. The ideas embodied in this project are similar to the many other "self-sufficient" settlements that were promoted and realized throughout the 1970s – from the New Alchemy Institute founded by John and Nancy Jack Todd in Woods Hole, Massachusetts, to the "sustainable" planning documented by Gary Coates in his book *Resettling America* (1981) (Fig. 6).[2]

Premising their argument on a disaster scenario, the Olkowskis ask us "what would you do" in your present way of life in the face of a transit strike, a gas shortage (like the 'oil scare' of 1973), or a drought (experienced by most Northern Californians in 1977)? As your neighbors drop off like flies from chemical poisoning and cancer, they say, it is only to be expected that "people need to believe in their own ability to create and maintain their basic life-support systems in order to feel at least somewhat in control" (Olkowski et al., 1979). While the impulse may be survivalist, the response looks different from the underground shelters advocated by cold war survivalists in the California hills. The Integral Urban House offers a model self-contained 'ecosystem' that can be realized in virtually any urban or suburban setting in the country. It aims to transform "denatured houses into finely tuned, multichanneled, closed-looped, organic instruments for processing nature's flow" (Olkowski et al. 1979: 35). The Olkowskis remind us that there is a moral imperative in this mission. They are not advocating self-sufficiency – that would be too isolating. Rather, they are encouraging self-reliance, that part of the national myth, they say, that is known as 'Yankee ingenuity' (Olkowski et al. 1979: 4).

The Integral Urban House does not mimic the forms of nature, as would a dome or spiral house, but it takes the idea of interconnectedness into the scale of the house. It looks to apply "lessons from the biology of natural systems" to design human habitats (Olkowski et al. 1979: 16). The goal is human evolution and this is to be carried out on a personal level, not at the level of global planning. "Nature's strategy to achieve stability," they say, is the "closed integral loop." Here, the house starts to get interesting. These loops allows for recycling and self-regulation, in positive and negative feedback systems. "The wastes of one system," they continue, "are the necessary inputs of the other." "Webs" are the connections that comprise living systems, "energy and nutrients flow along these pathways" (Olkowski et al. 1979: 20).

The diagrams accompanying the book show these loops: the house acted on by the elements, circulating its nutrient and waste flows in a dynamic cross-section that shows the plumbing and heating systems, the plants extracting nutrients from the soil and turned towards the sun to photosynthesize, the bees hovering over their hive, the fish processing grey water, the sun heating up solar tanks. A second diagram shows the *Life Support System of an Integral Urban House*, with all the components of a small farm installed on a 50' by 100' inner city lot. We see insects, fish, small game, vegetable, rooftop and greenhouse gardens; the composting of human and animal wastes and wastewater; a capture of solar radiation in collectors, thermal storage and solar ovens. Everything is linked into systems of 'flows', 'webs', and 'loops' (Fig. 7).

Embedded in the "ecosystem," the sheltered human is surrounded by a plethora of "energy transformers." This is not an idealized or abstract hymn to technology like we find in the works of architectural design groups like Archigram, it is rather a highly elaborated and precisely worked out technological recreation of biological processes, with every input and output identified and calibrated, as it would be on a spaceship. According to Timothy Miller, communes saw themselves either like a "lighthouse," serving as a beacon to the masses, or like an "ark" – a self-sufficient enclosed society, riding out the impending deluge. The creators of the Integral Urban House saw it as both lighthouse and ark, setting an example for others to follow, and creating a virtually autonomous ecosystem.

7: Lisa Haderlie Baker, Life Support System of an Integral Urban House, 1979. Reprinted with permission by Sierra Club Books.

Arks

The idea of the ark as a biologically self-sufficient system takes root in the American consciousness. The whole Earth itself is like a spaceship, Fuller tells us. The economist Barbara Ward picks up this image in her *Spaceship Earth* of 1966. "Globalization," she says, "has led to the planet Earth acquiring the intimacy and vulnerability of a spaceship" (Ward 1966: 5). The image of intimacy and vulnerability evokes the widely-published photographs of the fetus *in utero* by Lennart Niilson. Like the astronaut in space, the fetus floats in a liquid void. This endoscopic image is always framed by a circle. In the words of Alvin Toffler,

> The [space] craft [is] a wholly self-sufficient universe, in which algae is grown for food, water is recovered from body waste, air is recycled to purge it of the ammonia entering the atmosphere from urine, etc. In this totally enclosed fully regenerative world, the human being becomes an integral part of an on-going micro-ecological process whirling through the vastness of space (Toffler 1970: 212).

The image is simultaneously technological and biological. It is a synthetic nature, an artificial environment. For Dorion Sagan, the Aquarian child of biologist Lynn Margulis and astronomer Carl Sagan, the space colony, that "encapsulation of Earth life in the technological extrastructure of a biosphere represents an Earth 'seed' – part of a pod-forming or blossoming process." "Biospheres," he continues, are the "miniaturized offspring" of the Earth.

> If the Earth is looked at as a flower, then the formation of ecospheres, biospheres and other self-sustaining communities represents the putting to seed of this flower. [...] New Alchemy and Ocean Ark designs [...] Biosphere 2 represent the first buds and blossoms of a cosmic springtime in which the Earth itself will bloom into the space between the stars, copying itself over in miniature (Sagan 1999: 158-9).

8: Human embryo, 1965. Photograph Lennart Nilsson.

Ship metaphors re-appear in closed ecological systems throughout the 1960s: from the New Alchemy Institute's *Ark* on Prince Edward Island (1977) and their *Ocean Arks International*, to Paolo Soleri's urban *Arcologies*, and the Farrallones Institute's *Integral Urban House*. The most complete version is *Biosphere Two*, built in Arizona in 1990 with the intention of replicating the processes of the first biosphere, the Earth. Both low-tech and high-tech versions aim to be self-sufficient settlements, to produce their nutrients, and process their wastes. They are 'complete' systems, their complex diagrams of feedback loops and closing circles proving that, theoretically at least, they can replicate the 'essential' life-supporting features of the planet Earth. They are, in this sense, perfect representatives of Fuller's technological optimism and visionary ambitions.

They are also colonial models: the self-sufficient houses aim to fix the 'sick' metropolis, and *Biosphere Two* is meant to colonize outer space, the desert, the polar ice caps, or the bottom of the sea. Yet the designer at the center of these 'self-sufficient systems' is far from realizing Fuller's dream of an automatic aesthetic response to the flows of energy and goods. While Fuller hoped that his geoscope would allow one to grasp the totality of the planet at one glance, like a general in a war simulation room, the earnest alchemists of alternative architecture in the 1960s spend an inordinate amount of time on plumbing diagrams which connect one part of the 'system' to another, calculating BTUs, detailing instructions for the fertilization and slaughter of small creatures, and meticulously dissecting the cycles of putrefaction. Aesthetics is nowhere to be seen. Rather, we see the earnest morality of the reformer, a religious sensibility directed outward, in practice. If the new age consciousness focuses on the upper *chakras*, this desire for self-mortification corresponds to the lower.

The satisfaction is ethical, moral. As the Olkowskis have explained in an earlier chapter, the point is not merely to collect energy-saving tips or grow a backyard garden to help save on food prices. This is, after all, Berkeley, and all the participants are college-educated scientists. These goals alone would not make an integral urban house. What drives the idea behind this house is a *bioethic*, "a system of moral concepts that deal with the relationship of humans to all other living organisms and with the conditions that sustain life and ultimately make continued human survival possible" (Olkowski et al.1979: 45). The last "thrival commandment" states, "Respect for self and nature have a common root."

Notes

[1] The information depicted comes from Fuller's *World Resources Inventory*, housed at his Southern Illinois University headquarters. Described by Fuller as "an accounting system to examine human evolution," this inventory has taken Fuller forty years to bring to a state of "high perfection" (Sieden 1989, 429).

[2] The New Alchemists also constructed a self-sufficient *Ark*, on Prince Edward Island, in Canada, in 1976. This flagship project shared many of the features of the Integral Urban House, but was designed for a rural setting. It received wide coverage in Canada and was opened by the Prime Minister Pierre Elliot Trudeau.

9: Spacewalk, Gemini 4, 1965. Photograph NASA.

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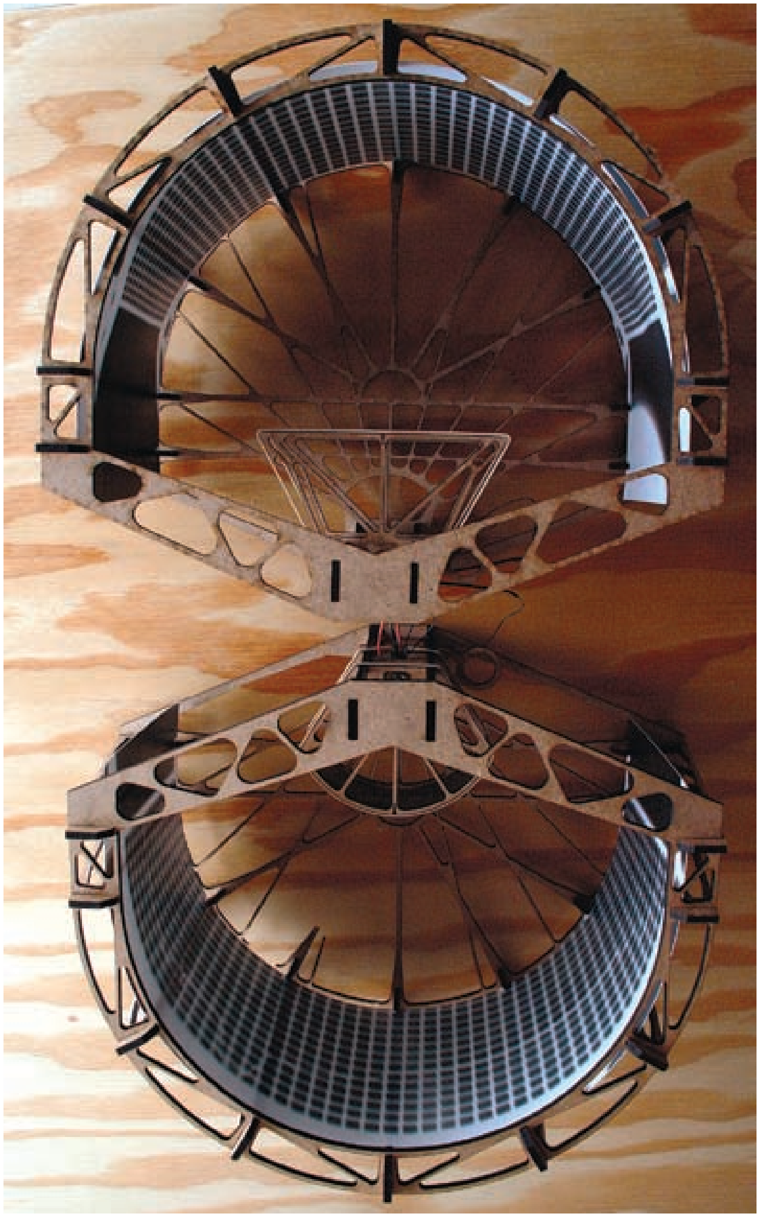
READING THE ORGANIC



1: Two dioramascopes created photograms projected onto the diorama shell by a small bulb behind each picture plane. Top unit has a flat picture plane (Jacques' method), bottom unit a curved picture plane (Wilson's method).

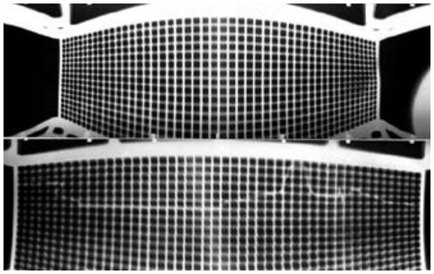
Drawing Indeterminate Architecture and the Distorted Net

Nat Chard

This paper relates to a broader interest in how architecture acquires meaning through the act of interpretation as much as it does through the act of authorship. In making such a proposition, one is immediately faced with the question of whether it is even possible to draw architecture in a way that is open to interpretation. After all, architectural drawings employ representational conventions precisely with the aim of ensuring that everyone interprets them in the same way. They are designed to prevent people from contributing new, unintended meanings.

This paper proposes something very different – a shift in the way we might engage with a drawing, a move away from questions of interpretation and towards a spatial relationship between a drawing and an observer, where the observer becomes implicated by their position in relation to the work. Two methods of representation have commonly been used to this end: *anamorphism*, which is strictly pictorial, and a *folding of the picture plane*, which is a stereotomic strategy. The opportunities offered by these methods can be seen in a close study of their use in habitat dioramas of the kind found in natural history museums. In particular, I am interested here in the dioramas of James Perry Wilson, a renowned diorama artist, whose work forms a large part of the collection of dioramas held by the Peabody Museum of Natural History, at Yale University in Connecticut.

To understand how Wilson distorts an image to register a normal view on a folded picture plane, we will employ here the device of a *net*. Not only does a net offer a way to abstractly visualize the geometric adjustments made to such images, it also serves as a practical method to create a convincing diorama background. Finally, the paper presents a camera built by the author to capture, in one photograph, the full range of transformations that Wilson made to his picture planes. This is intended as a way to understand his method.



2: Two photograms of grids from dioramascopes: (top) projected through a flat picture plane, and (bottom) through a circular, or Hauck, picture plane. The lower photogram corresponds to the Mule Deer diorama at the American Museum of Natural History, and the line in the image is the horizon in the diorama. The grid corresponds to the one used by Wilson to transfer his painting to the diorama shell.

Interpreting Architectural Drawings

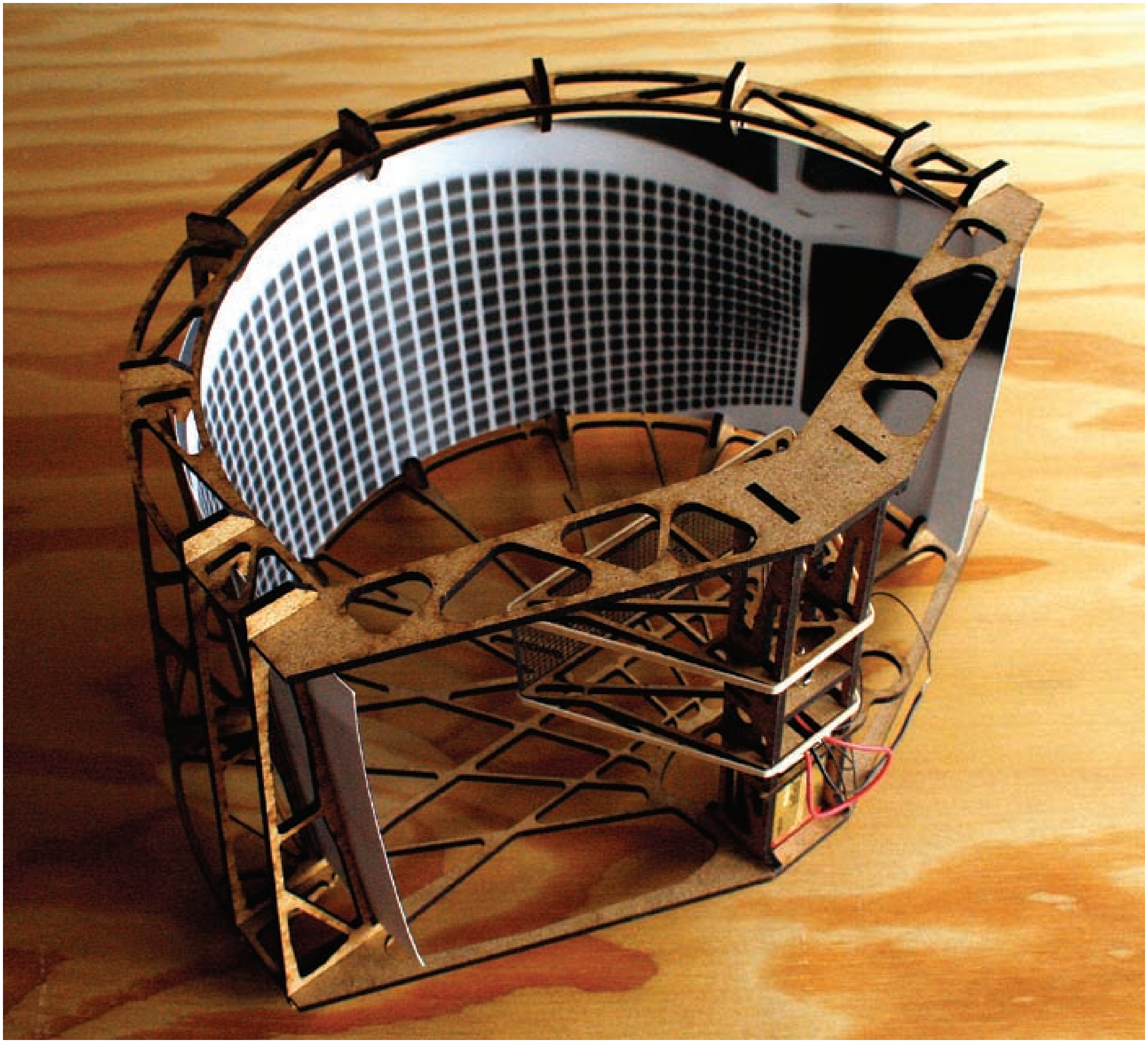
Architectural drawings today have reached a level of sophistication where we expect their meaning to be clear to everyone who reads them: contractors, building inspectors, cost estimators and the like. As construction documents, they must be incontrovertibly prescriptive and precise, so an architect's intentions are directly translated into a builder's actions. To guarantee this, architectural drawings require specific modes of interpretation.

Interpretation is one way for an observer to 'enter' a painting or drawing, provided the artist allows such participation in the work. We are all familiar with this practice to some degree – for example, if we know much about the context of a certain genre of painting (say a 17th century Dutch still life), we might be able to read it like a text as much as we do like a picture, and perhaps even before we see it! How might we draw such a condition?

This question is complicated by the relationship between content and technique in architecture. The high cost of building necessitates some sort of relationship between the way we build and our ambition for the architecture, a necessity that has been turned into a virtue. Because architectural drawings are a side-effect of the discipline's practice of making construction drawings, the particularity of a construction method to a school of thought can be revealed in seemingly neutral projections. If we look at a plan of a gothic cathedral next to one of a classical temple, we can not only tell that one building is different from the other, but also a great deal about the unseen parts of both, at least to an extent that is unlikely to surprise us when the elevations or sections are revealed. It is a little like shorthand writing, where we can assume more than is immediately apparent. The drawing requires us to interpret it and our familiarity with this practice limits our potential relationship to the drawing.

If one of the limits of architectural drawings is that we are so familiar with them, that we read rather than experience them, then one possible route to opening up to new meanings is through the way we engage them. There are several implications to this line of thought. One is the separation of idea and technique, yet this too, might in time just become a familiar code for a certain sort of architecture. Another is the attempt to erase meaning in architecture. There are also problems with this as well. For instance, in self-consciously minimalist projects, it is often actions such the attempt to open handle-less cupboard doors that lead to traces (one of the mechanisms that establish meaning over time through occupation) that are reflexive in that they reinforce the conscious absence of the handle rather than the contribution of the person that tried to open the door. Another is that if erasure is too successful, the architecture loses its capacity to provoke. For example, a book that teases our imagination might involve us more than one with empty pages – the latter demanding so much of us (that we write the whole story) that we choose not to engage at all.

Indeed, if we think of the territories that engage our imagination the most (and through that, implicate us in their meaning) they are often those that provide a considerable provocation but without closure. An example of this is our relationship to the archeological site – no matter how rich in artifacts, it is always fragmented and strewn about so we are stretched in our attempts to find some sort of closure and to speculate on what was there. If we look at examples of the uncanny, we often find a similar situation without closure, in that each attempt to resolve our unease is defied by another possibility. Such a dilemma may elongate our engagement. This refusal of closure is a central feature in achieving a condition of indeterminacy and a prolonged engagement with the matter at hand.



3: View of dioramascope for flat picture plane showing relationship between projection net and the projected photogram on the diorama shell. The projection bulb is located at the ideal viewing position for the diorama.

Returning to architectural drawing, we face the question of how the drawing can open up our engagement with its content to the extent that we take part in producing its meaning. In other words, how the drawing might lead to an indeterminate architecture. One way of shifting our engagement with the drawing, so we are more independent of the conventions of interpretation, is to establish a spatial relationship with it. This also opens up the possibility of the drawing becoming architectural.

4: Original Kodachrome survey slide, with superimposed net scratched on plastic sheet. Courtesy of Michael Anderson.

Normally, when we look at a picture, our position in space only matters to the extent that we are close enough to see the image well, and far enough away to see it all. Because we understand the convention of the 'frame' and we have learned to compensate for parallax, we can understand the image in the same way whether we are near or far from it, to one side or the other, or directly in front. There are two critical exceptions to this. One is in the case of an anamorphic image, which requires one to be in a specific location to resolve the image, which is meaningless from any other point of view. The other is a folded picture plane or pictorial surface, where the foreshortening of different surfaces conspires to dissolve our ability to compensate for parallax. To experience such drawings, or works of art that combine the two strategies, such as 17th century Dutch 'peep shows', we have to move around them to engage them for a longer period of time.

There is yet another exception, where the picture plane is developed as a strong presence in its own right, establishing a visceral relationship between the person who created the painting and the one who encounters it. This is the case with works such as Robert Rauschenberg's blueprint photograms of Susan Weil, or Yves Klein's *Traces of the Blue Period* (*Anthropométrie de l'Époque Bleue*, 1960), or in situations where something is drawn at a very large scale and the draftsperson becomes a direct measure of the thing that is drawn. But this is a whole other discussion into which I will not enter here. The limitation of pictorial anamorphism is that the moment one resolves the image, one also interprets it. Closure comes quickly, and on its heels, the end of our engagement. Even if the work sustains our interest, the collapse of the image as soon as we move away from it makes a relationship between the normal and anamorphic realms difficult to sustain.

The Cultural Politics of Indeterminacy

Up to this point, we have centered our discussion on media. This may be appropriate for a paper about 'drawing indeterminate architecture', but why is drawing so important to an indeterminate condition? To some extent, the desire to create a condition of indeterminacy is a political act, meant to empower the person who interprets (or inhabits), over the author, artist or architect of the work. While this could be seen as a refusal, I would rather discuss it in more optimistic terms – that indeterminacy could be a goal in its own right, an attempt to establish a certain condition of being. As such, its politics are cultural politics, that shift the responsibility for meaning from the author to the interpreter or inhabitant. The condition that provokes the inhabitant to become engaged makes them active in many ways, one of them politically (in as much as all acts of authorship are

5: Bog camera photograph of Wilson's Cold Bog diorama at the Yale Peabody Museum of Natural History. It shows the diorama background painting as if peeled open and laid flat. Compare with normal photograph of the diorama below.

6: Normal photograph of the Cold Bog diorama. The picture is taken from further back than the ideal viewing position, so the horizon is slightly flattened.

political). Therefore in an indeterminate architecture the inhabitant would be implicated politically as well as creatively. The mechanism for this state to take place is through engagement.

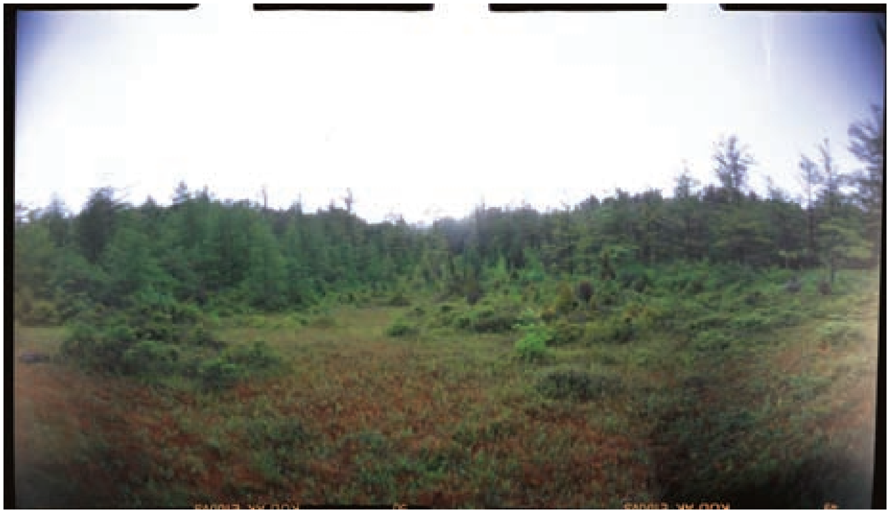
The obvious paradox in trying to make an indeterminate architecture is that architecture demands a certain amount of prediction. We design buildings imagining the activities that will take place there. This goes as much for the romantic folly as the factory. In making an indeterminate architecture, we are not asking whether or not it will be inhabited, but rather *how* someone might live there. Indeterminacy in literature and film has been achieved not by finding a special form, but by establishing a special engagement with the reader or the audience. This points a way to developing an indeterminate architecture, and the important question is how one might establish a medium to study engagement. My speculation is that this lies somewhere between the drawing and the model, or between two- and three-dimensional modes of representation.

Anamorphic Images and Folded Picture Planes

It is hard to separate the folded picture plane from the anamorphic image. The picture plane is an imaginary surface that comes between the observer and the content being observed. In a painting, this might be the pictorial surface, like a window behind which lies the content of the image. But for the artist, there is another possible picture plane – like the frame Fillipo Brunelleschi set up to visualize his proposal for the Piazza del Duomo in Florence, or the gridded net Albrecht Dürer placed between himself and his nude female model in 1525, as he transcribed the exact image he saw through the net onto an identically proportioned gridded canvas.

The problem with the flat picture plane is that despite its geometric precision, the images that derive from it look strange. The standard proof of the need to adjust the picture plane is the frontal view of three circular columns (Panofsky 1991: 79). If the view is centered on the middle column and drawn with a flat picture plane parallel to the columns, the outer columns measure wider in the perspective than the middle one, even though they are further away. Only by curving the picture plane towards the viewpoint either side of centre, can the outer columns be made to measure the same or less than the middle one. There is no problem with a flat picture plane if your (monocular) eye is positioned exactly where the artist's was, since the perspective of the drawing will compensate for the geometric distortion. It is only in other positions that marginal distortions will occur.

Since at least the late middle ages, (notably in the work of Nicholas Fouquet), artists have experimented with deformations of the picture plane to make a truer image. If, by bending the picture plane an image can be made *truer* to the eye's experience, could not such bending also bring its 'truth' into question? Either the 'net' through which the artist sees, or the 'net' over the drawing must be distorted, but not both, or at least not to the same degree. Consequently, there will be some anamorphic distortion of the image in



7: Bog camera photograph of the original Cold Bog site, June 17, 2001. The anamorphic has the necessary adjustments to become the background image for the geometry of the Cold Bog diorama shell at the Peabody Museum.

8: Normal photograph of the Cold Bog site, June 17, 2001. Note horizon compared with the bog camera photograph above.

the painting. And since the painting is flat, its surface will contain the idea of this other curved surface within it.

As we discussed earlier, one way of implicating us in the drawing is to make it spatial, so that our engagement depends on our positional relationship to the image. Although this is possible with anamorphic images painted on flat surfaces, the possibilities multiply when the surface is folded. One of the thrilling potentials in van Hoogstraten's peepshow of a Dutch house (circa 1655-60, National Gallery, London) is that the surface of the box and the image at times appear to be a space; at times a perspectival picture; and at times both space and picture. And sometimes it creates a space between 'resolved' conditions, especially when it is viewed from the side that lets light in – the unintended view. It is this condition that is so tantalizing for the purposes of drawing an indeterminate architecture, as it lies between pictorial and material space. Natural history dioramas too, exemplify this 'in-between' condition, providing a soft anamorphism in which the image registers and decays gradually.

Dioramas and the 'Dual Net' System of Projection

The shell of a habitat diorama painting is a material space. This is a slight paradox as the purpose of the form is to deny any registration of itself as a thing while supplying a surface to paint the background image and allowing enough room for the stuffed animals that inhabit it. The strangeness of this relationship is apparent when one looks at photographs that document the field studies for the dioramas and the process of painting them. The former show a landscape with an artist in the foreground painting a canvas at an easel. In the latter, the painting and easel stand in front of the landscape the artist is painting.

There are other examples of similar composites, such as the anamorphic and vaulted painted ceilings in baroque churches. But one advantage of looking at dioramas is the documentation available on the projection techniques of one of the greatest exponents of the art – James Perry Wilson (Morrill 1996). Before Wilson, diorama projection involved a lot of eyeballing and judgment (Jacques 1931). Wilson had trained as an architect at Columbia University and practiced in that field for twenty years before turning to diorama painting, so he brought with him the discipline of descriptive geometry, architectural perspectives, and drafting, as well as a passing knowledge of meteorology and astronomy, and the experience of many summer holidays painting landscapes (Anderson 2000). There are many things to say about Wilson's work, but this paper will concentrate on his grid, or 'dual net', technique of diorama projection.

The dual net system clarifies the stages of transformation between an image and the shape of the shell onto which it will be projected. Wilson made study paintings of the sites he translated into dioramas to document the colour more accurately than he could with Kodachrome slides. For geometry, he relied on a series of photographs that could be assembled into a panorama, each segment with views up, down and horizontal to collect the sky and ground as well as the horizon. If we imagine these views reduced

9: Pinhole photograph of Copenhagen harbour taken with a flat picture plane.

10: Bog camera photograph of Copenhagen harbour, taken from a slightly different position than the pinhole photograph above. The anamorphic distortion created using the bog camera is clear.

to a net (without the image) like the one in Dürer's woodcut, and we were to assemble the flat nets together, we would get a faceted series of nets, a kind of polygon with netted surfaces. If this were only a net, one could imagine a light source at the radial centre that would project the lines of the net onto the curved diorama shell. The light source would need to be positioned at the ideal viewing point for the diorama. If you traced the shadow of the net onto the diorama shell and then translated each segment of the image held in the net to the appropriate segment on the shell, there would be a true transformation of the flat picture plane onto the curved diorama shell, as long as it was observed from the ideal viewing position (Fig. 1, 2 and 3).

Wilson achieved this transformation in two steps – thus, the 'dual net'. Rather than using a rectilinear net, he calculated the deformation of the net for the focal length of his camera lenses and for the angle of deviance from the horizontal that the photograph was taken, so that he could convert the faceted picture plane into a cylindrical one. You might ask why he did not convert entirely to a spherical picture plane, but then, dioramas try to keep all physical features (except the sky) on the more vertical portion of the shell. This is because if a mountain, for example, were to stray onto the domed ceiling section of the diorama, it would appear distorted as you move around the image. Wilson scratched the 'net' onto a sheet of clear plastic (Fig. 4) and superimposed it on a slide so that he could work directly from the projected slide. But since the surface he was painting on was not circular, and it was very complicated to work out the deformation of the net to compensate for the focal length of the lens and the shape of the diorama shell all in one action, he divided it into two. Having calculated the net to convert his photograph into a cylindrical picture plane, he then made the simpler calculation of how to transfer a cylindrical picture plane onto the shell he was using. This new net would have the same number of vertical and horizontal lines as did the adjusted photograph, and the same angle of view between vertical segments.

When he had drawn the shell-shaped compensating (second) net onto the shell, he would translate the content of the slide (superimposed with the first net) onto it in charcoal. As with the curved picture plane we saw earlier, there is an intermediate surface that is never realized in form or image, a calculated surface which does not exist but nevertheless influences the final image. To understand Wilson's projective geometry and to develop a tool to work between the anamorphic image and the folded picture plane, I designed a camera that could make all his calculations in a single photograph. In fact, I made three cameras, so that I could take stereoscopic photographs (the width of the camera was such that two cameras could make accurate stereoscopic photographs of the diorama at normal human eye separation) and still have a backup in case of failure in the field. Wilson also used stereoscopic photography in making his site surveys, but that is another story.

11: Photomontage of Wilson's panoramic photographs of the Cold Bog site, June 17, 1949. Original images courtesy of Michael Anderson.

12: Michael Anderson and Ruth Morrill at the Cold Bog, June 17, 2001. The cameras in the foreground are set up for stereoscopic shots.

The 'Cold Bog' Camera

The cameras are specific to Wilson's Cold Bog diorama in the Peabody Museum. They use a pinhole to provide the depth of field to cope with the curved film plane. In the camera, the pinhole is placed in the scale position of the ideal viewpoint, for the film plane is a scale model of the diorama shell. In front of the diorama the pinhole is located at its ideal viewpoint. When photographing the original site the camera produces an unfolded image of the diorama shell. When photographing the diorama the images show an accurate unfolding of the painting. When you view a stereo pair of normal photographs of the diorama you see the form of the curved picture plane. When you view a stereo pair from the Bog Camera, the three dimensional material in the foreground emerges in three dimensions but the diorama shell appears perfectly flat, a confirmation of the accuracy of the camera (Fig. 5-13).

Wilson scholar Michael Anderson from the Peabody Museum arranged for the diorama glass to be opened and for access to the original site. Fifty-two years to the day after Wilson's original survey, Anderson and Ruth Morrill, who assisted Wilson in some of his late work, accompanied me and helped to find the original survey viewpoint. The nature of the place, a bog of sphagnum moss, made setting up the cameras interesting, as one tripod would move on a raft of moss as the next was set up. Comparing my cameras' photographs with normal views of either the site or the diorama show the anamorphic distortion required to register the image on the curved shell. Comparing my cameras shots of the site and from the diorama, despite half a century of growth, reveals the precision of Wilson's technique. The whole pursuit promises a way of drawing that is between material and pictorial space.

Notes

Nat would like to thank Michael Anderson of the Peabody Museum for his help, advice, and generosity with his extensive research into J.P. Wilson's work.

Photographs are by the author unless otherwise noted.

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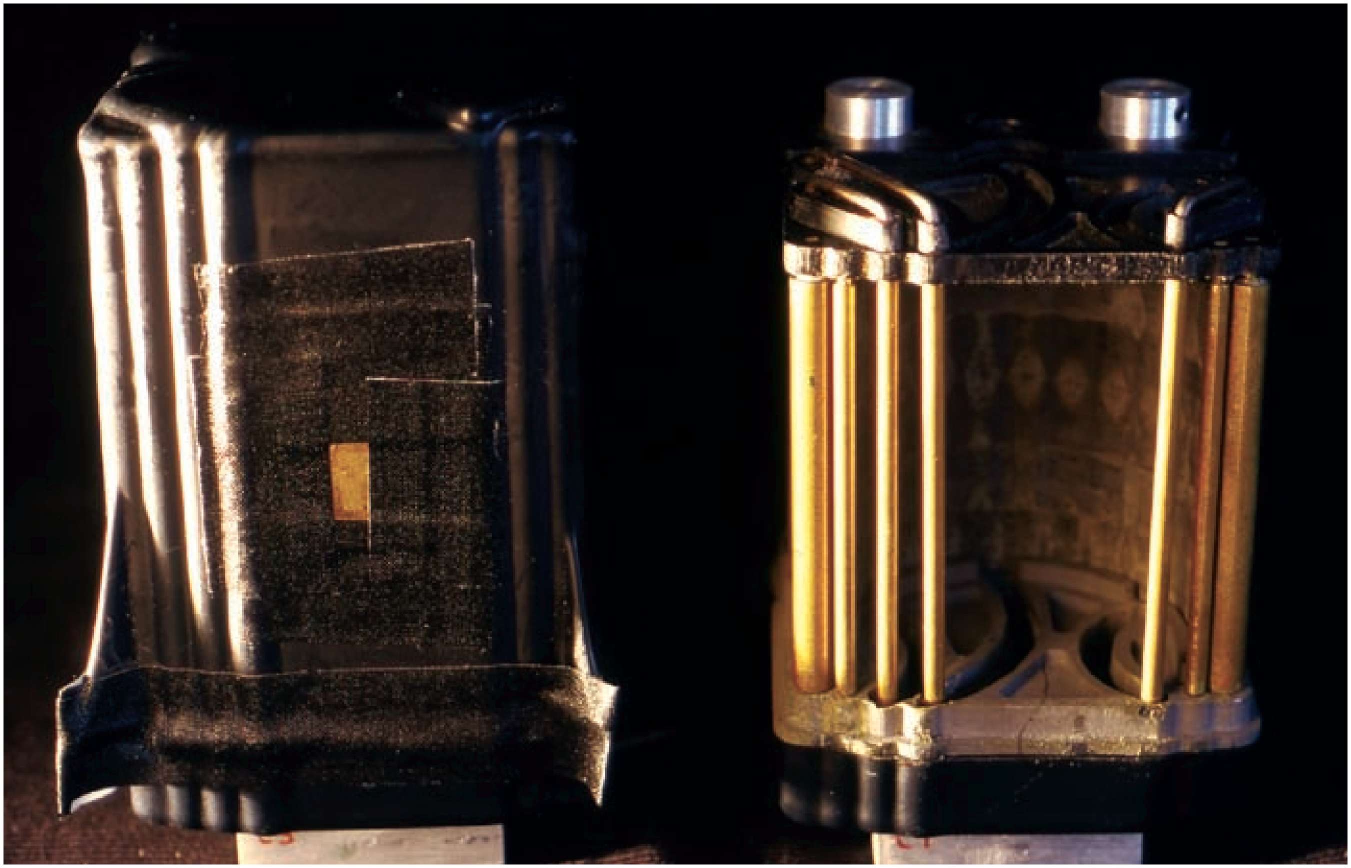
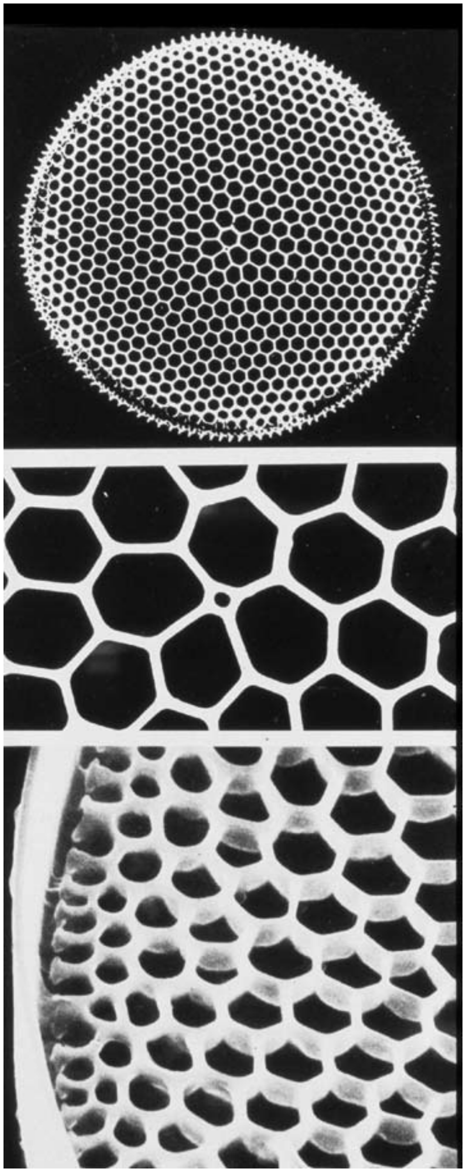


13: Closed and opened Bog cameras. The vertical rollers keep the film on the curved picture plane during winding.



1: Void as a structural principle. Institute of Lightweight Structures Archives.

Naturalization, in Circles: Architecture, Science, Architecture

Reinhold Martin

I would like to consider the axis that has historically connected architecture with science from the point of view of the 'outside world.' Specifically, I want to suggest that more often than not, the projection of science onto architecture has operated as a defensive mechanism. This projection has repeatedly sought to reground architecture in a naturalized homecoming, as it withdraws from a world that is – like ours – fraught with violence and uncertainty. In other words, to speak about architecture and science, or for that matter about art and science, is very often also to speak indirectly about war.

Historically, war has often accelerated scientific and technological advances that were subsequently internalized in architecture. Take, for example, the Second World War, which saw unprecedented collaborations between research universities, corporations, and the military in the form of such efforts as the Manhattan Project – the postwar momentum of which spawned what is now known as "Big Science." Walter Gropius summed up the architectural response to these developments in a brief text titled "Architecture and Design in the Age of Science" written in 1952 – the same year that Lever House and the United Nations headquarters were completed and the first hydrogen bomb was tested,

> If we are ever to catch up with our runaway civilization, industry will have to make use of the essential value of higher quality through *organic* design by having the machine controlled not only by the scientist and the engineer, but by the artists as well, who is their legitimate brother (Gropius 1952: 4, emphasis added).

In writing these words, Gropius was echoing themes elaborated by Siegfried Giedion, in *Mechanization Takes Command* (1948), as well as those of their mutual friend György Kepes. The aftermath of the war had brought new and potentially even more destructive threats in the form of atomic weaponry and what some, like Giedion and Kepes, saw as a loss of control in the face of relentless scientific advances. Indeed, for many humanists and many scientists, Hiroshima and the concentration camps mirrored one another in demonstrating the destructive potential of an unregulated scientism. And so they appealed to the very same new nature that had been revealed by scientific advances made during wartime to, in effect, correct the course of postwar science as though it were a guided missile. Seen in its historical context, this amounted to an effort to domesticate science and its perceived effects with the help of art and architecture.

Thus, to my subject: Naturalization. In brief, this can be understood as the process of converting works of culture into acts of nature. As such, naturalization is also the process of constructing self-evidence, of legitimizing – not through argumentation, but through an epistemological sleight-of-hand. Who, after all, can argue with nature? And as I have already hinted, naturalization also harbors overtones of domestication, in the sense that to declare something natural – in this context at least – is to reterritorialize it, to reground it, and thereby to domesticate it.

What I'd like to do here, then, is run through a series of instances in which architecture has participated in processes of naturalization by forcing a contrived unity between art and science, and where science has reciprocated – sometimes directly, sometimes indirectly. I should add immediately that I am making no claim whatsoever here as to the validity of the scientific knowledge and discourse cited. My only concern is to understand its role in the commerce of ideas that, from the point of view of architecture, has produced a series of powerful phantasms.

Complexity Theory

My first example comes from the mid-1990s, in the popularization of the mathematical and scientific hypotheses loosely known as "complexity theory." Perhaps the most lucid expositor of these ideas for a lay public (including architects) has been the theoretical biologist Stuart Kauffman, author of the popular *At Home in the Universe: The Search for the Laws of Self-Organization and Complexity* (1995). Describing his work as bound to a "mystical longing," Kauffman earnestly and continuously repeats his claim in the book that organic life, the preeminent example of so-called "organized complexity," is fully at home within the natural order of things, and not merely an astronomically improbable accident. Again, what is important for us here is not so much the scientific legitimacy of Kauffman's theses, but their metaphysical ambitions. In Kauffman's universe, organic life – whose history has until recently been understood as largely subject to the brutal, chance mutations of natural selection – has actually been at home all along, thanks to the principles of "self-organization," defined by Kauffman as the capacity of a system to evolve in the absence of an external impetus. Conversely, within such a universe, governed by laws of what amounts to historical necessity, there can be no life without a home – that is, without a self-organizing system.

This projection of science onto history has been translated into many aspects of technical endeavor, including efforts to utilize these models for economic analysis and forecasting, infrastructure planning, manufacturing, and so on. As Kauffman sees it, "like co-evolutionary systems, economic systems link the selfish activities of more or less myopic agents," while going on to suggest (with unbelievable innocence) that "The edge of chaos [the home of organized complexity] may even provide a deep new understanding of the logic of democracy," a set of statements that have the cumulative effect of domesticating the inherently agonistic or conflictual dimensions of any authentic democracy by correlating them with a thoroughly naturalized form of market capital.

I mention this not only because in the 1990s such ideas had substantial resonance in architecture, but also because similar pronouncements issuing from journalists like

Kevin Kelly and others in the pages of *Wired* magazine, including econo-futurists like George Gilder, played a significant role in constructing the destructive image of a self-authorizing, self-regulating, bottom-up and supposedly benign "new economy" associated with neoliberal ideology. But I want to put off analyzing recent architectural misadventures from this point of view in order first to consider their historical antecedents.

Self-organizing Systems in Architecture

The first architect of importance to cite scientific research on self-organizing systems was Christopher Alexander. He did so in his first major publication, *Notes on the Synthesis of Form* (1964). There, Alexander described "unselfconscious" vernacular design as "self-organizing," with reference to an important 1959 interdisciplinary conference on self-organizing systems that had followed on the heels of the postwar Macy cybernetics conferences. For Alexander as for Kauffman writing three decades later, self-organization implies a set of depoliticized, fully "natural" social structures. Likewise, as the more recent work on self-organization and "emergence" has done with abandon, Alexander sought to model these life systems digitally, appending to his book examples and diagrams one step away from implementation as computer-modeled, naturally evolving ecologies.

This is not to suggest that Alexander's ideas influenced Kauffman – only that they appealed to reciprocal forms of the same logic. Where Alexander saw self-organization as a new grounding for architecture, Kauffman sees the architectural figure of the home as the *telos* for complexity theory. Complexity theory thus becomes the art of homebuilding.

Now, for my second example I move to the 1980s, and to an issue of the journal *Nature* published in 1985. There, a piece of architecture makes an unlikely appearance on the cover, in a diagrammatic image. This is not an image of some proto-architectural natural form, but of a form borrowed from architecture to describe a molecule which had not yet actually been seen. It is an image of C_{60}, or buckminsterfullerene, a new form of carbon discovered inadvertently by Harold W. Kroto, Rick Smalley, Robert F. Curl and their colleagues. The diagram was based in part on the geometrical structure of Buckminster Fuller's geodesic domes, and its appearance marked the dramatic birth of what quickly became a new field of scientific and technological research propelled by the subsequent discovery of an entire family of fullerene compounds (Kroto et.al. 1985).

Confronted with the geometrical puzzle of describing the structure of a molecule that had appeared unexpectedly when graphite was vaporized under a laser, Kroto, Smalley and Curl had in fact looked to Fuller's domes for assistance. The molecule's stability indicated that it was some kind of closed cage, a spheroid in which the hexagonal lattice of graphite had somehow been rolled up and connected to itself to prevent further bonding. Reporting on their efforts to map such a spheroid, Kroto later recalled his visit to Fuller's dome at Expo '67, which to him seemed to be made up almost entirely of hexagons. So he and Smalley consulted Robert Marks's monograph on Fuller, concentrating on a photograph of the dome Fuller had built for the Union Tank Car Company, but they could not fully understand its geometry. Further experimentation with a paper model revealed that twelve isolated pentagons are necessary in addition to the more noticeable hexagons to produce a spheroid with sixty vertices. A subsequent inquiry placed with the Rice University mathematics department as to the nature of the resulting figure drew this response: "What you've got there boys, is a soccer ball."

Smalley later reminisced, "Imagine this excitement that you've discovered a way of putting sixty carbon atoms together that is not only beautifully symmetric, but it's a soccer ball, too." Fuller's name was permanently affixed to the molecule (the "bucky ball") in honor of his role in its visualization. Illustrated on the cover of *Nature*, the geodesic structure of buckminsterfullerene remained speculative, but Kroto was confident that their hypothesis would ultimately be confirmed. As he put it, "it was so beautiful that it just *had* to be right."

As it turns out, another team of researchers, led by Donald R. Huffman and Wolfgang Krätschmer, had independently encountered empirical evidence of C_{60}'s existence, but dismissed the mysterious material as "junk." Seeing the Kroto / Smalley / Curl paper in *Nature* however, Huffman had second thoughts. Over the next five years, he and Krätschmer eventually succeeded in synthesizing C_{60} in crystalline form. Their cover article in *Nature*, which appeared in September of 1990, began with a tribute to the work of their predecessors in discovering what it called the molecule's "elegant structure." Thus, with the intervention of the speculative elegance of the "beautifully symmetric" hypothetical bucky ball, Huffman and Krätschmer were able to turn their laboratory "junk" into what they called "an incredibly beautiful sight" whose readily observable geometries confirmed earlier speculations (Krätschmer et al, 1990).

Whether or not the supposed elegance of the truncated icosahedron model caused Huffman and Krätschmer to re-evaluate their junk, and thus to convert it into an easily produced crystal with significant scientific and technological potential, exclamations concerning the molecule's "beautiful symmetry" and "striking" features punctuate the otherwise dry scientific literature surrounding the discovery of buckminsterfullerene. These are not merely incidental expressions of aesthetic pleasure, but rather repetitive reassurances – on the part of a scientific discourse that honored Fuller with his own molecule – that the apparent efficiencies of nature, like Fuller's architecture, were indeed as natural as we might have hoped, comparing favorably with modernism's own search for an equally natural economy of means.

Fuller called his version of this economy of means *ephemeralization*, a concept most famously expressed in his much-repeated question to architects: "How much does your building weigh?" And indeed like his geodesic domes, which had assumed their spherical shape in order to achieve maximum enclosure with a minimum of material, images drawn from science were central to Fuller's program of steering humanity toward evolutionary success by optimizing the performance of technological systems under the regime of a post-political, self-regulating totality. Fuller collected, produced, and reproduced such images, feeding them back into the technological complex from whence they came as regulators intended to enhance further the system's overall performance. Taken to its hypothetical conclusion, this process would continue to generate ever greater efficiencies, measurable in terms of weight, or performance per pound, Fuller's favorite criterion. The lighter the structure, the greater its efficiency, until the structures themselves dissolved into the very images regulating them – weightless.

So what we have here is a kind of feedback loop. Fuller used scientific images in part to naturalize the essentially arbitrary aesthetic choices he made in the domes, while science, in the discovery of buckminsterfullere, used Fuller's dome as a kind of template both to visualize and to aestheticize its own objects. Thus, in the scientific exclamations regarding the molecule's so-called "beauty," authorized in advance by the supposed beauty of Fuller's domes, we can find something like the naturalization of nature itself.

War and Ephemerality

And what does this have to do with war? Well, there are a number of levels on which this question can and must be answered. The first and most empirical level would note the degree to which Fuller's project of 'ephemeralization' was put to use by the United States military in the prosecution of the cold war. The most notable example of this was to be found in SAGE, or Semi-Automated Ground Environment, the name given to the defensive early-warning system put in place near the Arctic Circle during the mid-1950s. A kind of proto-Star Wars apparatus that figures prominently in cold war films like *Fail Safe*, SAGE was a complex servomechanism at the scale of the North American continent, designed to retrieve information as to the location of incoming enemy bombers and feed it into computerized command centers located further inland, which would in turn orchestrate a military response. The radar listening posts located at the "Distant Early Warning" or DEW line were housed in geodesic domes designed by Fuller specifically for this purpose, which he called 'radomes.'

In addition to being easily transportable functional enclosures, these radomes were also images, representations extrapolated from science and deployed in the name of maintaining the homeostatic cold war equilibrium of MAD, or "Mutually Assured Destruction." That is, at the level of representation, they were instruments of balance that utilized the logic of feedback not only to defend against enemy planes, but also to defend against the disorienting effects of science, technology, a fragmented consumerism, and the competing ideologies of the cold war.

Kepes and Organicism

This dimension of Fuller's work is most visible in its links to the organicist project of György Kepes, epitomized by Kepes's theoretical writings and edited collections. Beginning with *Language of Vision* (1944), Kepes had been engaged in a campaign to reorganize a dynamic visual equilibrium through which the bewildered postwar subject could navigate in a world seemingly out of control. Such a world produced an excess of information intelligible only to specialists, accompanied by an excess of sensory stimulation – or what Siegfried Kracauer referred to at the time as a "pictorial deluge" (Kracauer 1950). Visual imagery was becoming a privileged means of communication in both the social and technical spheres, yielding within the span of two years both Marshall McLuhan's *The Mechanical Bride* (1951), an analysis of the maelstrom of images saturating consumer culture, which he designated "the folklore of industrial man" and Francis Crick and James Watson's spectacular double-helix diagrams illustrating the structure of DNA (1953).

By the mid 1950s Kepes had become a major supplier of scientific images of natural patterns to architectural discourse, as well as a leading advocate for the unity of art and science. Fuller appreciated Kepes's work, having visited an exhibition organized by Kepes, in which black-and-white photographs of abstract paintings were mixed with photographs taken by scientists of similar patterns occurring in nature. The exhibition, titled "The New Landscape in Art and Science," was a descendant of the "The New Landscape," an exhibition of exclusively scientific images curated and installed by Kepes at MIT's Hayden Gallery in 1951. Its contents also formed the basis for an edited volume likewise titled *The New Landscape in Art and Science* (1956), in which prominent artists, architects, and scientists joined Kepes in theorizing parallels between patterns visualized in the artistic and scientific realms. Kepes extended this project into the 1960s as editor of the *Vision + Value* series published by George Braziller, featuring texts by prominent thinkers in diverse fields that grew out of interdisciplinary seminars convened by Kepes in the School of Architecture at MIT beginning in 1956.

Fuller was among the many figures who published in Kepes's *Vision + Value* series, in this case, in the 1965 volume titled *Structure in Art and Science*. There as elsewhere, Fuller scoffed at the idea of a "pure" art, in favor of the potential utility of artistic abstractions. He rhapsodized over the ability of industrialization to overcome the inequitable distribution of resources plaguing the human enterprise if managed by what he called "an emerging synthesis of artist, inventor, mechanic, objective economist and evolutionary strategist," a so-called "comprehensive designer," whose role in the new "interactive continuities" of global industrialization would be analogous to that of the architect in feudal society.

Fuller had by this time also adopted the term "synergy", or the behavior of the whole not predictable by that of its parts taken separately, to describe what he called the "essence" of progressive, irreversible industrialization: its increasingly synthetic, integrated nature. He frequently used the example of chrome nickel steel, an alloy whose tensile strength far exceeds the sum of the tensile strengths of its components, to illustrate the idea of improved performance through integration into a whole. "Ephemeralization" was a corollary to this, expressed elsewhere by the slogan "doing more with less," his endlessly repeated parody of the Miesian "less is more." These terms and phrases appear again and again throughout Fuller's writings of the 1950s, 60s, and 70s, taking on varying nuances as they respond to different contexts. Referring to the "comprehensive designer's" role in the acceleration and management of industrialization, "doing more with less" meant an economy of means based on a handful of general principles, beginning with the principle of synergy.

Fuller illustrated such principles with a series of images of geodesic-like organic forms recently made visible by science. Indeed, by the early 1960s, tiny domes had already been spotted by scientists peering through electron microscopes, in the form of the protein shells of certain viruses. And in uncanny anticipation of the saga of buckminsterfullerene, one of the scientists studying the viruses, Dr. Robert Horne, waxing lyrical over the little creatures' "wonderful underlying symmetry," tells of being referred to a monograph on Fuller while working on them (Ubell 1962).

Seen in the context of Kepes's project then, Fuller's scientific images thus allegorize the unification of art and science in a universal system of informatic exchange. Within this system architecture, operating like a nature in reverse, converts images into organisms and organisms into images, migrating back and forth across disciplinary boundaries

Organic Processes

So: my third and final example begins with the words 'on growth and form.' In 1951, the artist Richard Hamilton organized a small exhibition titled "Growth and Form" at the Institute for Contemporary Art (ICA) in London, which took its name and its inspiration from the morphologist D'Arcy Wentworth Thompson's *On Growth and Form* (1917, 1942). Like Kepes's "The New Landscape," which took place the same year, "Growth and Form" was an exhibition of scientific images intended to elucidate the physical and mathematical laws governing natural form at all scales. The exhibition was accompanied by a symposium titled "Aspects of Form," in which a group of prominent scientists reflected on what Lancelot Law Whyte, editor of the symposium transcript published later that year, refers to as "tantalisingly subtle" questions of form with which scientists from various domains had become increasingly preoccupied. In observing that what he calls "complex form" still baffled mid-twentieth century science, Whyte asserts that "the artist knows well the pervasiveness and subtlety of form." Thus the scientist looks to the artist for assistance. Whereas, in his preface to the "Aspects of Form" publication, ICA director and art historian Herbert Read goes even further, claiming that "Aesthetics is no longer an isolated science of beauty; science can no longer neglect aesthetic factors." Significantly, Read bases this claim largely on the emergence of Gestalt psychology as a model for theories of perception that sought to revise modernist aesthetics after the war, a project identified with a variety of modernist efforts, including those of Kepes, to deploy a reoriented cultural production – including art and architecture – to naturalize and thereby equilibrate a technoscientific milieu run amok.

Meanwhile, theoretical biologist Conrad Waddington's contribution to *Aspects of Form* takes up the problem of complex form and aesthetic perception from the point of view of biology. As Waddington puts it: "Organic forms develop. The flow of time is an essential component of their full nature" (Waddington 1966). With reference to the vitalist philosophical hypotheses of Alfred North Whitehead, Waddington extrapolates this temporalization of the organic Gestalt into the notion of a balanced, rhythmic harmony of continuous variation. Thus the shell of the unicellular organism *Aulonia hexagona*, a kind of miniature geodesic dome, exhibits tiny rhythmic variations in its patterns of hexagons. Reading against such a biological background, we would be thus obliged to see in the standardized repetition of hexagons in a Fuller dome a mechanical stiffness to be overcome by an architecture more sensitive to the complexity of organic processes. This is a refrain that has been repeated by contemporary architects asserting the advantages of computerized mass-customization over mere modular repetition, advantages that must be understood as more ideological than technological, in the sense that they subsume the threatening artificiality of computer-driven effects into – again – a scientifically-ratified naturalism. As it stood in 1951 however, Waddington's citation of D'Arcy Thompson comparing a bone from a vulture's wing to a Warren truss (to suggest the adaptive, emergent structural efficiency engendered by the slight variations in the thickness of the bone's "struts") merely went on to become part of Louis Kahn's slide library, among other things.

Waddington, who was among those biologists responsible for the early articulation of what Donna Haraway has described as a paradigm shift that resolved the earlier mechanism-vitalism debate into a new, dynamic, systems-based organicism, would become increasing preoccupied with what he took to be the common, rhythmic thread connecting modern biology with modern art, a thread that he follows in the *Aspects of Form* article by identifying organic rhythms in the works of Henry Moore, Barbara Hepworth and others. Waddington was to pursue these ideas further in his new book, as well as in a number of related texts, including the contribution to Kepes's *Vision + Value* series titled "The Modular Principle and Biological Form," which confronted the idealized rigidity of Le Corbusier's Modulor with the dynamic rhythms of biology. So perhaps it is not entirely by chance that Waddington's own use of visual form to describe complex – and at times invisible – biological processes appears in recent feedback loops connecting architecture with science.

In the early 1990s, Sanford Kwinter used Waddington's diagrams of the "epigenetic landscape" to illustrate the properties of what he (Kwinter) calls a complex, or "soft" system, the formal properties of which are indeterminately and nonlinearly "emergent," systems that he asserts are "increasingly assimilated with, and described by, the processes of *life*" (Kwinter 1992: 164-166). At both the global and molecular level, according to Kwinter writing with a Fulleresque flourish, such systems anticipate "a world where everything flows seamlessly together in real time." However, Kwinter is at times less than sanguine about the desirability of such a world, despite the occasionally millenarian tone of his art-science rhetoric. The same cannot be said for those who have taken up such notions in the more deterministic realm of design theory.

"Animate" Architectural Form

One such theorist and architect is Greg Lynn, who in the 1990s followed Kwinter and others in projecting the popularized versions of theoretical biology and complexity theory onto computer-aided architectural design in a number of texts circulated in channels such as Cynthia Davidson's ANY project. Lynn refers both to Waddington and to complexity theorist Stuart Kauffman as sources for what he calls a "landscape model" for a loose, rhythmic, computationally nonlinear and developmental model of "animate" architectural form. D'Arcy Thompson is also lurking in the background here, in particular with Lynn's earlier comparison of D'Arcy Thompson's gridded diagrams showing the inscription of physical forces on the body-forms of various fish with Rudolph Wittkover's patterned diagrams of eleven Palladian villas (Lynn 1999, 1992). Lynn's argument, that the biological model of continuous and complex formal transformation across a generative developmental "landscape" offers new possibilities for advancing the so-called "interiority" of architecture beyond modernist repetition and stasis, is an exercise in Gestalt-formation with new tools. Despite Lynn's (and others') anticipatory denials to the contrary, what is being proposed here is a new organicism that substitutes the equally totalizing, equally naturalizing, patterned, Gestalt-like representation of open-ended biomechanical evolution for the closure of the formerly figural organic "whole".

Conclusion

The implications of such an approach are visible in Lynn's insistence on the figure of a "landscape," which (despite its dynamism) acts here as an instrument of regrounding. We have seen similar gestures in Kepes's inventory of what he called a "new landscape" of natural patterns made visible by scientific photography. The difference is that modernists like Kepes, Giedion, and Gropius self-consciously marshaled the aestheticized weaponry of science to defend against an over-specialized, de-humanized repetition of the horrors perpetuated during World War II. In contrast, members of the generation that has followed the generation of '68 (of which Lynn is exemplary), have shown themselves all too eager to forget the violence still embedded in scientistic ideologies. Instead, they redeploy old ideas in the name of a 'new' (yet all too familiar) architecture-as-nature. Consequently, rather than genuinely experiment with the deterritorializing effects of computers, contemporary architects often work to domesticate them through naturalization, which is the oldest trick in the book.

Now, I just want to add one more point here. I have argued elsewhere that attempts on both sides of the Gray-White debate of the early 1970s to defend "architecture as such" against the incursions of geopolitics in the form of the Vietnam-era atrocities floating across American television screens took the form of a repression, a turning inward and away from the mass-media logic of the postwar curtain wall. Similarly, in the circular exchanges that we just traced we find another repression, in the efforts to rebuild a home for architecture in the face of new threats. This is what joins today's versions of morphological complexity and "self-organization" with the active and more visible metaphysics of figures like Christopher Alexander.

Indeed, some may remember the debate between Alexander and Peter Eisenman that was published in the *GSD News* and then in *Lotus* in the mid-1980s. There, Eisenman recalls that when he was a student at Cambridge, he was given a copy of Alexander's PhD dissertation, which became the basis for *Notes on the Synthesis of Form*. According to Eisenman, "the text so infuriated me that I was moved to do a PhD thesis myself" (Alexander and Eisenman, 1982). His was called "The Formal Basis of Modern Architecture." And certainly, the differences between the output of Eisenman and that of Alexander are well known. How is it, then, that Lynn and other descendents of the New York Five have come so close to rehearsing the very positivism against which Eisenman directed his own critical energies? In many ways the answer to this is simple, though its psychodynamics are not. Eisenman was right, I think, to object to Alexander's efforts to overcome alienation by appealing to domesticity. In essence, he was objecting to Alexander's efforts to reterritorialize the alienating tremors of modernity, which Eisenman continues to see as productive. And yet, contemporary architecture naively continues to seek a home in science, to naturalize the profoundly destabilizing effects of another round of tremors. This time the tremors are associated not only with a new digital environment, but also with the loss of the black and white (and gray and white) pseudo-certainties of the cold war, the aestheticizing of techno-scientific perception in the bombsights of the Gulf War, and perhaps now in the perpetually-deferred visual stimuli of what has been called a 'new' war. This latest war has already been thoroughly naturalized in the networked, mediatized, and violently organicist bond of citizen to citizen that, by early 2003, authorized full mobilization and silenced criticism, in an extraordinarily efficient substitution for the mythically 'organic' forces that supposedly bound together the fluid, pulsating seamlessness of the recently defunct 'new' economy.

It is my own hope that architectural discourse will take this moment to reflect on the hollow, beleaguered triumphalism implicit in attempts to use technology to convert products of culture into objects of nature. This is the triumphalism of an architecture whose repression of that threatening exterior that we can simply call 'the world' has occurred with the help of science, in a process that all too often comes full circle: from the phantasmatic homecomings of science to the phantasmatic homecomings of architecture, and back again.

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NATURE AS TEACHER

1: Ann Richards, pleated fabric.

"A Diagram of Forces" : Form as Formation in Nature and Design

Ann Richards

There has been a long tradition of artists and designers drawing upon ideas and images from biology. But it is also the case that biologists have taken ideas from human design. These range from the 'argument from design' during the 18th and 19th century, in which the adaptations of organisms were taken as a basis for natural theology, for example by Paley (Paley 1802), through to the modern use of ideas from human practice in biomechanics. For example, Gordon describes how fabric shear has provided an inspiration for the investigation of worm biology and Wainwright has suggested that the science of biomechanics would benefit from developing a concept of 'workmanship' (Gordon 1978; Wainwright 1980). D'Arcy Thompson is one of a number of biologists who have taken ideas from human practice as metaphors for nature, most notably in his classic text, *On Growth and Form*, first published in 1917. In this paper I want to look at the relevance of his ideas to my own work as a designer/maker, and reflect, more generally, on design as a human activity, rather than as a purely conceptual project.[1]

A 'Diagram of Forces'

The visual forms of nature as static configurations have traditionally been sources for artists and designers, but D'Arcy Thompson invites us to go further and consider form in dynamic terms. He presents a vivid metaphor of form as a 'diagram of forces', which reveals the forces acting on an object over time.

> The form, then of any portion of matter, whether it be living or dead, and the changes of form which are apparent in its movements and in its growth, may in all cases alike be described as due to the action of force. In short, the form of an object is a 'diagram of forces', in this sense, at least, that from it we can judge of or deduce the forces that are acting or have acted upon it (Thompson 1942: 16).

This idea of form as a representation not only of present but also of past forces is an important point, encapsulated by Thompson's description of the organism as "an 'event in space-time' and not merely a 'configuration in space.'" Bringing in the element of time defines form as intimately related to growth and thus *dynamic* rather than static.

This is an idea that has been picked up by other biologists. Hallé and his colleagues analyze the form of tropical trees and forests in terms of the 'architecture' of the tree, by which they imply more than merely a static conception of form. Like Thompson, they see form as something that develops through time. In explaining their view, they comment that "the concept of architecture involves the idea of form, implicitly containing also the history of such a form" (Hallé, Oldeman and Tomlinson 1978: viii).

Artifacts as 'Diagrams of Forces'

If living organisms are 'diagrams of forces', so too then are artifacts – their finished form reveals the presence of existing forces but also bears the traces of the process that brought them into being. As a practicing designer-maker, I am conscious that my textiles are 'diagrams of forces', since they reveal, in their finished form, the energy that has shaped them. I make extensive use of high-twist yarns; these store strain energy which is only released when the fabric is wetted out in the finishing process (Figs. 2, 3). Spontaneous spiralling movements of the yarn, within the fabric, then create texture and elasticity (Figs. 4, 5), particularly when these energetic yarns are used in varying weave structures and played off against stiffer and less springy materials.

In addition to my reliance on these natural forces to achieve particular fabric qualities, I have also explicitly drawn many ideas for the forms and textures of my textiles directly from nature. These natural forms, as 'diagrams of forces', reveal the history of their formation, and hence offer ideas about the forces that might create similar forms in textiles. Natural forms I have drawn upon in this way include the structure of bats' wings, pine cones, sea shells and the pleated structure of dragonfly wings (Fig. 6). Forms such as these have given me a starting point for a variety of fabrics in which, through the action of high-twist yarns in combination with a range of weave structures, the cloth becomes 'self-folding'. Through the release of the stored energy in the twist of the yarn, the cloth organizes itself into pleats or other textures.

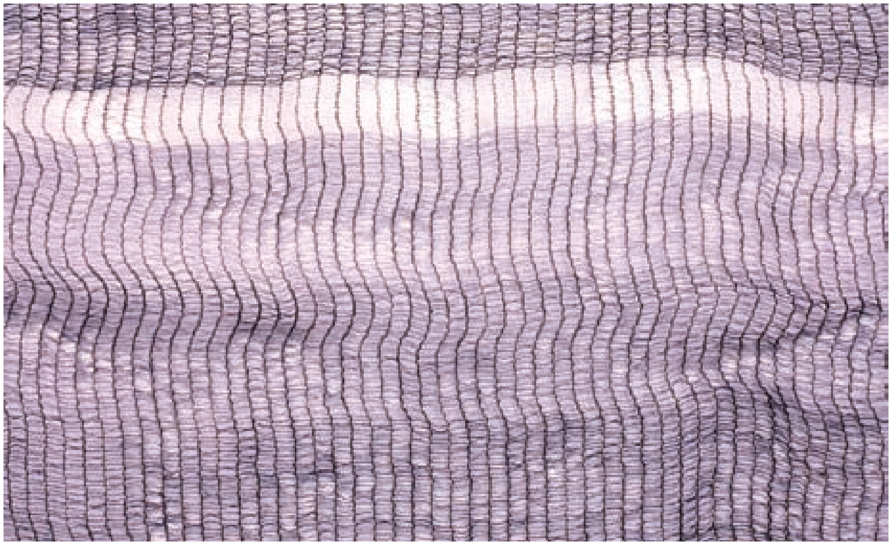
I find it helpful to think of the forces involved in creating my textiles as aspects of growth, in D'Arcy Thompson's sense, since he uses the term growth to mean not only an *increase* in size but also stresses that "*all* changes of form, inasmuch as they necessarily involve changes of actual and relative magnitude, may in a sense be looked upon as phenomena of growth" (Thompson 1942: 81). My work relies on growth in this wider sense, since the textures, and even the shapes, of pieces of fabric may be formed by variations in the forces established in different parts of the fabric, through the contrasting properties of materials and yarn twists. I also find it helpful to see analogies, as D'Arcy Thompson does, between growth in organisms and in simple physical systems.

> If a sheet of paper be made to expand here and contract there, as by moisture or evaporation, the plane surface becomes dimpled, or folded, or buckled, by the said expansions and contractions; and the distortions to which the surface of the 'germinal [embryonic] disc' is subject are [...] precisely analogous (Thompson 1942: 83).

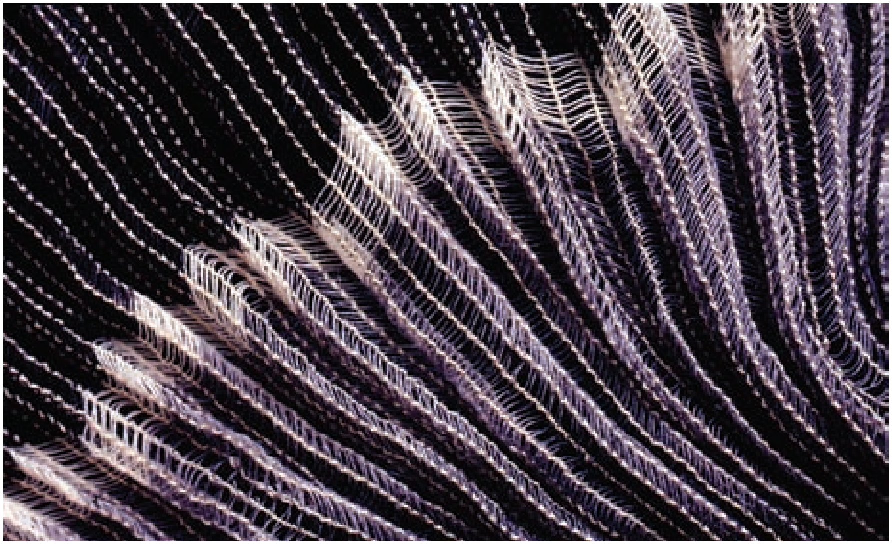
Thompson extends this idea with a further example that relates still more closely to the effects I explore while making textiles. Describing the creation of an "artificial blastoderm" from pellets of dough, which are caused to grow at different rates through the addition of yeast, he comments that,

2: Skein of high-twist yarn. The strain energy stored in this yarn will not become obvious until the yarn is wetted out.

3: Sample of high-twist yarn after wetting out, showing contraction and spiraling of the yarn.



4: Gauze (loomstate). A sample of a gauze (crossed warps) fabric as it comes from the loom.



5: Gauze (finished). The gauze fabric shown in Fig. 4 after wet finishing. Spontaneous spiraling movements of the yarn are responsible for the pleating that has developed.

> it is not only the *growth* of the individual cells, but the *traction* exercised on one another through their mutual interconnections, which bring about foldings and wrinklings and other distortions of the structure (Thompson 1942: 84).

To extend such analogies of growth in physical and biological systems to processes of designing and making is to raise the question of intentionality. While designing, I am constantly responding to the material, aiming to work *with* it rather than rigidly imposing a preconceived idea. This is not to say that I see myself as passive, at the mercy of physical forces, because I bring ideas to the process. It seems necessary to see designing and making as an emerging process to make sense of the interactive relationship between the practitioner and the material. In the remainder of this paper I want to consider the ways in which D'Arcy Thompson's dynamic view of form can be seen to have anticipated modern ideas about emergent processes both in biology and design.

Preformation versus Formation

When *On Growth and Form* was first published in 1917, Thompson already appeared to be swimming against the tide of modern biology. He expressed views opposed to aspects of Darwinian theory and genetics, and as the century progressed, his isolation on many issues became more noticeable. The discovery of the structure of DNA promoted a view of the genes as a specification for the organism and this approach has culminated in the genome project. But now the tide is turning; D'Arcy Thompson's ideas seem prescient since, from the middle of the 20th century, another scientific paradigm has been gathering pace. A rapidly growing body of work on emergent properties and self-organising systems now offers an alternative approach, closer to Thompson's idea of *underlying principles* shared by both inorganic and organic nature. Viewing form in dynamic terms, as an emerging process, this approach offers a useful corrective to current tendencies towards preformationism both in biology and design.

A crucial aspect of Thompson's view of form is his emphasis on *energy* and therefore *process*, rather than simply material.

> Morphology is not only a study of material things and of the forms of material things, but has its dynamical aspect, under which we deal with the interpretation, in terms of force, of the operations of Energy [...] the common language of the books seems to deal too much with the *material* elements concerned, as the causes of development, of variation or of hereditary transmission. Matter as such produces nothing, changes nothing, does nothing; [...] we must most carefully realise in the outset that the spermatozoon, the nucleus, the chromosomes or the germ-plasma can never *act* as matter alone, but only as seats of energy and as centres of force (Thompson 1942: 19-20).[2]

This emphasis on the importance of energy in the creation of form favors the idea of an emerging process, and contrasts strongly with the preformationist account of form that has become the norm. An increasing number of workers have become dissatisfied with the preformationist approach. Within this dominant approach, as Goodwin has put it,

> Organisms, those familiar plants and animals, including ourselves, that we see all about us [...] have disappeared as the fundamental units of life. In their place we now have genes, which have taken over all the basic properties that used to characterize living organisms (Goodwin 1994: 1).

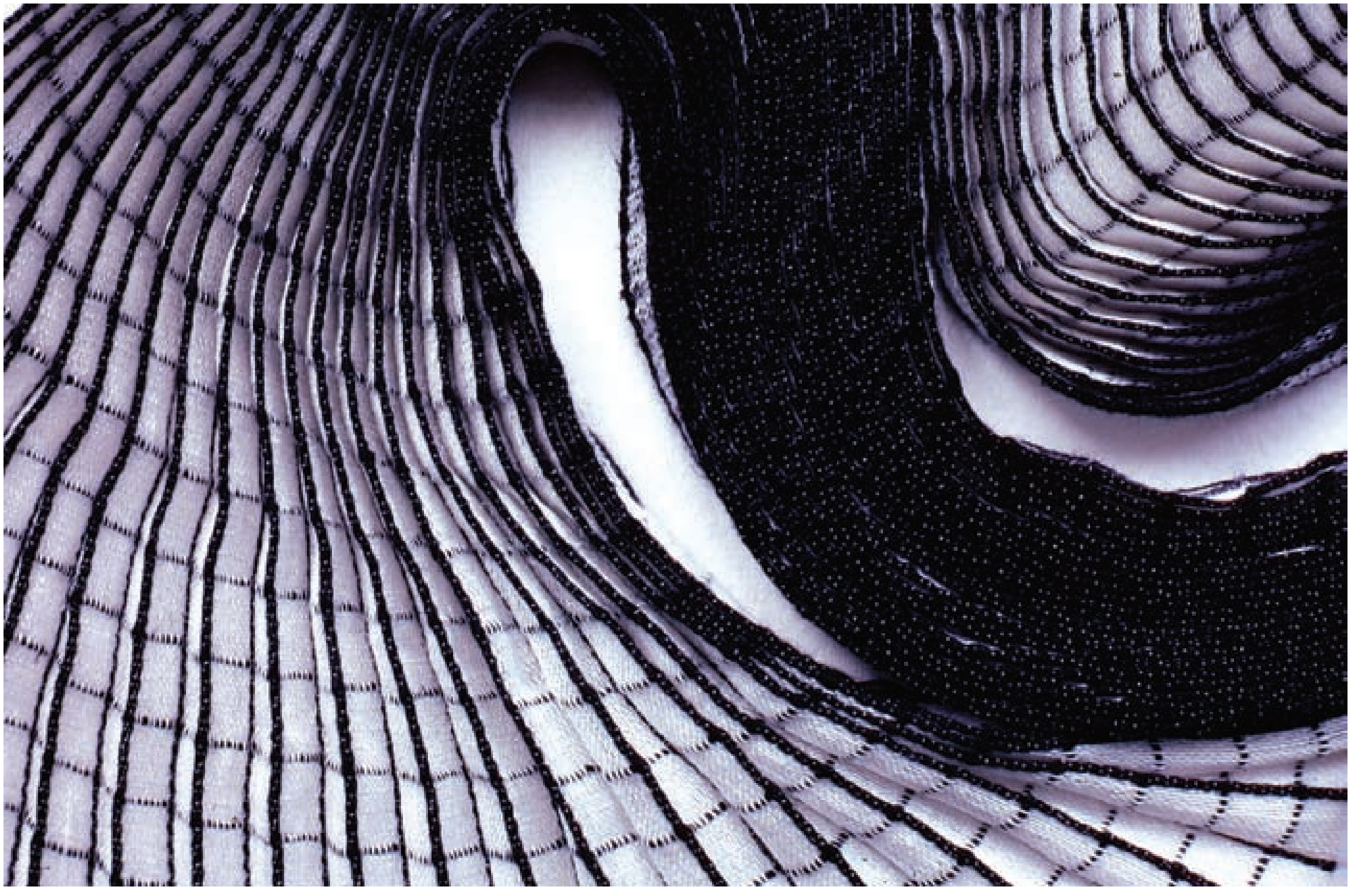
An equivalent situation has developed in design. Just as genes have come to be seen by some biologists as more real than the organism itself, there is a risk of the 'design' being viewed as more real than the object. As in biology, this approach has not gone unchallenged. Hulme, writing about garment design, contrasted two conceptions of design: that of the artist who "conceives of design as a drawing on a sheet of paper," with that of the industry which "takes the view that true design is the production of the garment itself" (Hulme 1948: 16).

This contrast between design as preformation and design as a *process* clearly relates closely to conflicting views of form in biology.[3] This resemblance is made more noticeable by the tendency of both designers and biologists to take ideas from one another as metaphors for their own practice, often transforming these in the process. The 'blueprint', originally referring to a drawing that dictates how a building will be constructed, has been widely applied to DNA, which is now often referred to as the 'blueprint' for the organism. In the hands of biologists, this term has come to suggest a much tighter specification than most designers would attribute to a real blueprint. Thus transformed, the new image of DNA is ripe for re-importation into design, to create further confusion.

For example, a strongly preformationist use of DNA as a metaphor, in the field of textiles, can be found in the ideas of Dass. She works extensively with computer programs and suggests that these could be used to generate new weave structures on the basis of an analogy with the replication of DNA. In her view,

> Weave is no longer simply a result of a realization process [...] but can be understood by its own conceptual development and by its power to transform its own form by infinite generative mutations (Dass 1996: 49).

As something of an afterthought, she suggests that "successful weaves can be realized in material form, thus providing a physical record of the particular weave species." But this begs the question of which designs are indeed successful, when none of them has been tested as real objects. This proposal suffers from the same weakness as a preformationist approach in biology, namely, a disregard for the totality. After all, weave structure in fabric design, like the genotype in organisms, is only one factor in the complex process of creating form. Anni Albers, a weaver at the Bauhaus, perfectly captures the interactive nature of weave design by emphasizing the importance of *both* material and structure. As she says, "the interrelation of the two, the subtle play between them in supporting,



6: Dragonfly Pleat. A fabric based on a natural form (the pleated structure of dragonfly wings). The release of energy from the high-twist yarns has created the form of this textile.

impeding or modifying each others characteristics is the essence of weaving" (Albers 1965: 38). She further stresses the weakness of attempting to impose a design without reference to the material.

> Designing today is indirect forming. It deals no longer directly with the material but vicariously: graphically and verbally [...] The material itself is full of suggestions for its use if we approach it unaggressively, receptively (Albers 1961: 6).
>
> A design on paper cannot take into account the fine surprises of a material and make imaginative use of them. (Albers 1961: 13)

Albers can been seen as an early critic of the preformationist approach. As time has passed, she has been joined by others, both in biology and design, and there seems now to be an increasing willingness to contemplate the complexity of an idea of form as an emerging process. For example, Goodwin argues for an 'organocentric' approach in biology, paying tribute to D'Arcy Thompson's work in shifting the focus from natural selection and inheritance "to creative emergence as the central quality of the evolutionary process" (Goodwin 1994: xiii). Oyama has also been a prominent critic of the preformationist account of the development of biological form, proposing instead a "constructive interactionism" to describe the relation between genes and environment (Oyama 2000).

On the designing/making side, the ideas of the anthropologist Tim Ingold seem to be heading in the right direction. This is how he contrasts the different viewpoints, drawing an analogy between biological form and the activity of skilled making.

> the form of an organism is said to be given in an evolved design specification, the genotype, in advance of its 'phenotypic' expression in an environment. And in modern architecture the form of a construction is supposed to exist in miniature, in models, drawings and plans, before any building work begins. To take this view, however, is to deny the creativity of the very process of environmentally situated and perceptually engaged activity, that is of use, through which real forms emerge and are held in place. It is the activity itself – of regular controlled movement – that generates the form, not the design that precedes it (Ingold 2000: 354).

Some forms of work are more suited to this improvisatory approach than others. A good account, by someone who is a designer/maker rather than a theorist, is given by the potter Elizabeth Fritsch in a radio interview.

> Well, I don't do any drawings in advance and I discovered when I was collaborating with three jazz people who – they work on their technique to a very high level and then they just improvise in a performance – that I was actually doing the same thing but on a much longer time scale. Once I start a piece of work – you know, I've had some creative ideas flowing – and then once I start on a piece of work, I let the work itself control what happens. And I try not to think too hard about it while I'm actually making it (Fritsch 2001).

In the light of such an account of making, by a practitioner, Ingold's view is persuasive in many ways, but I believe it gives too little weight to the *ideas* of the maker. Although he acknowledges that, for example, a basket-maker may begin work with "a pretty clear idea of the form she wishes to create", he claims that the form of the basket does not, in any sense, come from this idea, but that "the form of the basket emerges through a pattern of *skilled movement*." This raises the question of the meaning of the term skill. David Pye makes a useful point when he draws a distinction between skill as dexterity and skill as 'know-how' for, as he says: "know-how, in making, is design" (Pye 1979: 52).

He gives the example of dry stone walling, pointing out that, in his terms, anyone has the skill to build such a wall but few know how to *design* one,.

> In that work the so-called 'skill' is in deciding what shapes and attitudes will be allowable in the stone destined for some particular position, not in recognizing a stone which has the shape already in the mind's eye nor in putting it in the envisaged attitude (Pye 1979: 52).

The ability of the designer/maker to judge what is *allowable* is crucial to design as a dynamic, emerging process. At present, two viewpoints seem to be in conflict: on the one hand there is a view of design that gives absolute primacy to the *idea* and on the other, in reaction to this, a view of human activity as situated action, which seriously downplays the importance of plans and designs. As a corrective to preformationism, I am sympathetic to this view, but I think it goes too far.

In designing and making, I would consider that form is generated *both* by design in Pye's sense of know-how and decision and also by active engagement, as Ingold describes. Only in relation to the worker's overall intention (which might well indeed change) can decisions be taken that influence the direction of growth of the form. The worker's active engagement implies a constant reassessment of the state of things - as to whether the work is going badly or well - which would be meaningless in the absence of any idea of the form that is desired. To say this is not to imply that the form *pre-exists* in the mind's eye or in a blueprint, but is to emphasize the importance of plans and designs as a resource for action (see Leudar and Costall 1996).

Understanding the relationship between planning and action in human activity is essential to making sense of the processes of designing and making. An adequate account of the designing and making of artifacts must encompass both the intentions of designers – the plans and blueprints that are such a useful resource for action – and the active engagement with the material that produces (usually rather different) artifacts. In addition, even an extensively 'planned' object may be further transformed by the active engagement of users. The architect Gustavo Ribeiro describes urban form as "a dynamic entity in continuous change through certain patterns of use" (Ribeiro 1997). This view does not disregard the importance of planning but sees urban form as arising both through planned and unplanned activity. As Ribeiro points out,

> While many interventions in such settlements may be planned (blueprints, building regulations, verbal descriptions given to master builders, culturally derived building typologies, etc.), the evolution of the vernacular fabric itself is essentially the result of unplanned people/environment interactions in the course of many years – often centuries. The case of York, England, for instance, like that of other colonial vernacular settlements, illustrates how an originally rationally planned Roman fortress (ca. 71 AD) can assume an organic configuration through its interaction with successive groups of users (Ribeiro 1997: 291).

Conclusion

An adequate account of the designing and making of artifacts must encompass *both* the intentions of designers and their active engagement with the material. In arguing for such an interactive view of the design process, I find myself in full agreement with D'Arcy Thompson, when he explains his real purpose in writing *On Growth and Form*. His aim was to redress a balance of explanation in biology that had shifted too far in the direction of final causes:

> Time out of mind it has been by way of the 'final cause', by the teleological concept of end, of purpose or of 'design', in one of its many forms...that men have been chiefly wont to explain the phenomena of the living world (Thompson 1942: 4).

But Thompson insisted that his intention was not to "refer all natural phenomena to mechanism and set the final cause aside," but rather to argue for a balance of these different explanations. In a similar way, I am arguing for a recognition of the importance, in design, of both idea *and* process. For me, this view is perfectly encapsulated by Thompson's apt metaphor of a woven textile,

> like warp and woof, mechanism and teleology are interwoven together, and we must not cleave to the one nor despise the other; for their union is rooted in the very nature of totality (Thompson 1942: 5).

Notes

[1] This paper was previously published in *Arch+* in 2002 under the title "Ein Kräftdiagramm" and in *Textileforum* in 2003 under the title "Form as Formation in Nature and Design." Permission has kindly been given for it to be reprinted here.

[2] More recently Lewontin seems to have unconsciously paraphrased this idea: Genes 'do' nothing, they 'make' nothing, they cannot be 'turned on' or 'turned off' like a light or a water tap, because no energy or material is flowing through them (Lewontin 2000: xiii).

[3] Ingold draws the analogy between biology and designing/making very clearly,

> Now it is very often assumed, in the study of both organisms and artefacts, that to ask questions about the form of things is, in itself, to pose a question about design, as though the design contained a complete specification that has only to be 'written out' in the material […] Thus it is supposed that the basic architecture of the organism is already established, as a genetic 'blueprint', from the very moment of conception; likewise the artefact is supposed to pre-exist, fully represented as a 'virtual object' in the mind, even before a finger has been lifted in its construction. In both cases the actualisation of the form is reduced to a simple matter of mechanical transcription: all the creative work has already been done in advance, whether by natural selection or human reason (Ingold 2000: 343).

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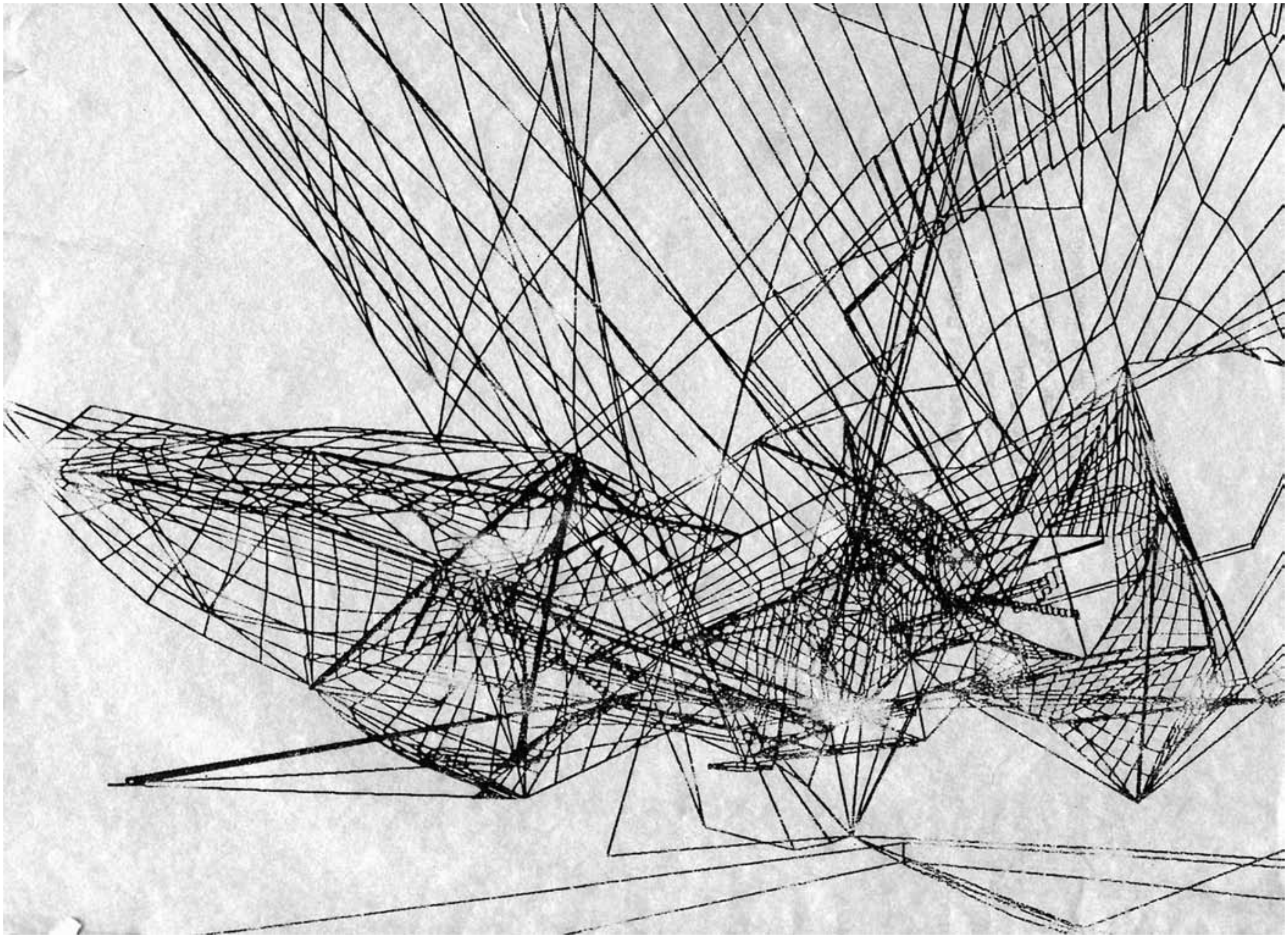
Note: All textiles and photographs are by the author.



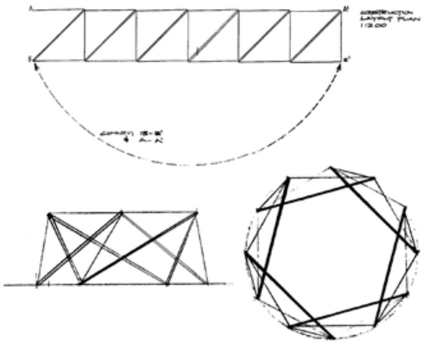
1: Simon Taylor, *A Quest for Romantic Technology*, M.Arch. thesis, University of Waterloo, 1993. Cover image.

Tensegrity Complexity

Thomas Seebohm

In 1993, in a final thesis in the Bachelor of Architecture program at the University of Waterloo, Simon Taylor investigated the properties of tensegrity structures by developing various two-dimensional topologies of wooden struts and elastic cables that would, when released, form three-dimensional tensegrity structures (Taylor 1993).The types of tensegrity structures were those defined by Buckminster Fuller, who coined the word as a conjunction of the words tension and integrity. In Fuller's tensegrity structures, struts are always separated from each other by tension members (tension members are referred to as cables or tendons below). Of particular interest in Taylor's study was his conclusion that tensegrity structures with prime numbers of struts (that is, numbers that are not divisible by any other number) behaved oddly and did not form symmetrical structures. When these odd structures were combined into multiples of odd structures he predicted that the behaviour would be regular resulting in symmetrical structures. He also speculated that it would be possible to arrange groupings of simple strut configurations in such a way that groups of struts were arranged in the same way that individual struts in simpler stuctures are arranged. In other words, the structure appears the same at different scales. Or to put it yet another way, where individual struts are located in simple tensegrity structures, more tensegrity structures of the same type as the overall structure appear on zooming in with the view. This is exactly what fractal behaviour is about. Again he speculated what the behaviour of these complex fractal structures would be. Would they become chaotic with prime numbers of struts or groupings of struts?

Simon Taylor developed his study entirely on the basis of these physical models because neither he nor I were able to locate any analytic means or software to extend and verify his conclusions. The physical models required for verification were just too labour intensive to carry out. The conclusions from the thesis languished in my mind. No one I asked was able to solve the problem of how to go from a two-dimensional topology of struts and cables to the corresponding three-dimensional structure that would result when released. Until 2001, that is, when I discovered the Struck software by Gerald de Jong through a reference on the Web. The software was freely available for downloading on the Web (de Jong 2000). It is written in Java and will now run directly on Mac OS X which comes with Java and can run on Windows computers although the Windows Java installation is somewhat complicated. Struck allows one to set up three-dimensional structures of struts and cables (or of generic elements that can both stretch and compress). The interface does not conveniently allow complex topologies to be entered, however. In particular, it is not set up for entering two-dimensional topologies. My innovation is an AutoLisp program that allows one to draw two-dimensional topologies of struts, cables and links (cables that



2: Simon Taylor, (above) Six-strut, single layer topology; (below) elevation and plan.

link the ends of flat topologies thereby making them three-dimensional when released) and then creates the input in the form of an Elastic Interval Geometry (EIG) file for Struck. The combination of Struck and the AutoLisp program finally has provided the solution that eluded me for a decade. Struck iterates until the two-dimensional topology is transformed into a three-dimensional tensegrity structure, if the structure is stable. So far, whenever there is a stable solution, Struck has iterated to the stable shape very quickly. It is quite dramatic to watch Struck iterate to a solution. For those who are able to adjust their eyes appropriately, it is even possible to watch the iterations and the final structures in stereo.

Since the presentation of the original paper I have become aware of the considerable research on tensegrity structures that has been conducted since Snelson introduced these structures and the popularization by Fuller particularly in the last thirty years. Motro gives an overview of the state of the art (Motro 1992) where he mentions some work on form-finding, the term used in engineering circles to find the form or geometrical configuration of structures whose shape depends not only on geometry but also on a balance of forces among self stressed members. Most of the work on form finding for tensegrity structures is very recent as noted in the paper by Tibert and Pellegrino where different classes of form finding methods are reviewed (Tibert and Pellegrino 2003). As will be explained, the method used by Struck for form finding is related to the force density method described by Tibert and Pellegrino but different in its iterative, computational solution. After the original presentation of this paper I was fortunate to meet Walter Whitely who has done considerable mathematical analysis on the stability of tensegrity frameworks (Whitely and Roth 1982) and their relation to sheet structures (Whiteley 1987). In what follows stable tensegrity structures are those described by Connelly and Whiteley as pre-stress stable (Connelly and Whitely 1992).

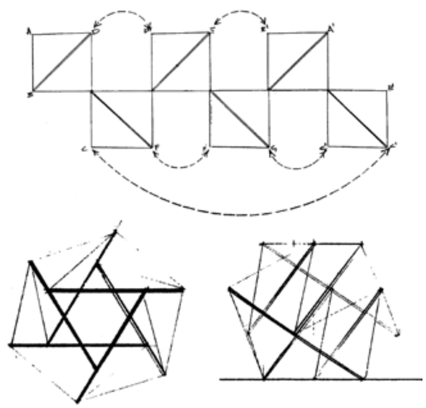
In spite of the above considerable research, Taylor's conjectures and findings, represent, I believe, new contributions to the field. His research, and research on tensegrity structures in general, is becoming increasingly important not only because of the possibility of constructing light-weight architectural structures but because tensegrity structures appear to be the bases of living organisms at the scale of proteins (Caspar and Klug 1962), where extra molecular forces provide the tension members, in cellular structures and in the muscle-skeletal systems of mammals and birds (Ingber 1998).

Tensegrity deformation, which has promise for deployable structures, is also the basis of locomotion in animals and humans. This is the direction that de Jong and others are pursuing by developing simple tensegrity systems in which the tendons flex (de Jong 2006). Indeed Struck already has this capability to apply oscillating stresses to the tendons. It also appears that in animals and humans everything is actually in continuous oscillatory motion (Gleick 1987). It is natural, therefore to wonder about the stability of oscillating tensegrity networks. Can motion deflect a tensegrity structure from returning to its stable position? Can the structure deflect to another, alternate stable position? Is it possible to have chaotic behaviour and no stable position under certain conditions? All of these issues were touched on by Simon Taylor's thesis and are explored below using the AutoLisp and Struck software combination to examine what Taylor was not able to do with physical models because of the limited complexity that he could deal with. While I have been able to examine Taylor's conjectures below in a more rigorous manner, the exposition is still a work in progress.

Generating Complex Tensegrity Structures from Two-Dimensional Topologies

Layer Topology

When Taylor first began building physical tensegrity structures he used a method he called the layer system whereby struts and elastic tendons are laid out flat in a row (layer) and then, after each end of the row is connected with additional tendons, a three-dimensional tensegrity structure jumps into shape. Fig. 2 presents illustrations from his thesis showing a six-strut, single layer tensegrity structure and its flat topology. A two-layer, six-strut topology and the resulting structure, also from Taylor's thesis, are shown in Fig. 3. Taylor noticed that when the layers contained more than six struts, the resulting structures were not very stable because they easily collapsed on themselves. He reasoned that this was due to the fact that the difference between tendon and strut lengths was small. In other words, there was not much triangulation for stability. Taylor also discovered two other flat topologies that turn out to be the ones called the circle and the zigzag pattern by Pugh (Pugh 1976). After explaining Struck and the AutoLisp program that is used in conjunction with Struck, the results of applying Struck to various two-layer topologies is demonstrated in what follows.



3: Simon Taylor, (Above) Six-strut, two-layer topology; (below) plan and elevation.

The Need for an Analytic Approach

As noted there is a need for an analytic approach to the study of tensegrity and Taylor's conjectures because of the limitations of the complexity of the physical models that he could build. In particular, a form-finding solution was needed that could iterate to the final solution not just from a topology that was close to the final form but from the flat topologies that Taylor was using to develop his tensegrity structures and speculations. The Struck software provides the type of iterative form-finding solution that is needed to find the three-dimensional form resulting from a two-dimensional topology.

While no detailed description of the analytic method used by Struck is available, its method can be deduced from watching the iterations and from what de Jong has stated on the Struck Web site (de Jong 2000). It appears that, at each node, the net force is calculated from the compressive and tensile forces in the struts and cables acting on that node and the node is then moved a distance in the direction of the net force, most likely in proportion to the magnitude of the force. The number of nodes that will be moved in one iteration or tick is variable. The tensile or compressive force in the struts and cables depends on how far they have been stretched or compressed, respectively, from their at rest length. Gerald de Jong gives the force in a cable in tension as

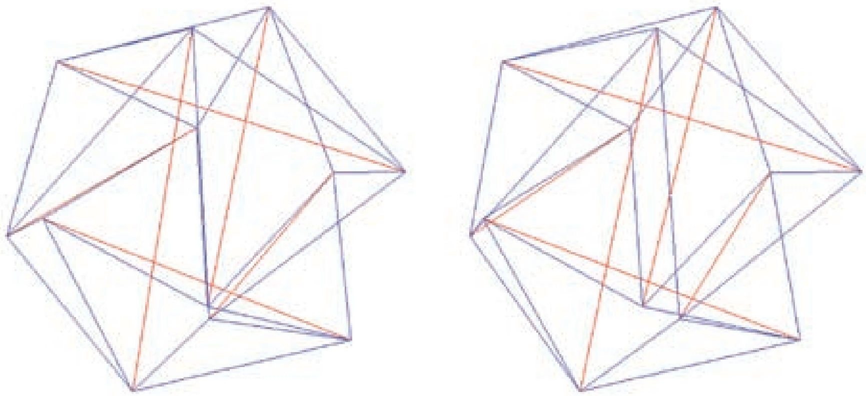
PullInward = log (Actual Span) – log (RestSpan)(de Jong 2000)

The same relation is used for compressive forces in a strut, in which case the compressive force will be negative. In a more mathematical formulation with r being the at rest span and Δr being the change in length from the at rest span, the pull inward or outward, F, can be written as

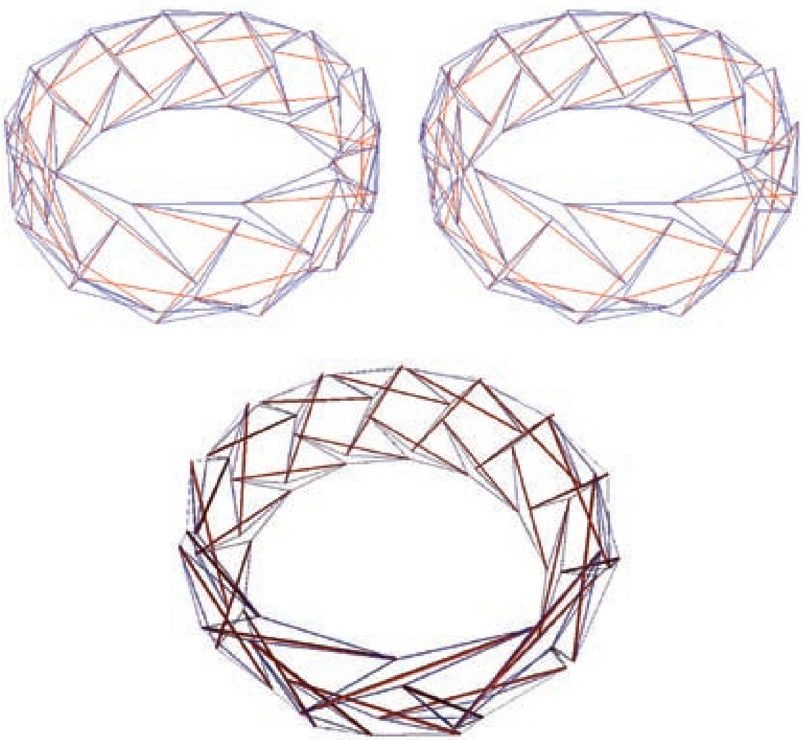
$$F = \log(r + \Delta r) - \log(r)$$
$$= \log(r + \Delta r)/r$$
$$= \Delta r/r - (\Delta r/r)^2 + \ldots\ldots\ldots\ldots \text{ as a series expansion.}$$

For small Δr in comparison to r the force, F, is proportional to $\Delta r/r$, which is Hooke's law and approximates the linear stress-strain behaviour of metal rods and cables when not overstressed. When Δr is negative and approaching r in magnitude, as in a tightly compressed spring, the compressive force in this logarithmic relation becomes very large. In other words, a spring with this stress-strain relationship will strongly resist compression as it is compressed towards zero length. Additionally, de Jong wanted the force relationship to be such that a spring (cable) elongated by half its length would be subjected to a tensile force equal to a compression force in a compressive member (strut) that was equal to the tensile force. It turns out that this is not exactly true for de Jong's logarithmic stress-strain relationship but close enough. It appears that the actual stress-strain relationship used to calculate the force in the struts and cables is immaterial to the shape of stable tensegrity. That is, the actual stress-strain relationship does not influence the stable geometric configuration because it depends only on geometry. It is possible, however, that non-linear stress-strain relationships (where the stress is not proportional to strain but in a more complex relationship such as de Jong's logarithmic relationship or a quadratic relationship) may influence how a configuration approaches stability. We will come back to this topic at the end. Struck also provides a damping factor that one can adjust to dampen wildly fluctuating iterations but it is not clear how that is done (damping results in a force proportional to the velocity at which a node moves, or would like to move in an iteration resulting in less distance moved).

The Struck interface, as noted, provides no way to enter flat tensegrity topologies to which form-finding can be applied to determine the geometric configuration of the stable configuration if one exists. The key to making flat topology input possible (indeed any kind of topology) lies in the format of the input EIG files. These are text files easily opened in a text editor. The files use an XML type encoding that is easily deciphered. The solution to the input problem was to write an AutoLisp program that would read an AutoCAD drawing with the flat topology and produce as output an .eig file. When drawing the topology in AutoCAD one must make sure that struts are drawn on a strut layer, cables on a cable layer (there is more than one in case there are cables with different initial lengths) and links are drawn on a link layer, links being the cables that tie opposite ends of the layer topology together). In addition, one must make sure that the ends of struts, cables and links snap into common nodes by drawing on a snapping grid.



4: Six-strut, two-layer tensegrity structure in Struck stereo view.



5: 36-strut, three-layer tensegrity structure in Struck stereo view (top); SpringDance view (bottom).

The AutoLisp program sets default values for the at-rest length of the cables, struts and links but these can be changed in the Struck interface once an EIG file is loaded.

Fig. 4 shows the six-strut double layer topology of Fig. 3 in Struck after the iterations have converged on a stable geometric configuration identical to Taylor's and others. Since Struck was developed, another piece of software, SpringDance, has been developed with the same intent as Struck but not with all the functionality. SpringDance has been written explicitly for Windows interfaces by Alan Ferguson (Ferguson 2006). SpringDance will not, however, iterate from a flat topology to a three-dimensional configuration. It will only iterate to the flat, stable configuration if there is one. Struck, in contrast, will first iterate to the flat stable configuration and then, slowly, will begin iterating out of the plane into the third dimension. It is not clear why Struck has this ability while SpringDance does not. In any case, SpringDance has the useful ability to show a three-dimensional image of a tensegrity structure represented in an EIG file produced by Struck in which the struts are represented by thick cylinders and the cables by very thin ones making the resulting image much clearer (Struck can only distinguish between compression and tension members by showing each in a different colour: red for compression and blue for tension). Fig. 5 shows a three-layer, thirty-six strut flat tensegrity topology after it has stabilized in Struck and in SpringDance (To view the Struck images in stereo one must cross one's eyes so that the two images come together and ignore what the eyes see in the periphery). This configuration takes a long time to iterate to a stable configuration. Long iteration times are usually related to configurations that are not very stable. That is, they are easily deflected from their stable configuration in agreement with Taylor's observation of layer topologies with more than six struts.

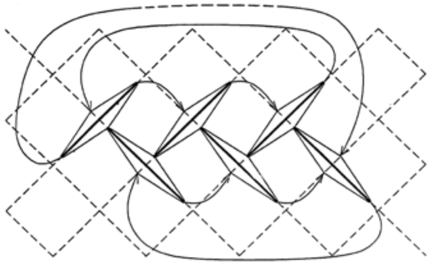
The Effect of Prime Numbers of Struts and Fractal Behaviour

After Taylor had built quite a few different tensegrity structures he noticed that all were multiples of four or six struts. Determined to find out what happens to tensegrity structures with numbers of struts falling between these numbers, he found that some of these structures behaved differently from the others. To make these structures stable, "tendons were having to double up". The configurations that were problematic were those with seven, thirteen and nineteen struts. Taylor produced a table summarizing his findings concerning patterns and discrepancies as redrawn in Fig. 6.

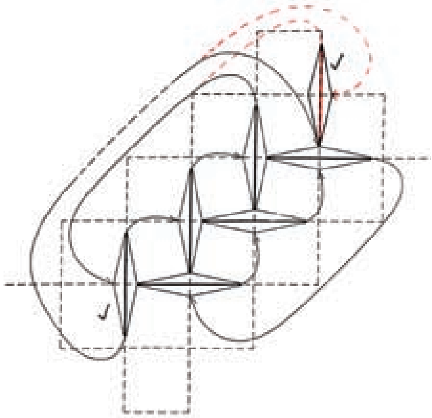
For the prime number configurations he shows the numbers of tendons for which the structure is unstable. Adding one more, that is, causing doubling up of tendons, brings the structure back to stability but not symmetry. It occurred to Taylor that this deficiency in the pattern of odd structures with prime numbers of struts compared to those whose numbers of struts were not prime might be corrected by joining deficient structures together so that as he put it "so that they in fact share the properties that they are lacking when alone". Or one could think of the prime numbered structures has having an extra cable (or unattached bond in the sense of molecules) that could be used to join structures with prime numbers of struts together to make them whole. It occurred to Taylor that the

No. of Struts	No. of Tendons	No. of Eq. Tri.	No. of Squares	No. of Sep. Surf.	No. of Degrees	No. of Tri. Surf.	Deviant Y/N
6	24	8	0	20	3600	20	N
7	27	6	2	22	4320	24	Y
8	32	8	2	26	5040	28	N
9	36	8	3	29	5760	32	N
10	40	8	4	32	6480	36	N
11	44	8	5	35	7200	40	N
11 two layer	43	9	1	34	7200	44	Y
12	48	8	6	38	7920	44	N
13	51	6	8	40	8640	48	Y
Patterns	Strut. No. x4	8	Prev. +1	Prev. + 3	Prev. +720	Prev. + 4	N

6: Regular and deviant configurations of tensegrity structures after Taylor



7: Horizontal diamond pattern for a six-strut, two-layer topology



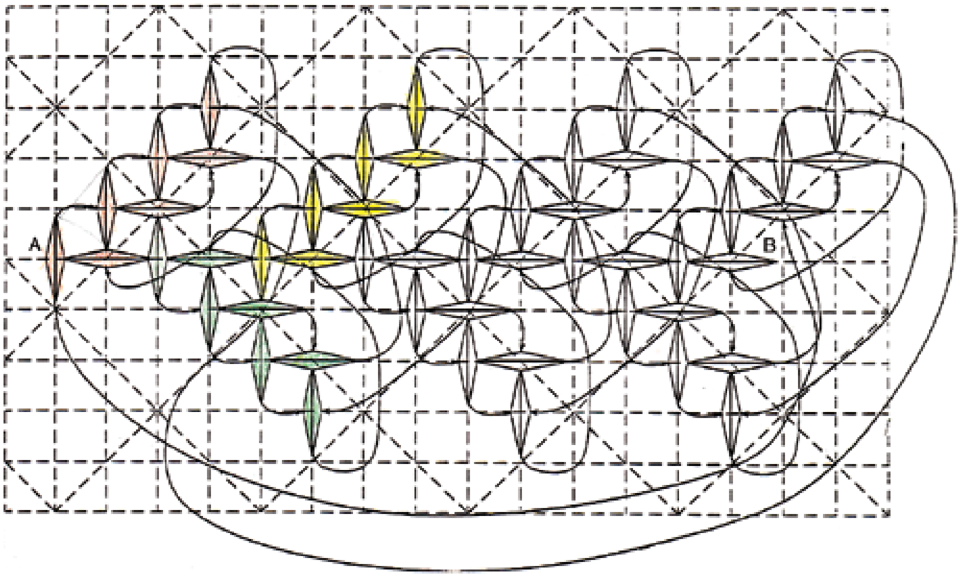
8: Diamond pattern at 45 degrees for a seven-strut, two-layer topology

principle for joining the deficient structures together might be that of fractals where what occurs at one scale is repeated at a larger scale. In other words, the way single deficient structure is connected together with cables is repeated at the next level of scale at which structures at the first scale are connected together at the next scale.

In order to pursue this line of reasoning Taylor switched to the diamond pattern for representing the earlier square layer pattern as shown in Fig. 7 for a six-strut pattern. Fig. 8 shows the seven-strut topology drawn in the same way. The dashed lines show how the seven-strut configuration is obtained from the six-strut version by redirecting certain cables as shown by the red dashed lines. The two cables with a check mark are the ones that are actually duplicates. That is, they join the same end points.

Fig. 9 shows how Taylor connected seven sets of seven tensegrity structures together to make a forty-nine-strut structure. Note that he neglected to show the cables linking points A and B. The way Taylor connected the seven sets together reflects the way individual structures of seven struts are connected together. That is to say, in the interior of each structure each strut is connected to four neighbours and the last strut is connected back to the first. This pattern is demonstrated in Fig. 9.

After reflecting on what he had accomplished, Taylor realized that this method of connecting smaller tensegrity units into larger ones was not restricted to structures with odd numbers of struts. Fig. 10 shows how Taylor's method also works for six structures of six-strut tensegrity structures.Although, Taylor's method of connecting smaller units into larger units involves connecting interior structures to four surrounding structures, it seemed to me that his pattern did not quite follow how the struts were connected together in the smaller units in that there was a line of connections running on the outside of the structures from one to the next strut rather than crossing over to the opposite side as in



9: Simon Taylor, Seven sets of seven topology.

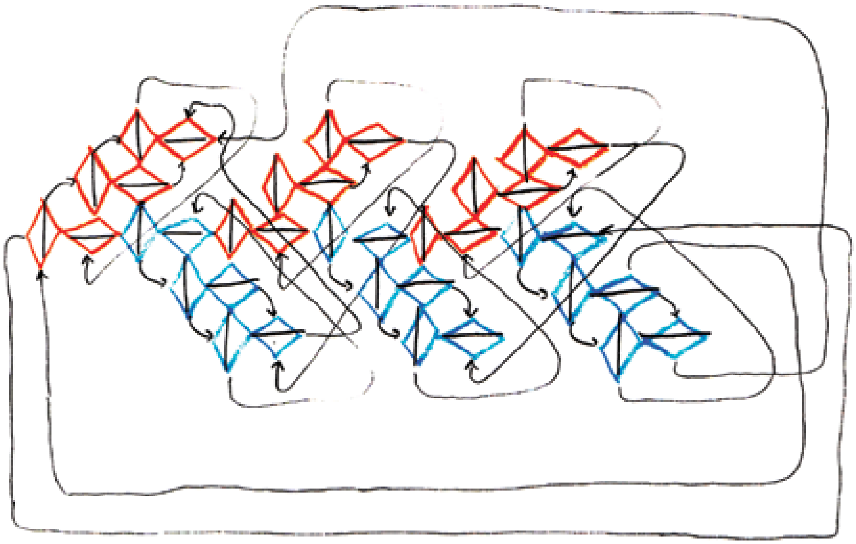
Taylor's. Fig. 11 shows the author's version without connections crossing over.

Iterating over the topologies for six sets of six and seven sets of seven produces the following results: Of the two sets of six sets of six only Taylor's topology resulted in a stable geometric configuration as shown in Fig. 12 in stereo as displayed by Struck and and SpringDance. Of the two sets of seven sets of seven both topologies by Taylor and the author resulted in stable configurations but the author's is completely chaotic, though more spherical, while Taylor's is more orderly and ring-like but asymmetrical as shown in Fig. 13. While both of the seven sets of seven topologies are stable they are clearly asymmetrical. They are also not very stable because they took a long time to iterate to a stable configuration.

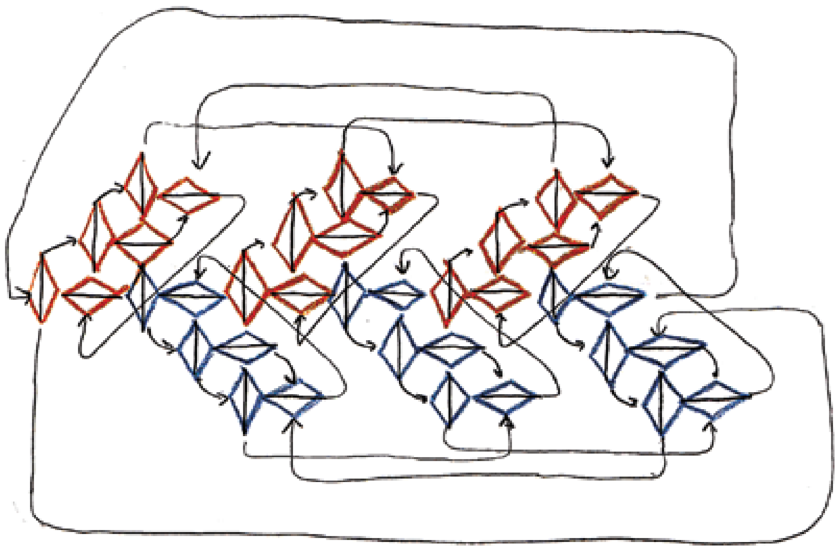
Discussion

In this section Taylor's hypotheses are considered and whether or not they have been confirmed by form-finding software, in this case, the AutoLISP-Struck combination. In the conclusions we will then consider some larger implications.

The hypothesis that double layer tensegrity structures with prime numbers of struts are asymmetrical and only stable if tendons are doubled up between two particular nodes was easy to confirm for seven struts. While cases with thirteen and nineteen struts



10: Six sets of six Taylor's topology.



11: Six sets of author's typology

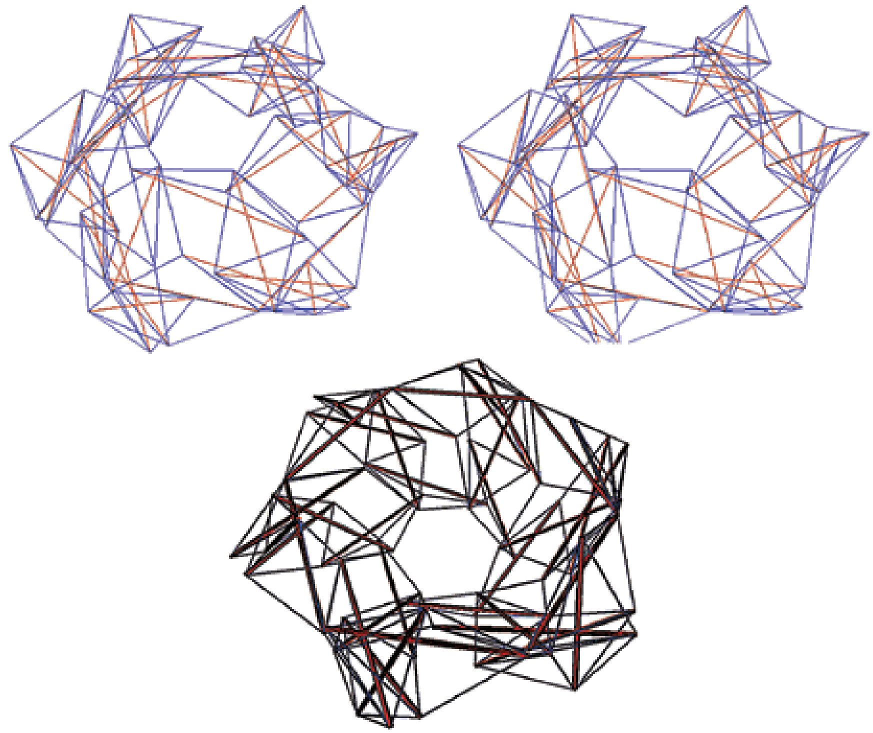
have not been tested, it is assumed that similar confirmation will be obtained given that Taylor actually built these structures. Note that a configuration with three struts is stable without double tendons but this is not a double layer structure.

It was also confirmed that it is possible to connect small double layer tensegrity structures in a manner similar in principle to the way individual struts are connected together to form larger tensegrity structures in the manner of fractals where what appears at one scale is repeated at higher scales. If the individual double layer structures that make up the larger structure have a non-prime number of struts (as in six structures of six struts) the result is a symmetrical structure. Not all such interconnections of smaller units into larger ones produce stable structures but Taylor had an intuitive sense of what would be stable. Connecting together double layer substructures with an odd number of struts (seven sets of seven struts) resulted in a stable configuration also but an asymmetrical one. Contrary to Taylor's prediction, asymmetrical behaviour at the smaller scale is repeated at the larger scale although the doubling up of tendons disappears. There is more than one way to connect subunits together as was demonstrated with one configuration that was chaotic in appearance but stable. There may be yet other ways to connect subgroups more literally in keeping with the way individual tendons are connected in the subgroups but the author has not succeeded in this. Taylor was therefore correct in surmising that he had found a fractal method of building up larger tensegrity structures.

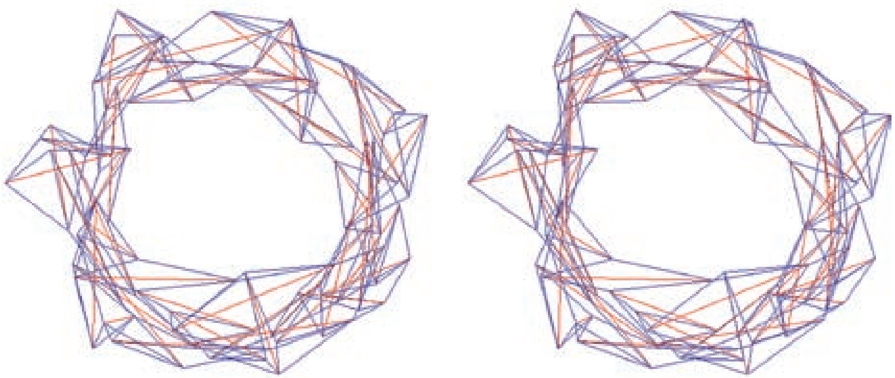
The principle that the greater the number of struts the less stable is the structure was confirmed by the length of time configurations took to iterate to a stable configuration. Now one might well ask if the way configurations oscillate in Struck when they iterate towards a stable configuration (or not) is actually representative of what such tensegrity structure would do physically. The answer is yes if one considers each node to have an identical mass located there (but the rods and cables are without mass). The reasoning is as follows assuming no damping for simplicity. At each node the force balance is $f = ma$ where f is the net force acting on the node due to the cables and struts connected there, m is the mass at a node and a is the acceleration at the node in the direction of the net force. Integrating this equation gives, $\Delta s = f\Delta t^2/m$, where Δt is the time interval of one iteration and Δs is the distancethe node moves in the time interval Δt. That is, the distance moved is proportional to the net force acting on the node during time interval Δt assuming the force is constant over the interval (it is also proportional to the mass, m, but his does not change and is the same for all nodes). This is exactly what Struck appears to be doing, namely, moving the nodes at each time interval a distance proportional to the net force.

Conclusions

Having summarized what can be confirmed of Taylor's hypotheses with form-finding software, consider now some wider implications. The demonstration that tensegrity structures can be built up in the manner of fractals with the same structure appearing at multiple scales, naturally leads one to wonder if there are other characteristics normally



12: Six sets of six tensegrity structure in Struck stereo view (top); and in SpringDance (bottom).



13: Seven sets of seven tensegrity structure using Taylor's topology in Struck stereo view.

associated with fractals that one should be looking for. The question is all the more important when one considers that in nature nothing is static, all organisms' internal structures (not to mention external ones) are constantly in motion down to sub-atomic scales (Gleick 1982; Wilczek 2006a). If the structures of organisms are based on tensegrity structures as noted earlier, and also oscillating, then one should be particularly concerned if a stable configuration can easily be disturbed to become unstable or if not in a stable configuration, how easily it might be brought back to stability. One of the classic demonstrations of fractal behaviour is the population growth model of Verhulst (Peitgen and Richter 1986) where, depending on the growth parameter, the population converges on a stable population by oscillating about the stable value with smaller and smaller oscillations.If the parameter is increased, it oscillates between two values, then four, then eight until eventually there is no stable value, only chaos. Is it possible that tensegrity structures built up in a fractal manner might, depending on some parameter, exhibit more than one stable state and with further changes of the parameter exhibit chaotic behaviour, never settling down to a stable value? Taylor envisaged this behaviour with his thesis cover shown in Figure 1. In the large fractal-like tensegrity configurations there was an in-between state observed in Struck where a sort of figure eight formed before finally unraveling and converging on the stable configuration. Further research is required to answer this important question. The question is important because tensegrity structures, being basic structural systems of organisms, show the principle of self-organization that seem to be so fundamental in nature. That is, without external influence structures organize themselves into certain configurations.

Now tensegrity systems are non-linear systems which one observes when setting up the form-finding solution by means of simultaneous equations (Tibert and Pellegrino 2003b).This is in keeping with fractal behaviour which is characteristic of some non-linear systems. Another source of non-linearity is the stress-strain relationship that was assumed by de Jong. It was noted that this relationship was linear as long as $\Delta r/r$ the ratio of the change in length from the at-rest position to the at-rest length was small. While this is not always the case in the examples demonstrated in this paper, it is probably close enough to linear not to influence the conclusions of the paper.

While this author is not aware of what the stress strain relationships are in natural systems like the human body, Wilczek points out that the structures of protons which are to ninety percent made up of gluons and quarks, is bound together by field "springs". According to Wilczek, Fermi, in one of his last papers was looking at the stability of structures tied together by non-linear springs. Contrary to what one would expect – that stability, if it exists, is rapidly approached – Fermi found that in systems coupled together with non-linear springs (e.g. stress might vary as the square of the strain rather that in direct proportion) that the approach to equilibrium is not straight-forward at all. There are emergent structures and "collective excitations" that can continue indefinitely. Wilczek points out that "the profound and somewhat nebulous question, central to an understanding of Nature, of how ordered structures emerge spontaneously from simple homogenous laws and minimally structured initial conditions spontaneously began to pose itself" (Wilczek 2006b).

One of the aspects of Taylor's thesis that I have always found so moving was his intuitive feeling for the relationship between abstract analytical concepts such as the role of prime numbers or the way tensegrity subsystems should be connected to form larger wholes and reality. It is not surprising that the most profound questions in the structure of matter and the universe are being approached in this spirit where one wonders to what degree abstract numbers systems still to be discovered might "help us to describe nature" (Wilczek 2006c).

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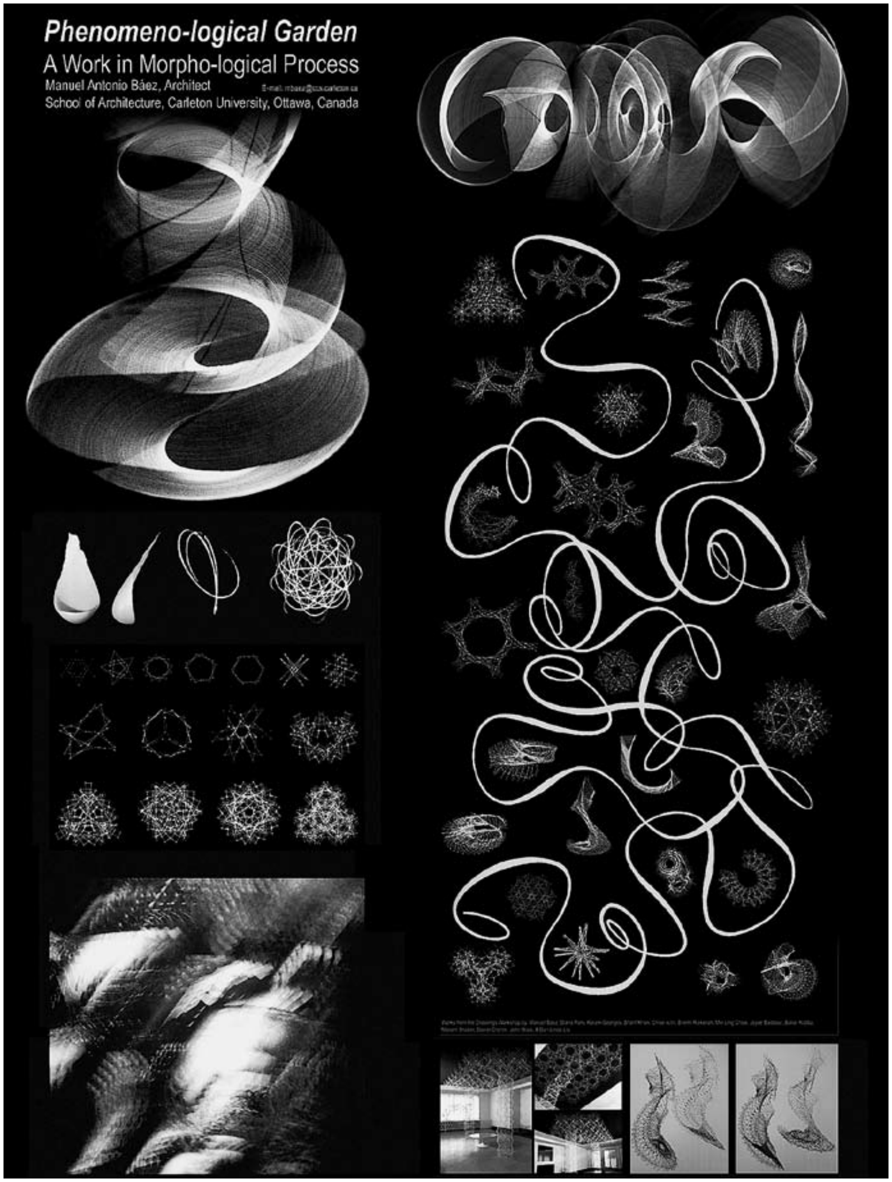


1: Ariadne's Thread/Rumi's Ocean & Suspended Animation Series. (Left column, top to bottom) Three dimensional string formation with shadows; wax-forms, string formations and cellular form studies. (Right column, top to bottom) collaged 3-dimensional string formations; undulating string collage surrounded by cellular form constructions; installation views and shadow 'castings.'

Phenomeno-Logical Garden : A Work in Morpho-Logical Process

Manuel Báez

> Morphology is not only a study of material things and the forms of material things, but has its dynamical aspect, under which we deal with the interpretation, in terms of force, of the operations of energy. [...] I know that in the study of material things, number, order and position are the threefold clue to exact knowledge (Thompson 1992:19, 1096).

Through his descriptions of the forms of the natural world, D'Arcy Wentworth Thompson offers insights into the nature of the processes that generate these forms. They are fertile processes, self-regulating and systematic, and from them emerges the rich realm of the natural world. To understand natural processes of form generation, says Thompson, we must first understand the role played by 'number, order and position'.

This essay discusses a way of constructing forms inspired by Thompson's insights into natural processes, published as *On Growth and Form* in 1917. It explores the form-generating potential of natural processes and searches for the elemental components involved, their integrative properties and pattern-generating capabilities. It uses number, order and position to generate reciprocally-related organizational structures and forms. Such a process is relevant to the study of morphology in architecture by embracing a deeper understanding of complex 'operations of energy' for conceptual and philosophical inspiration.

The Book of Nature

> Philosophy is written in this enormous book which is continually open before our eyes (I mean the universe), but it cannot be understood unless one first understands the language and recognizes the characters with which it is written. It is written in a mathematical language and its characters are triangles, circles, and other geometric figures. Without knowledge of this medium it is impossible to understand a single word of it; without this knowledge it is like wandering hopelessly through a dark labyrinth (Galileo Galilei quoted in Calvino 1988: 83).

In writing of nature as a book that is open to us if only we hold the knowledge to understand it, Galileo reflected a philosophical direction that was emerging in his time. He was also following a more ancient line of speculation about the nature of things in the physical universe. Lucretius' poetic meditation on this topic, *De Rerum Natura*, begins with an evocation of the goddess Venus, who symbolizes the dynamic and creative flows of nature. Philosophers, artists and scientists as varied as Pythagoras, Plato, Leonardo da Vinci, Newton, Leibniz, Goethe, Einstein and Richard Feynman have all contemplated the dynamic nature of the world around them. In the world of letters, the poetry of Wallace Stevens was inspired by this creative power. In such poetic meditations and scientific explanations, we find a profound appreciation and understanding of the importance of number, order and position, the 'threefold clue' which, according to Thompson, establish the pattern and relationships between things in the natural world.

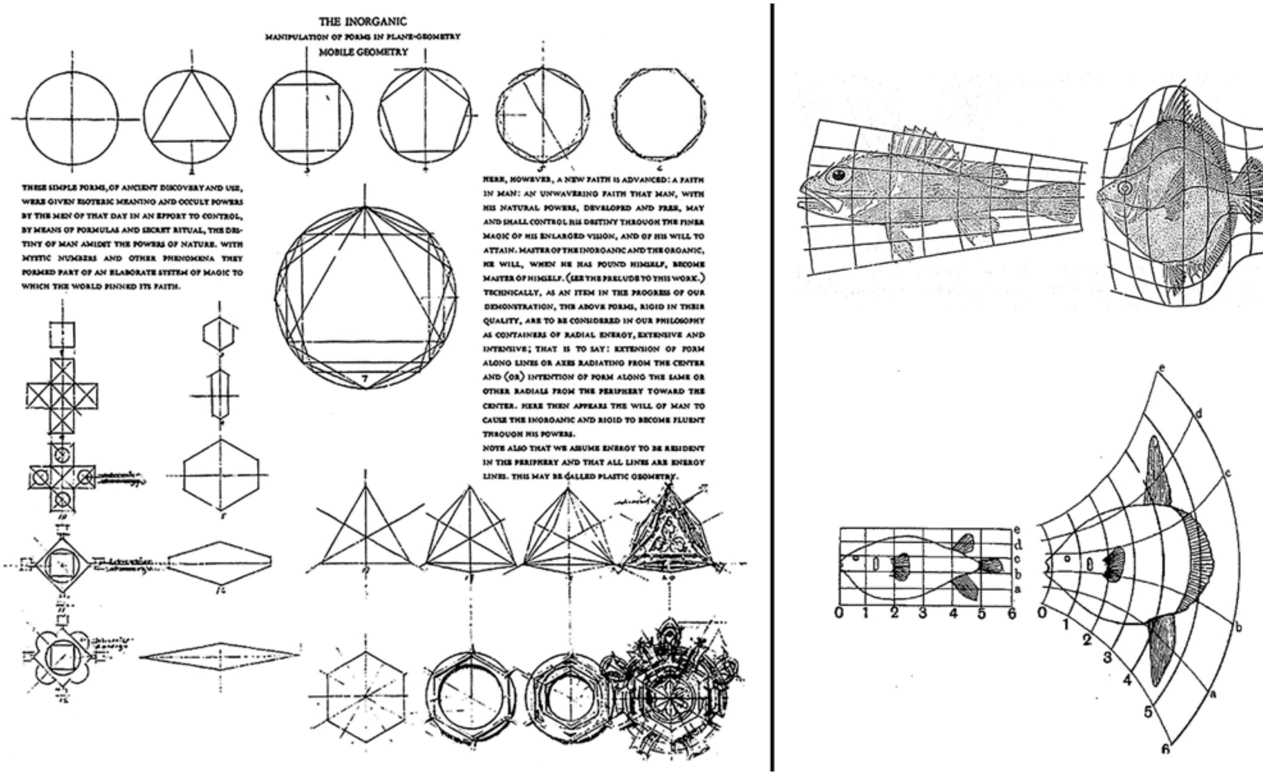
Essential Self-similarity

Throughout the natural environment, complex webs of systems and structures co-exist at vastly differing scales of observation. In the enormity of outer space, we find dynamically organized operations of light that remind us of patterns much closer to hand. The spiral is one example – found in cosmic nebulae and in the twisting double-helices of life itself. Other forms and patterns can be generated through vibrating liquids or fine powders, or heating dense fluids evenly. In each of these examples, events activated within a medium resolve themselves into resonant and fluently encoded networks of energy. When cellular units interact in diverse ways, we find they organize themselves into stable forms and dynamic structures at the scale of the network (created by interactions between units), and at the scale of each unit.

An interrelationship between scales of organization and between matter, process, and form is found both in physics and in biology. For Thompson, this involves a "search for community of principles or […] essential similitudes" (1992: 9). The anthropologist Gregory Bateson reminds us that such a quest requires us to discount "magnitudes in favor of shapes, patterns, and relations" (1980:11). Pattern, in nature, is a scale-less order or – perhaps more accurately – an order that occurs at myriad scales or magnitudes. Thompson illustrates this insight in his *Theory of Transformations*. Figure 2 shows two examples of Thompson's two-dimensional coordinate transformations, illustrating how different forms might be related and generated. He reflects on the potentials of this procedure,

> In this brief account of coordinate transformations and of their morphological utility I have dealt with plane coordinates only, and have made no mention of the less elementary subject of coordinates in three-dimensional space […] And that it would be advantageous to do so goes without saying, for it is the shape of the solid object, not that of the mere drawing of the object, that we want to understand; […] But this extended theme I have not attempted to pursue, and it must be left to other times, and to other hands (Thompson 1992: 1087).

If Galileo expected us to understand the language of nature in order to interpret it, Thompson and Bateson suggest there are principles or essential similarities of shape, pattern, and relation which make up this language.



2: (Left) Louis Sullivan, Manipulation of forms in plane geometry. (Sullivan 1924:); (right) D.W. Thompson, two-dimensional coordinate transformation (Thompson 1992:).

Galileo's vision reflects the influence of Plato's *Timaeus*, which asserted the primary importance of elementary geometries behind the material world. Before the scientific revolution, the world was envisioned as a living organism in which spirit, substance and form were inextricably linked. The new mechanistic vision of the scientists, armed with René Descartes' analytic method and triumphant in the grand synthesis of Newtonian mechanics, prevailed in Western science until the beginning of the twentieth century. Even so, an influential challenge to this mechanistic vision was mounted in the late 18th and 19th centuries, at least in the fields of literature, art and philosophy.

Primordial Seeds of Generative Potential

Johann Wolfgang von Goethe was a central figure in the Romantic critique of mechanistic science. Returning to Aristotelian philosophy, he focused his attention on the nature of organic and biological forms, emphasizing their dynamic developmental characteristics. He envisioned nature's creations as "patterned gradations" within a larger harmonious "moving order." He tried to resolve the dichotomy between substance and form, the whole and its parts, through a conceptual synthesis of both. He searched for nature's primordial developmental units while simultaneously being aware of their larger interrelated context. In the field of botany, for example, Goethe theorized a primordial plant held the basic organizational blueprint from which all other plants derived. This, he called the *ur-form* (original form) of the plant.

The American architects Louis Sullivan and Frank Lloyd Wright were inspired by Goethe's ideas. For Sullivan, the creative process was a transcendental experience that mirrored natural growth and development. Echoing Goethe's formulation of the *ur-form*, Sullivan referred to "the germ of the typical plant seed with its residual powers" (Sullivan 1924). In his designs for geometrically ornamented friezes, Sullivan imagined primordial seeds that possessed the 'residual power' to grow and generate organic forms. He illustrated the development of his ornamentation through the morphological transformations of these primary units (see left side of Fig. 2). For Sullivan, these units had a plastic and fluid geometry, a "radial energy" capable of projecting outwards or inwards through inherent "energy lines" or axes within the units. Both Sullivan and Wright were inspired by a comprehensive, dynamic, and generative vision of nature. Each of them developed a design method that relied on generative units that underwent systematic morphological permutations, limited only by the designer's imagination. In the words of Wright,

> All the buildings I have ever built, large and small, are fabricated upon a unit system–as the pile of a rug is stitched into the warp. Thus each structure is an ordered fabric. Rhythm, consistent scale of parts, and economy of construction are greatly facilitated by this simple expedient–a mechanical one absorbed in a final result to which it has given more consistent texture, a more tenuous quality as a whole. (*Wendigen* 1965: 57)

Sullivan, like Wright, envisioned an organic, versatile, vibrant and integrative design process. Recent developments in modern science and in the early part of the twentieth century reveal a similar conception regarding the complex nature of the physical world.

An Interactive Dance of Operations of Energy

With the dawn of the 20th century, around the time *On Growth and Form* first appeared, the scientific view of the physical world and its systems of organization was undergoing a fundamental conceptual shift. Matter, at its core, was revealed to consist of two contradictory yet intrinsic characteristics. Number, order and position in the world of physics – the stuff of organized matter – began to be understood as reciprocally linked to fluctuations of energy. Complex organizational processes began to be understood as three-dimensionally patterned networks of probabilities. In the words of the German physicist Werner Heisenberg,

> The world thus appears as a complicated tissue of events, in which connections of different kinds alternate or overlap or combine and thereby determine the texture of the whole. (Heisenberg 1958: 107)

This view posits nature as complexly organizing fields of energy. Yet this apparent contradiction – that matter is a form of energy – was but another instance of a question that has come down to us from antiquity: do things exist in themselves or only in relation? What is most essential, it seems, are the relationships between things, things themselves being webs of such relationships. Thus we are embedded, composed and maintained by Heisenberg's "tissue of events," that is, form-generating processes, not static forms. In the words of Gregory Bateson,

> We have been trained to think of patterns, with the exemption of those in music, as fixed affairs. It is easier and lazier that way but, of course, all nonsense. In truth, the right way to begin to think about the pattern which connects is to think of it as primarily (whatever that means) a dance of interacting parts and only pegged down by various sorts of physical limits and by those limits which organisms characteristically impose. (Bateson 1980: 11)

Today, techniques of computer visualization and analysis offer us further access to the structure and richness of these networks. Generative algorithms show us 'operations of energy' at work on simple cellular units revealing a wealth of detail. Once again, we find Thompson's "essential similitudes" and his ideas of 'number, order and position' playing a vital role in the relationships between interacting elements, at different orders of magnitude, along with their emergent patterns and behaviour.

In the world of biology, a fundamental characteristic of systems is continuity at the scale of the organism in the face of a constant metabolic transformation of its parts. The human body is one such system. Seventy-five trillion cells, of hundreds of types, are actively at work in our body. Thousands of these cells die every second, and billions are completely replaced every week, with no evident effect on our sense of self. The nucleus of each holds the genome for the entire organism, yet each cell reads only a small portion of that information. It is the interactive context within which the individual cell finds itself, that determines what bit of information the cell will read. Communicating with countless of its neighbours, our body's cells organize themselves into more sophisticated structures. In this way, local communication leads to the emergence of coordinated collective behaviour.

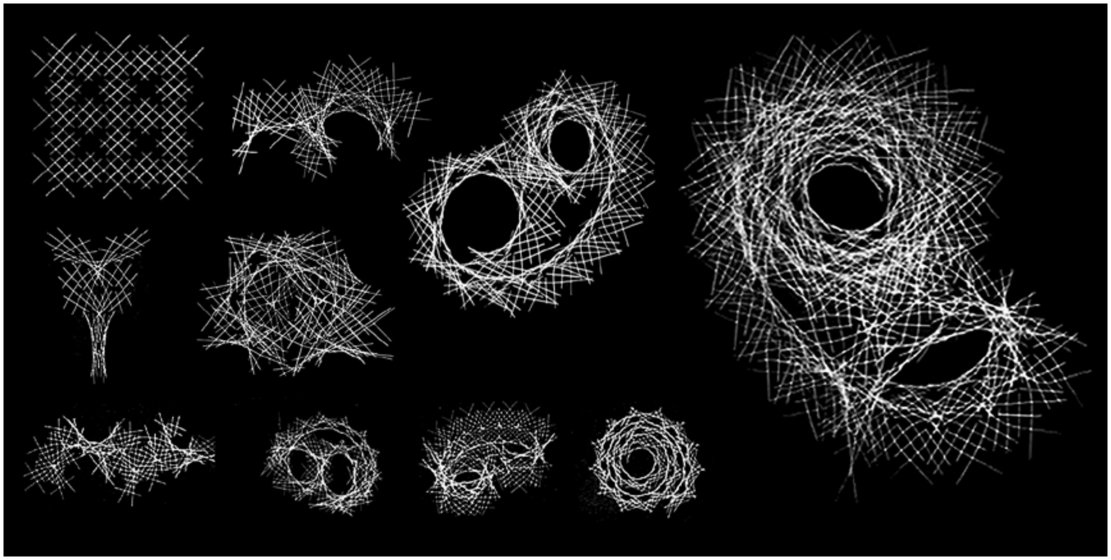
Works in Progress

The design research included here has been inspired by these ideas of form and pattern in nature. The first series involves a number of investigations using repetition as a way to generate form (Fig.1). An initial study used multiple-exposure photography to visually blend a repeated cell. To pursue this image in a more physically tangible form, a subsequent study used the rotary motion of a potter's wheel. A series of forms reminiscent of seashells and biological shapes generated by the spinning wheel were cast with a metal cylinder, hot water and wax. The potter's wheel also served to spin a string into wave formations that were stable at slower speeds, but dissolved into turbulence at higher frequencies. The project was called *Ariadne's Thread/Rumi's Ocean*, after Ariadne – the figure in Greek mythology who guided Perseus through the labyrinth with a ball of thread – and Rumi – the great Sufi mystic of the thirteenth century, founder of the whirling dance of the Mevlevi dervishes. Recorded from numerous vantage points, the project generated a wealth of forms and working procedures.

The Garden of Phenomeno-logical Paths

The next generation of studies incorporated a flexible joint as part of the assembly, mirroring nature's solution to dynamically complex structural conditions, such as bones in motion. Elemental shapes like triangles, squares, and pentagons were considered not as static diagrams, but as dynamic relationships. Made of bamboo lengths joined with elastic bands, they offer great flexibility and can be assembled in a variety of formations, creating cellular membranes. This set of studies forms the *Phenomeno-logical Garden* series.

The most frequently used cell in the series is the square, which offers an extremely versatile relationship within the assemblies. A portion of the basic cell can be seen in the upper left of Fig. 3, while a coiling structure 30 feet long is visible to the right. In this series, forms are generated by segmenting the membrane into its secondary patterns. These three-dimensional assemblies allow for a multiplicity of possible transformations. With experience, expressive forms and intricate structures come more easily, as one 'senses' and 'guides' the membrane into possible formations. In this way, a process that at first appears random allows one to discover unexpected arrangements and participate in emerging behaviours, that include fluid curves and organic-appearing forms and



3: Suspended Animation Series, 12" and 6" bamboo dowels and rubber bands, 1994-present. (From top to bottom and left to right, beginning upper left) Basic membrane of square cellular units; improvised assemblies; full constructions.

structures. The coiling structure to the right of Fig. 3 re-appears as the sculptural forms to the left of Figs. 4 and 5 – with the structure having been uncoiled and re-arranged into different configurations many times.

Figure 4 offers an overview of an installation at the Cranbrook Academy of Art in Bloomfield Hills, Michigan. By this time, the expressive potential of the process had become apparent. The installation was part of a symposium, *Metaphoric Interweavings*, exploring the use of modular composing procedures in the arts of weaving, musical composition and architecture. This installation was made entirely from the square cellular unit. Two supporting columns transform into an intricately patterned ceiling, while sculptural forms are displayed throughout the exhibition. The patterns that emerged from the form-generating process were rich and varied and, as one walked around them, constantly re-formed in new and unexpected ways from different vantage points.

As this project evolves, the shadows cast by the constructions have become increasingly relevant, adding another dimension to the work. Figure 5 shows a second installation at Cranbrook, this time at the Network Gallery. Here, shadows played a major role, as a series of improvised sculptural weavings and freestanding structures intertwine on the walls and floor of the gallery.

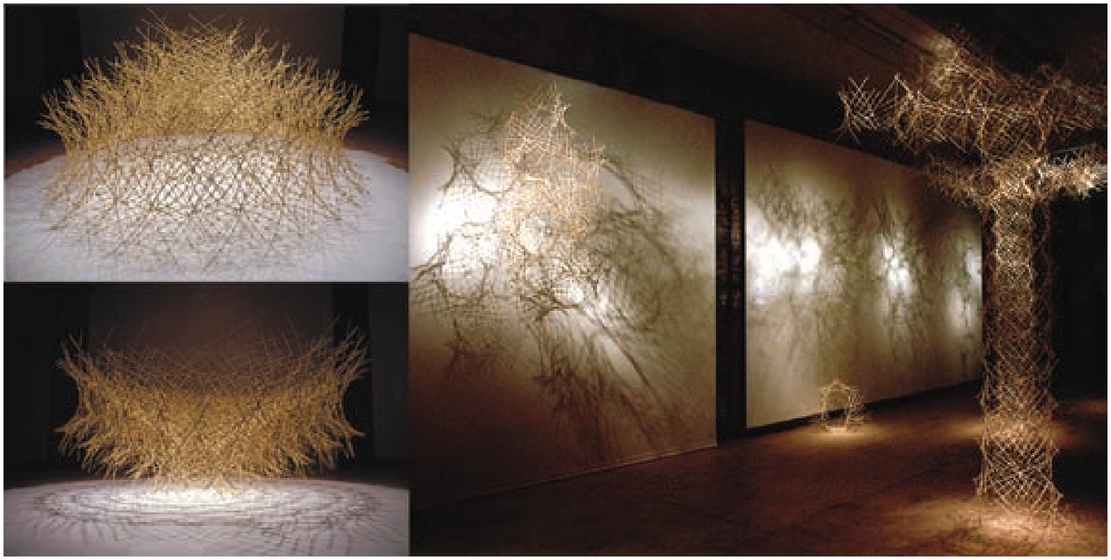
The Crossings Workshop

The Phenomeno-logical Garden has continued to evolve in scope and complexity. In workshops held at Carleton University, the research was brought into teaching, exposing students to a rich generative process and the history of such form-finding investigations (Figs. 6 and 7). In Fig. 6, a structure generated from a square cell is suspended from the ceiling revealing the effect of gravity in the subtle undulations of its structure. To its right are two configurations of a structure created from a heptagonal cell. Other constructions shown in these images were assembled with different cellular units and reveal the rich diversity of the process. The generative form-making process has led to unexpected patterns and dynamic arrangements, suggesting new and diverse directions for future assemblies.

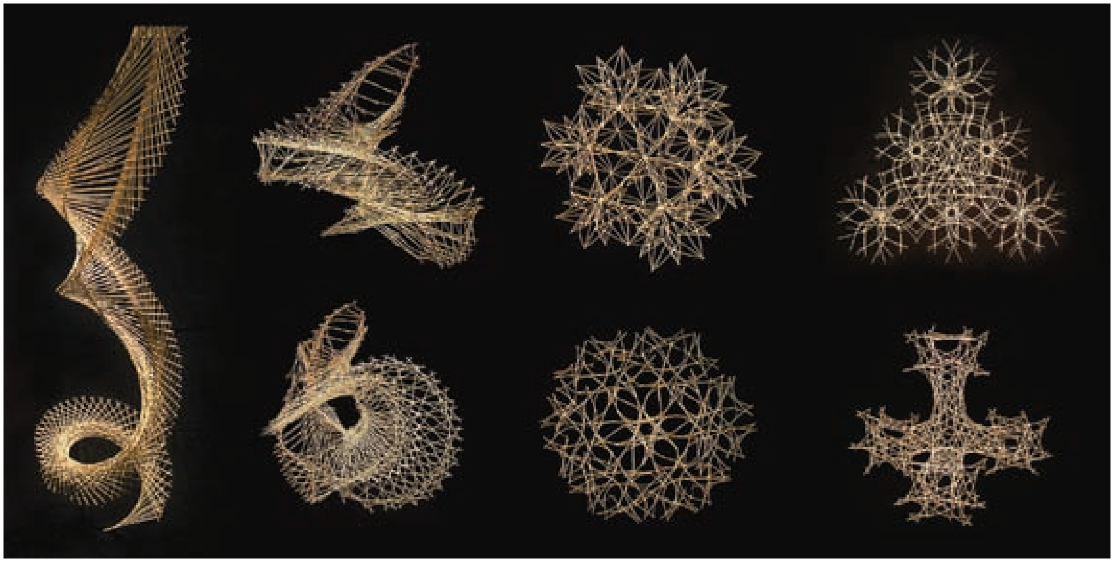
Generative Folding

The latest development of the project involves explorations into the structural and architectural potentials of a hexagonal field that incorporates the structural stability of an equilateral triangle as its generative cell (Fig. 8). The folding patterns in these fields can generate space-frames and double curves of hyperbolic paraboloids. More complex and versatile undulating capabilities are achieved by introducing other degrees of folding into the patterns. A digital model of the project can be seen to the left of the image, while the installation in the gallery space is to the right. This work is currently under development in the design of its joints and construction details.

4: *Phenomenological Garden, Metaphoric Interweavings* installation, Cranbrook Academy of Art, Bloomfield Hills, Michigan, 1998. Constructions with membrane from Fig. 3. Two columns are transformed into an intricately patterned ceiling structure. Patterns emerge throughout the installation.



5: *Phenomenological Garden installation*, Network Gallery, Cranbrook Academy of Art, Bloomfield Hills, Michigan, 1999. Developed from the installation in Fig. 4. Improvised sculptural forms and freestanding constructions cast shadows on the gallery walls and floor.



6: Marian Shaker, Diana Park, Daniel Cronin, Sharif Kahn, Karam Georges & Nathan Dykstra, Crossings Workshop Suspended Animation Series, cellular form studies of bamboo dowels and rubber bands, 2001-05. (Left column) square cell structure; (second column) heptagonal cell structure; (third column, top and bottom) structures of pentagonal cells, square cells; (fourth column, top and bottom) structures of square cells, pentagonal cells.

7: Diana Park, Mariam Shaker, Sherin Rizkallah, Raymond Chow & Natalia Kukleva, Crossings Workshop Suspended Animation Series, cellular form studies of bamboo dowels, rubber bands and plastic tubing, 2001-05. (Left) suspended heptagonal cell structure casting shadow on a wall; (middle) gallery installation; (right) square cell construction, top and side views.

Conclusion

As part of his memo on exactitude in *Six Memos for the Next Millennium*, the Italian writer Italo Calvino offers the following advice,

> The crystal, with its precise faceting and its ability to refract light, is the model of perfection that I have always cherished as an emblem, and this predilection has become even more meaningful since we have learned that certain properties of the birth and growth of crystals resemble those of the most rudimentary biological creatures, forming a kind of bridge between the mineral world and living matter.
>
> Among the scientific books into which I poke my nose in search of stimulus for the imagination, I recently happened to read that the models for the process of formation of living beings 'are best visualized by the crystal on one side (invariance of specific structures) and the flame on the other (constancy of external forms in spite of relentless internal agitation).'
>
> What interests me here is the juxtaposition of these two symbols, as in one of those sixteenth-century emblems [...] Crystal and Flame: two forms of perfect beauty that we cannot tear our eyes away from, two modes of growth in time, of expenditure of the matter surrounding them, two moral symbols, two absolutes, two categories for classifying facts and ideas, styles and feelings [...] I have always considered myself a partisan of the crystal, but the passage just quoted teaches me not to forget the value of the flame as a way of being, as a mode of existence. In the same way, I would like those who think of themselves as disciples of the flame not to lose sight of the tranquil, arduous lesson of the crystal (Calvino 1988: 70-71).

The paradox of complex simplicity in natural processes challenges our conceptual imagination. It occupied D'Arcy Thompson, in his *On Growth and Form*, and inspired the work of Goethe, Wright and countless other creative individuals. Calvino is no exception. For him, the crystal and the flame are symbolic metaphors for the paradoxical nature of matter as revealed in the twentieth century. "This is common to all our laws," states the physicist Richard Feynman, "they all turn out to be simple things, although complex in their actual actions" (1967: 33).

The work in progress presented here tries to address this paradox. It offers a revitalized direction to the field of architectural morphology, looking to complex natural phenomena to stimulate the creative imagination. "Nature," Feynman reminds us, "uses only the longest threads to weave her patterns, so each small piece of her fabric reveals the organization of the entire tapestry" (1967: 34). The way towards this rich tapestry is through fundamental rules that eventually reveal the paradox of constrained and versatile freedom.

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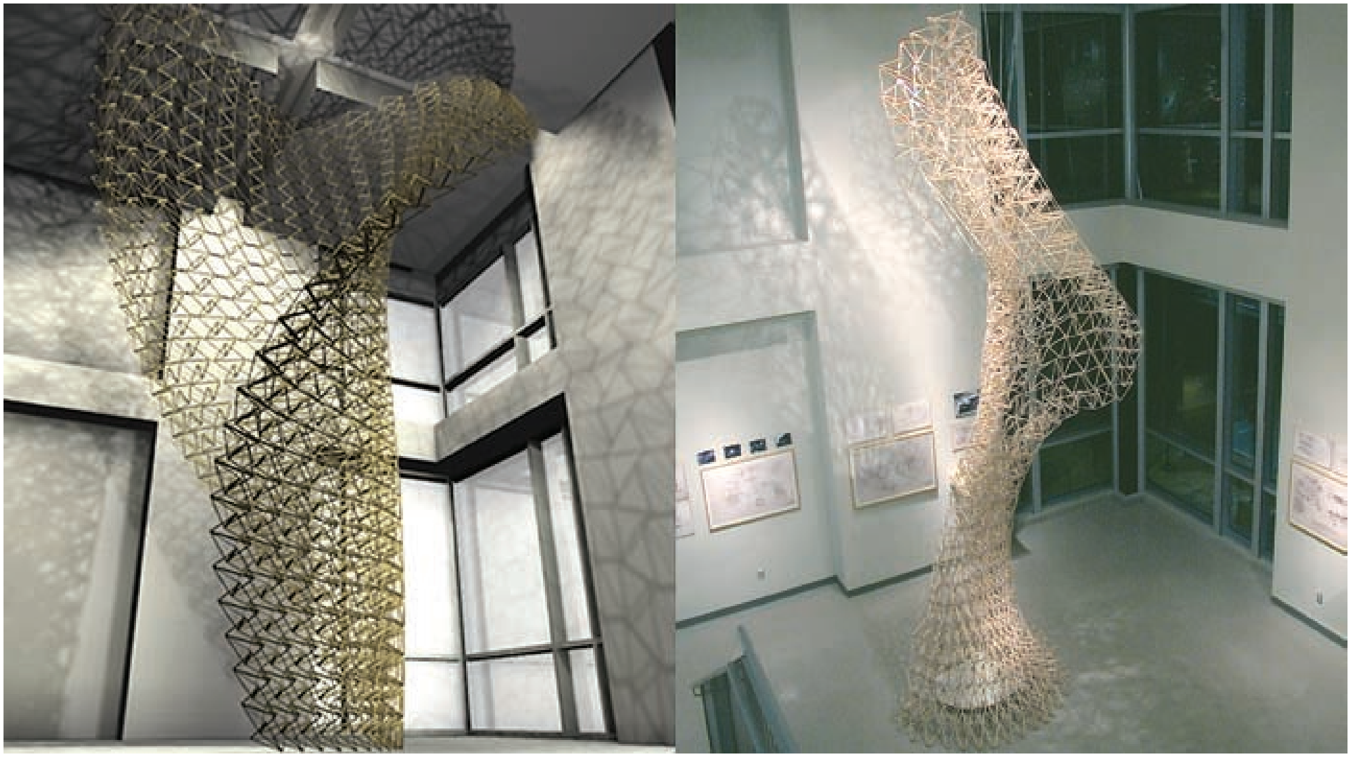
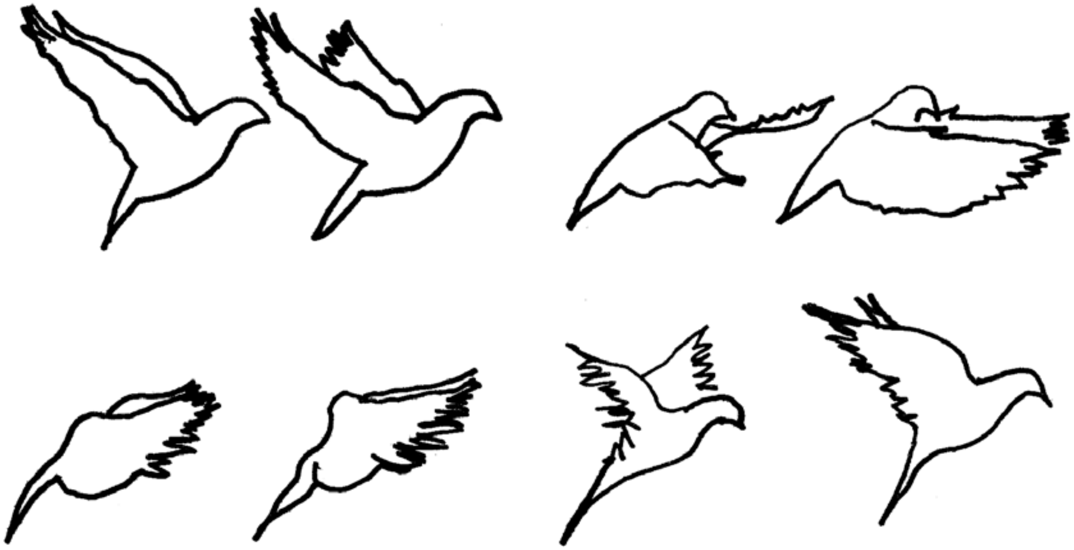


4: *Complex Simplicity* installation (part of an exhibition on architect James W. Strutt), David Azrieli Gallery, Carleton University, 2006. Wooden dowels w/plastic tubing. (Left) digital study; (right) installation view. Special thanks to research assistants Patrick Bisson, Elie Nehme and Adam Fingrut.



1: Sequence of positions in the flight of a pigeon, 2005. (After Stewart and Golubitsky 1992: 219)

Process in Nature and Process in Architecture: Inquiry into a Process of Unfolding

Hajo Neis

This paper discusses a way of designing and building that was developed by Christopher Alexander and his associates, from their observations of three natural processes of form-making.[1] The first one is 'smooth unfolding' in nature, which can serve as a basis for developing design and building processes. The second is 'structure-preserving transformation' – a sequential process useful for creating architecture. The third process – 'formation of centers and fields of centers' – sharpens the possibility for focused differentiation in design and building. A fourth process combines 'structure-preserving transformation' with the 'formation of centers' as a way to 'unfold' architecture. By way of a conclusion, the application of these processes in design and building projects is shown in a few examples, which point to their potentials and implications for architecture.

Process in Nature

Long before people began to create shelter, nature had been designing and building in an evolutionary way, refining its designs and constructions over eons, as it is still continuing to do. One could say that nature continues to be the 'greatest architect' on earth. When we refer to nature with a capital N, as Frank Lloyd Wright did, we are not only talking about organic nature but also inorganic nature, the whole of nature, which involves much larger phenomena than those in living, or once-living nature.[2] It involves the shaping of the earth, the slow moving of continents over millennia, the development of islands through volcanic activity, changes in climatic patterns that influence terrestrial landscapes, and the formation of hurricanes with their spiraling clouds winding around eerily quiet centers.

Unfolding in Nature

The unfolding process that nature provides in many forms and shapes, events, and scales, with all its good and bad sides for human habitation and life, forms the basis of much scientific interest in its various aspects related to a particular discipline. And while architecture and urbanism have traditionally concerned themselves with small and medium scales of inhabitation, the ever-increasing urbanization of the world has forced these disciplines to address much larger scale than they have in the past. Yet there are not only large processes of unfolding in nature, there are in fact thousand of processes going on all the time around us throughout the natural world, large or small, organic or inorganic, living and non-living. Everything comes into being continuously, grows and matures, lives and exists. And we are probably much more used to the immediate unfolding processes around us that impress us, such as the blooming of a flower, the growing of leaves on a tree, the birds with growing young and the changing colors of our gardens.

The Principle of Unfolding Wholeness

We do not have, however, enough understanding of how to comprehend this process of coming into being in geometric terms, the area most interesting for designers and architects. Here, the architect and mathematician Christopher Alexander has attempted to formulate a principle that might underlie all geometrical processes in nature and that is the principle of 'unfolding wholeness in nature.' Looking at various examples of processes in nature at different scales and different modalities, he comes to the conclusion that all processes in nature may be unfolding in a particular geometric way – in what he also calls 'smooth unfolding.'

The examples he uses come from a vast range of scales and disciplines. Starting with the formation of a spiral galaxy, he observes,

> The genesis of the spiral form in a galaxy, comes about because a disc of pre-galactic material spinning, includes some random motion. The random perturbations give rise to an oscillating pattern of gravitational waves of rarefaction and compression. As this wave-system develops, it can go only to two or three large scale forms. Much of the time it goes to a two armed spiral. The two-armed spiral is one of the simplest transforms of a slightly perturbed oscillating disc of material and space, in which a gravitational wave appears (Alexander 2002: 23).

He shows a computer simulation of the process – when breaking the infinite symmetry group of the rotating disc, one is left with the simplest symmetry group consistent with rotational motion, a spiral with arms.

While the first example is huge, far away from us, and involves inorganic structure and process, his second example is at a much smaller scale, biological and almost invisible to the human eye. He looks at stages in the development of a frog embryo, starting with a ball of cells. The ball splits down the middle. An axis is introduced. And, as Alexander observes, "The wholeness of each stage is consistent with the previous one. The centers which exist in the wholeness are largely left intact" (Alexander 2002: 25). A third example is the flight of a bird – visible to the eye but so fast one needs a slow motion camera to capture it.

> Here we see the same smoothness in steps that are only micro seconds apart. Each stage and configuration of the bird's flight follows smoothly from the previous one. In each stage we see the wholeness of the previous stage, almost entirely preserved as a structure, with insertion of a minor modification on the whole. Although the motion passes through phases unlike each other, from step to step there are no abrupt transitions that disturb the smoothness of the flow" (Alexander 2002: 27). (Fig.1)

Finally, we show an unusual example from the world of chemistry – the Belousov-Zhabotinsky reaction of chemical scroll waves.

> When we look at the photographs of the famous chemical waves studied by Prigogine and others, we see the startling patterns formed in the dish of chemicals. Although the patterns formed in the dish are unusual, and although the last stages are entirely unlike the first stages, we see a simple and natural evolution of the pattern from the patterns immediately preceding – a process without apparent discontinuity (Alexander 2002: 27).

According to Alexander, what underlies all of these cases – and many more –

> is a geometrical principle, reminiscent of the principle of least action but more general.[3] This principle may be formulated as follows: the evolution of any natural system is governed by transformations of the mathematical wholeness and by a tendency inherent in these transformations, for the whole to unfold in a particular direction. (Alexander 2002: 45-46)

And while this formulation may be too formal, a more simple interpretation is that any natural system that moves forward in its physical and geometrical growth always preserves the wholeness inherent within it. Or more simply: any stage in the development of a physical system always preserves the structure of the previous stage in some way.

Unfolding in Design and Making

Before the geometrical law of 'unfolding wholeness in nature' was formulated in its current form, attempts were made to apply the idea of unfolding wholeness to the design and making process in a meaningful way. In the early eighties for example, one of Alexander's research seminars focused on the question of unfolding in design and making. As a member of that research laboratory, I remember the many experiments, tests and attempts we made to come up with a useful principle or better, with a system of rules, that would actually work every time in evaluating a design process that was truly unfolding. What came out of this seminar was the principle of 'structure-preserving transformations' (Neis 1982).

The Principle of Structure-preserving Transformations

The principle of 'structure-preserving transformations' is fascinating not only because it works every time you apply it, but also because of the way it came into being by itself. It was only possible to develop this principle by doing a double experiment, in which the second experiment depended on the first experiment. And this is why the principle has at least two steps you have to perform simultaneously, and as you will see, you have to perform three steps simultaneously to not only perform a preserving transformation but also an enhancing transformation: The formulation from my notebook is this:

1. With each act of placing an increment of design and/or construction, we also have to *understand and respect the existing structure*.

2. With each act of placing an increment of design and/or construction, we also have to *preserve the existing structure*.

3. With each act of placing an increment of design and/or construction, we not only have to preserve the existing structure, but we also have to *enhance the existing structure* (Neis 1982).

While the process of structure-preserving transformations is in principle enough to create form similar to nature, it might take quite some time. Rule number three is the critical one, to ensure good design more quickly. And to enhance existing structure, it helps to understand the principle of the formation of centers.

2: Lower portion of the basalt wall, Borken, Germany, 2001.

The Principle of the Formation of Centers

The principle of the 'formation of centers and fields of centers', helps the process of unfolding in design and construction, by differentiating space and form more rapidly and in a more pronounced way than would be possible without it. Again, the principle is formulated in three rules that should be performed simultaneously, and can be checked analytically:

1. With each act of placing an increment of design and/or construction, as part of a field of centers, the entity you place has (to help) to create one larger center, which is larger than itself, and it also itself has to be a part of this larger center.

2. With each act of placing an increment of design and/or construction, the entity has to create other centers next to it, at approximately the same scale.

3. With each act of placing an increment of design and/or construction, the entity has to create other smaller centers within it. (Formulation from my notebook of 1982; see also Alexander, et al 1987: 92-99).

With the principle of 'formation of centers' and the principle of 'structure-preserving transformations', and their three precise rules respectively, we have in principle enough information and instruction to perform a process of unfolding in design and making similar to nature.

Process in Architecture

Process in architecture is generally divided into the two processes of design and construction – to the point that there are two different activities and professions. We can find numerous examples where the process of unfolding is applied purely to design of buildings. But designs still need to be built, and so the process would need to be applied again, most likely changing and modifying the design because of its own tendencies and needs for structure-enhancing transformations. For the purposes of this paper I want to stay with simple and straightforward cases: Since nature makes no distinction between design and construction, I too will also consider them one process, where design supports construction and construction supports design in a process of unfolding. Selecting three projects from my own work, we can move on to exploring applications of 'structure-preserving transformations' and 'formation of centers' in architectural projects.

The Growth of a Garden Wall in Germany

This garden wall in Borken, Germany may be a small example in architectural terms, but it is one which shows well the process of unfolding.[4] One of the first matters to be decided was the material for the wall – basalt being one possibility among others. Placing a few increments of stone on the site for the wall was indeed helpful, since it was local basalt that could be found right there if one were to dig, and of course it was available in the local quarry. This was a structure respecting and structure preserving act. But was it also structure enhancing? Put together in larger amounts, the basalt stones felt more like a cemetery wall, not exactly life-enhancing in front of a residence. A study of other walls in the town revealed that yellowish and reddish sandstone was quite often used in various quantities and arrangements to soften the harshness of the basalt and thus create a more pleasing overall color (Fig. 2).

3: Upper portion of the basalt wall, Borken, Germany, 2001.

With regards to form-making, two events in the process are worth talking about. The first involved shaping the exact form of the irregular wall on a slope at the entrance. I had made two design sketches for the part where a lower portion of a wall was to meet a higher portion of the wall. But I wasn't sure which of the two would create a better field of centers. My first guess was that the sloped version would be more smooth and harmonious. When the wall reached that particular configuration in the construction, it was easy to simulate the two sketches as mock-ups. And as it turned out in this process of testing, and trying to come to a structure enhancing transformation, it was a modified version of the straight solution rather than the sloped solution that created the best field of centers, from the point of view of the various people involved (Fig. 3).

One last incident was revealing with respect to professional designers working within this design process. I had retained a landscape specialist and explained the process to him. Yet it was not easy for him. I had told him we might have a flat concrete top or might not, depending on the way the unfolding of the wall turned out. I also told him that we could make an initial guess and maybe find some concrete tops for testing the idea. When it came close to that point in time, he revealed to me that he had already ordered a set of tops for the overall wall based on my first sketch. When we placed some of these concrete tops, the wall suddenly made a transformation to the worse. With some regret I had to tell him that this was terrible and that we could not use these tops. We ended up to not using any tops at all because the wall had reached a level of quality that was a pleasing field of centers.

The Growth of a House in New Jersey

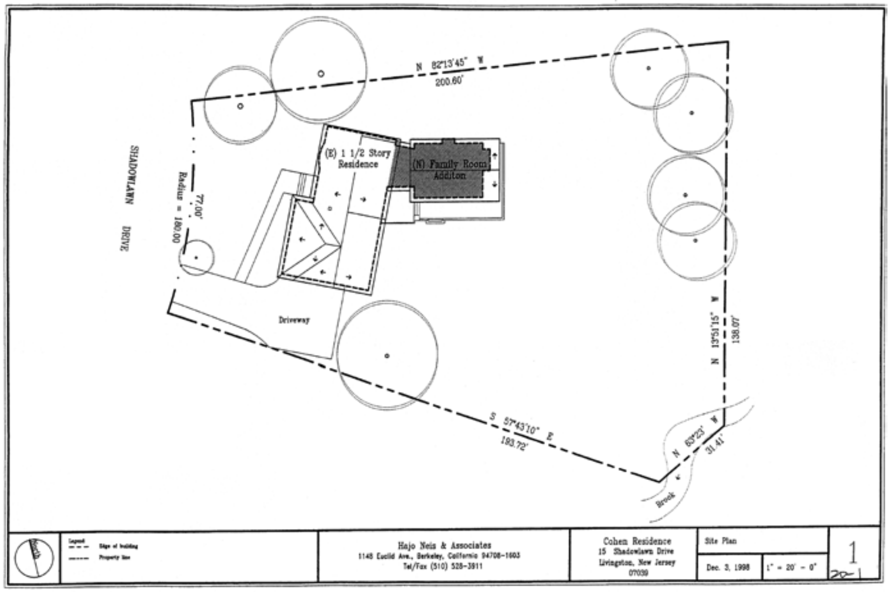
In discussing a house remodel and addition in New Jersey, I want to focus on an early point in the design and development of the project.[5] After an initial pattern language was formulated for the house (that dealt with its functional aspects and elements), we visited the site to determine the exact location, size, shape and height of the main addition to the residence that leads into the garden. This is a critical moment in the design of any building, because the volume must be placed to create a field of centers on all three levels formulated in the principle.

The house was on a wedge-shaped lot, with the existing house at the narrow edge of the property – opening up all kinds of angles and possibilities for an addition. But my client, a rational man, wanted the addition to project at right angles to the house. I staked out that idea, but was not happy with it because it didn't contribute to a harmonious larger field of centers. So I started to test a few other options. At the end of the day, after a few different stake-outs, I started to feel good about a particular one that located the addition at a slight angle to the house, creating a large garden center to the south, another garden area at about the same size as the new addition, and yet another smaller veranda zone on the inside corner. I slept it over, checked it out again on the next morning and felt that the process of 'structure-preserving transformations' and the process of 'formation of centers' together had created a pleasant overall field of centers that now had to take form and be embellished with a more detailed design of the building itself (Figs. 4 and 5).

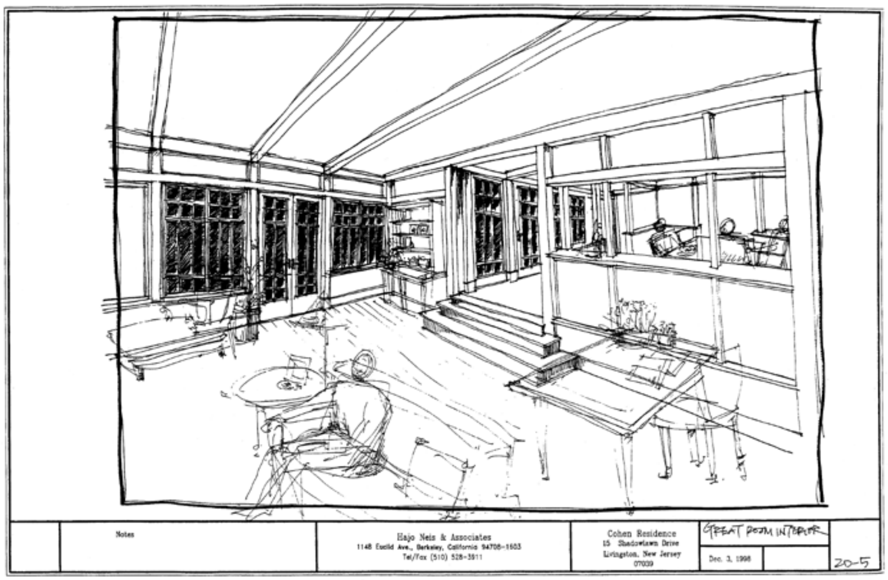
The Growth of an Apartment Building in Japan

This building is entered via a small bridge that leads to apartments and an artist studio on the second and the third floor. It is because of this little bridge that I think of it as a bridge building. This building outside of Tokyo, in Kanagawa Prefecture, was designed for an artist, Mrs. Sahara, who is a painter.[6] She wanted an apartment and a small painting studio, along with some special features which would identify this as an artist's residence. She also wanted several rental units to finance the construction of the building. The site is at the edge of the town, close to a forest on top of a hill. It is at the end of a cul-de-sac street, impassable to cars (Fig. 6).

The first challenge for the design was the hilly site. To turn it to the advantage of the building, and the building to the advantage of the site, I placed the main volume so it would create volumes and spaces within the site and its surroundings. A simple rectangular volume, it defines a private path on its north side lined with tall Japanese Keyaki trees, connecting the cul-de-sac on the downhill side with a street on the uphill side. In order to make this pathway useful for people who wanted to walk from the forest to the town, stairs were placed at each end. This is an example of a 'structure enhancing transformation'. Now the house defines a stepped path on its north side as it fronts a pleasant garden to its south, filled with trees and sunlight which floods the building. To avoid a bulky stairhall within the house, a bridge was placed up the hill to the east,



4: Transformed site plan of the Cohen Residence, New Jersey, 1998, showing the building addition into the garden creating a field of centers.



5: Interior view of the family room addition, Cohen Residence, New Jersey, 1998. HNA: Y. Sato, 1999.

connecting to an open gallery on the second floor and entrances to the apartments, including Mrs. Sahara's at the end of the gallery. At the lower level of the building and along the private tree-lined path, small house-like structures mark individual entrances for the first floor apartments – these are places where people remove their shoes before entering the dwellings. Eight apartments are distributed over three floors – a maisonette, two flats, four split-level apartments, and an apartment with stairs leading down to a tatami garden room. Each of the apartments contains a tatami room or the possibility of creating one. Mrs. Sahara's apartment features a painting studio next to a roof garden, and a small gazebo where she can paint in the open air (Fig. 7).

On several occasions, Mrs. Sahara expressed a wish to have a feature of the building show that it was the home of an artist. The north of the building was made of concrete, and the south finished in a light yellow shikui plaster. To connect these two zones, it seemed that a special wall tile might be just the right thing – to demarcate the location of the apartments, add color to the building and help mark special points such as the entrance to the bridge (Fig. 8). Developed with a local ceramic artist, this tile captures the spirit of this building in a microcosm, as a house for an artist. We may also say that the design and making of the building forms a successful 'structure-preserving and enhancing transformation'.

Conclusion

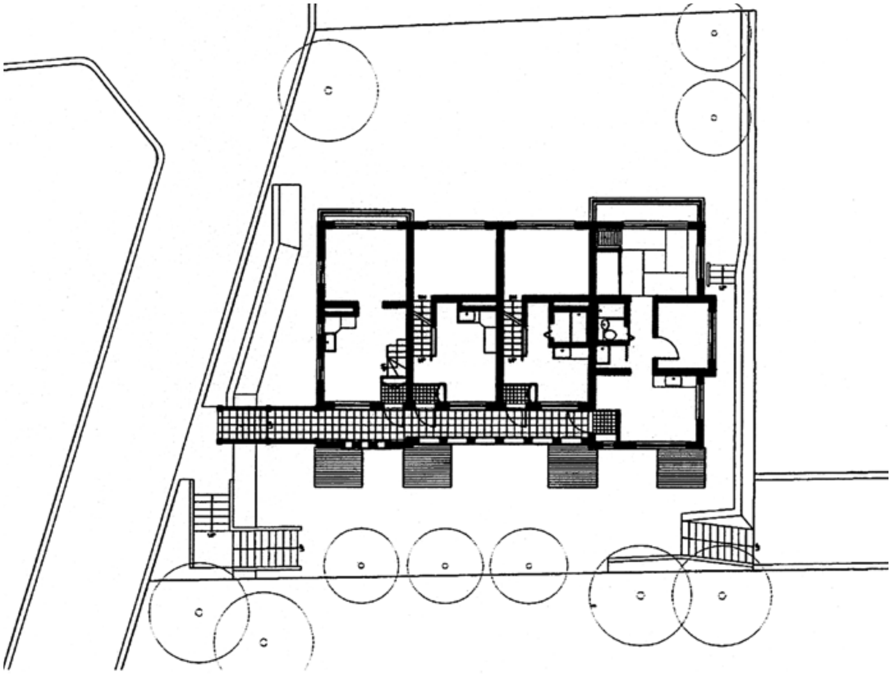
The process of architectural unfolding worked well for these three projects, yet it need not be restricted to small works of architecture. I have carried out much larger works using this method – the Eishin Campus for example, and the Komagome building, both in Tokyo. Now that we have experienced the process of unfolding in architecture in relation to actual built works, we may be able to conclude with a few summary points:

- While D'Arcy Thompson developed the insight that biological form may be best understood through biological process, Alexander has taken this idea further, applying it to all kinds of natural phenomena and formulating the principle of 'unfolding wholeness in nature'.

- The idea of process as a prime generator of form and the principle of unfolding wholeness, both derived from observations of nature, have been transformed into design and building processes that are similar to natural processes: these are 'structure-preserving transformations' and the process of 'formation of centers'.

- 'Structure-preserving transformations' can be applied anywhere to achieve a process of physical unfolding – by any designer and architect and for any kind of project, simple or spectacular. And if the process of unfolding in its applied formulation is more general, it also is more significant because of its wide applicability.

- But then of course there are many open questions that need to be answered, some of them having to do with the internal development of unfolding wholeness and others with



6: Centered site and floor plan of the Sahara building, Kanagawa Prefecture, Japan with semi-public stepped path to the north and garden to the south (north at bottom). HNA, 1989.

7: North elevation with bridge and gallery on the second floor and Japanese entrance rooms on the first floor. Sahara building, Kanagawa Prefecture, Japan, 1989. HNA, 1989.

questions coming from outside such as: Why should one follow and apply the process of unfolding in architecture in the first place, when there are other theories and principles in architecture that say the exact opposite?

• Finally, there is a question of the relation between the discipline of bionics and the idea of 'unfolding wholeness'. Bionics is both a modern and a long-established discipline that deals with the "application of biological principles to the study and design of engineering systems" (Otto 1988). Although bionics represents a large sub-discipline of architecture, it is usually applied to systems rather than to processes, while 'unfolding wholeness' relies on generative processes. In the end, 'unfolding wholeness' may turn out to become a promising area of research for improving architecture and urban structure in an ever-more complex world of processes.

8: Construction mock-up of a building corner, showing concrete, plaster and tile. HNA, 1989.

Postscript

Since this paper was written in 2001, four years have gone by and the world has turned around many times. During that time, Alexander's four volume series *The Nature of Order* has been published, including the second volume in the series, *The Process of Creating Life*, which deals with issues addressed in this paper. His organization has also established a website which further explores some of the questions discussed here (www.patternlanguage.com). The goal of this organization is to develop procedures for rebuilding the world based on generative processes.

Notes

[1] Hajo Neis has been a member of the Center for Environmental Structure (CES) since 1979 and an associate since 1982. He directed CES Japan for eight years, carrying out numerous projects during this period, including the widely acclaimed Eishin Campus in Tokyo. Hajo Neis also works from his own HNA office. He is an associate professor at the University of Oregon.

[2] Frank Lloyd Wright in one of his famous TV interviews in the 1950s.

[3] This is known as Hamilton's principle. Formulated in the 19th century, it states that the evolution of any dynamic system will always follow the path of least work.

[4] The garden wall was a commission from Amelie Ellrodt in 2000.

[5] The Cohen Residence in New Jersey was worked on as a design with initial construction experiments in 1998-99.

[6] Designed in 1988-89, the Sahara apartment building began construction in 1990, when it fell victim to an economic downturn in Japan.

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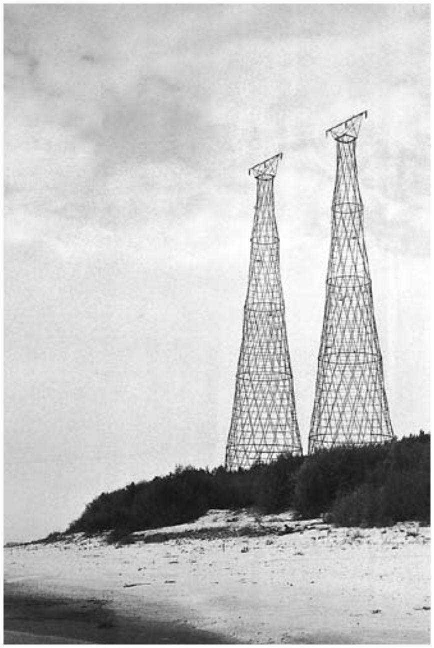
Synthesis of Form, Structure and Material: Design for a Form-optimized Lightweight Membrane Construction

Edgar Stach

What is lightweight construction? Of many possible definitions, one I like is: *a construction that is designed to optimize its loading capacity*, or, more precisely, one which optimizes the path forces take to achieve a reduction in built mass. Lightweight construction and its corollary, the optimization of form, have formed two significant themes in construction technology over the past half-century. Yet their antecedents can be traced further back into history. Since the Renaissance, architects and artisans have worked to achieve lightness and economies of form in designs for machinery, transportation devices and other ingenious constructions. At the beginning of the 19th century, the constructions by engineers began for the first time to have an impact on architecture. This paralleled broader transformations that were taking place in the sciences, and in the development of new materials, industrial processes, and ways of thinking ushered in by industrialization. Complex engineering works and new structural systems presented architects with new ideas about construction.

By the 1900's, biological discoveries began to affect the technical world of construction, through the work of the biologist Ernst Häckel. We see early examples of lightweight construction and the use of new materials at this time in greenhouses in England, such as Bicton Gardens. Yet the most significant innovations in lightweight construction came through developments in flight. Balloons, dirigibles, and airplanes generated new ideas about forms and construction methods that quickly found their way into a new kind of architecture. (Fig. 1)



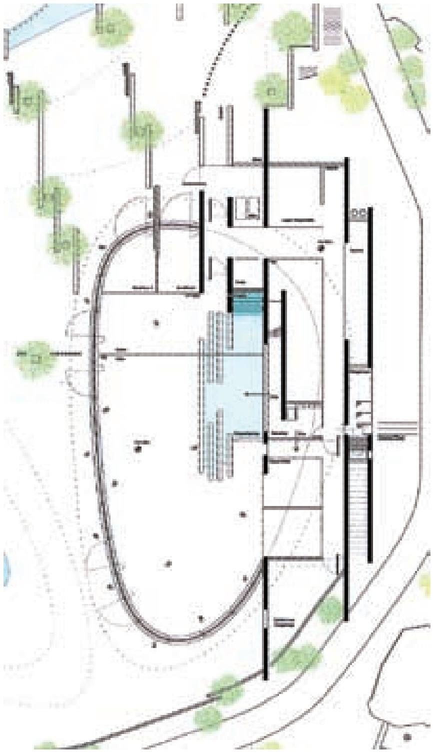
1: Vladimir Grigorievich Shukhov,Dzerzhinsk High-Voltage Mast, Oka River near Nizhniy Novgorod, Russia, 1927-29. Photograph Igor Kazus, 1989.

In recent decades, the accelerated development of computer-supported structural analysis and research into new materials has given architects ever-more possibilities for designing lightweight structures. The project presented in this paper – a new elephant habitat for the zoo in Cologne, Germany – is an exemplary study of the use of lightweight construction and form-optimization applied to a specialized type of construction.

The Elephant Habitat in Cologne

The Cologne Zoo wanted to conduct an experiment. Having recently acquired elephants raised in a natural setting, the Zoo decided to build an environment that better simulated their natural habitat. Instead of building a new 'elephant house', the zoo embarked on the construction of a naturalistic habitat for the animals.

An artificial ridge is in the center of the habitat, with terraced 'cliffs' blending interior and exterior space. Tree trunks and columns are dispersed irregularly through the space. The visitor moves along raised platforms behind green walls, under a sheltering roof



2: Roof plan of Elephant-Haus, Cologne, Germany, 1999.

that is as luminous as the open sky. Roof structure, columns, trees, and elephants cast shadows on the inside of the building, creating a dynamic image that changes daily and with the seasons (Fig. 2,3,4).

Developing the structural framework

The design concept was to develop a roof system that would be structurally optimized as an irregular spatial structure over a free plan, symbiotically merging the concept of an insect cocoon, the science of bionics, and the engineering goal of a spatial framework system, in the form of a 'roof cloud'(Fig. 5).

The requirements for the new roof came from the idea of a balanced, flowing, weightless form. The image of a cloud is given form through the new structural framework – a *structurally-optimized system* developed with the aid of digital design tools that permit dynamic modeling and calculation of force-paths, through an iterative process (Fig. 6). In this way, the design shares certain features with biological structures that can adapt their forms to carry the stresses and forces they encounter as can be seen in sea urchins (Fig. 7,8). In this design, the crucial parameters were: a) a minimization of stress in the centers of the fields, and b) an optimization of the load-bearing elements in scale and dimension. The naturalistic imagery of the roof would not have been possible if we had relied on more conventional framework, such as a cantilevered or cable-stayed roof.

The first step was to establish parameters for the design. These included an unconstrained roof line with long-span capabilities and three-dimensional waviness so it would appear 'cloud-like', and a seemingly random placement of columns beneath the roof (as in a forest), along with the possibility of angling the columns to provide the necessary stiffness to the building (Fig. 9,10).

The schematic design phase involved five steps: a mechanical analysis of a finite element model, a three-dimensional stress analysis using finite element method structural language [SLang], a spatial stress analysis and visualization of force paths within the volumetric model, a re-development of the finite element model based upon the direction and magnitude of the primary force paths, and lastly, visualization of the primary spans, to create the starting point for the design as resulting from a three-dimensional, optimized structure.[1]

After an analysis of the primary stresses, it was possible to orient the curved tubes of the spatial framework to follow precisely the force paths. We could then return again to

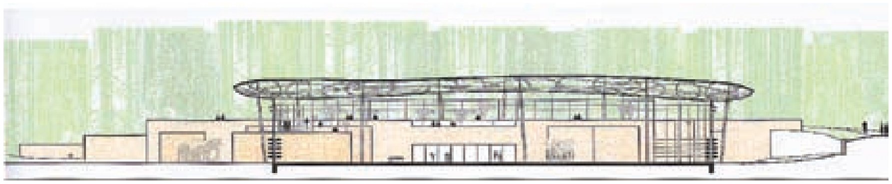
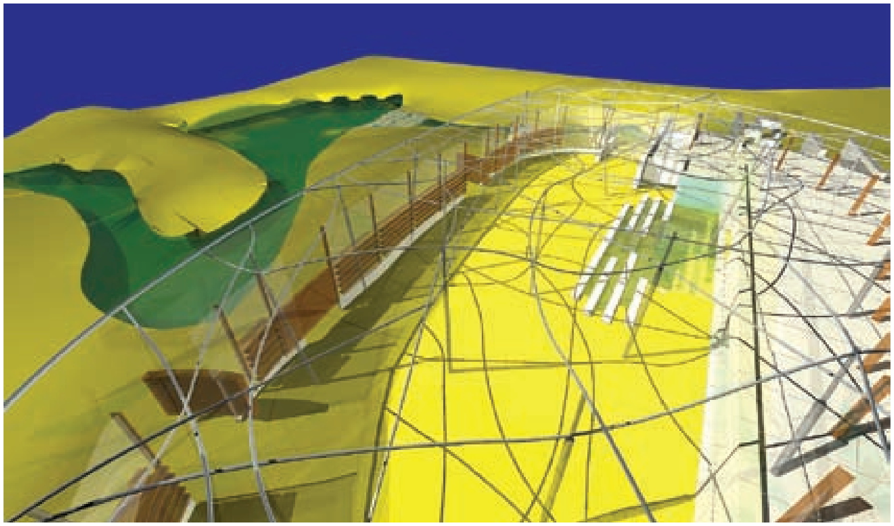
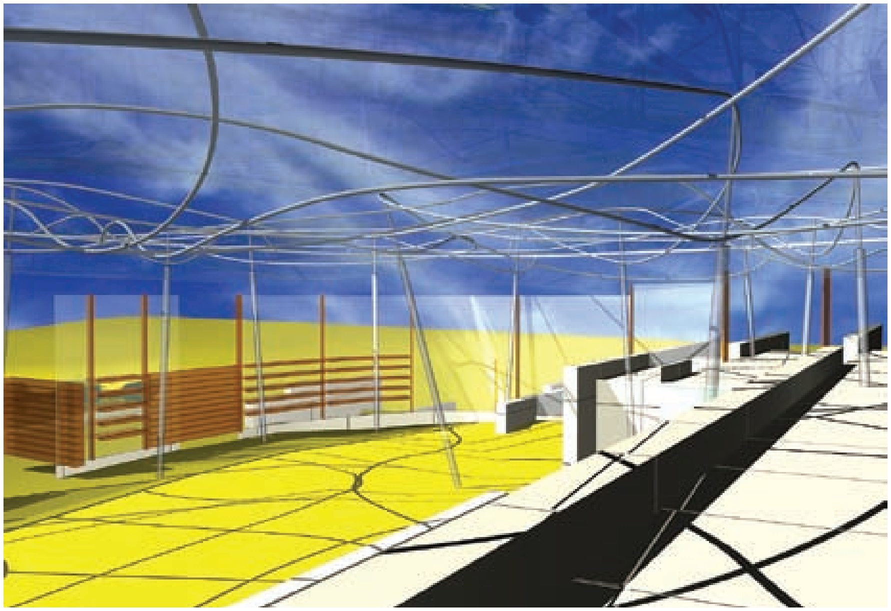


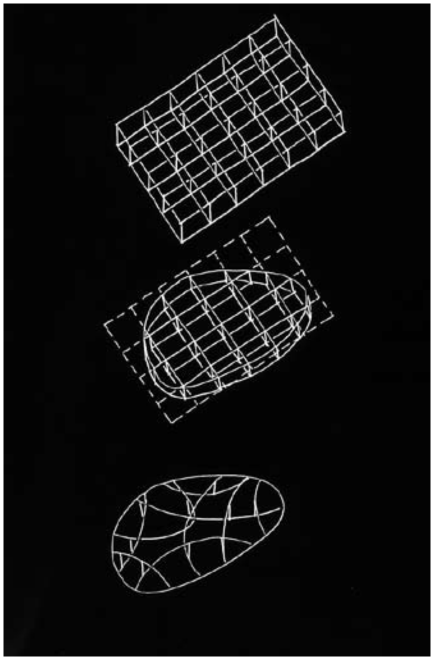
Fig. 3: Interior view of Elephant-Haus, Cologne, Germany, 1999.



4: Digital model of the Elephant-Haus, showing the concept: trees–clouds–sun– earth–stones–water. Interior and exterior spaces blend together into a spatial and functional continuity.



5: Digital model of the Elephant-Haus. A cloud hovers over the trees, a rough cliff face, a ridge holds them in place as elephants move past.



6: Orthogonally gridded space structure and non-gridded space structure.

a finite-element-model, this time of the actual spatial framework and, after that, a finite element re-analysis of the spatial framework for deformation, swinging and deflection. The finite element method is a procedure used to solve structural or mechanical calculations with precedence given to the three-dimensionality of the system. It involves breaking the construction into discreet elements – its 'finite elements' (such as columns, beams, plates, or shells) – that are characterized by their individual connections where they are combined with one another – the 'discreet points.' The result of this process is an extremely lightweight optimized structure that is based on the parameters of the column positioning within the free plan geometry.

In principle, there are multiple possibilities for structural optimization. One is presented here, where span-trajectories are made continuous to eliminate the elements that carry less weight, while subdividing the remaining ones. The result is continuous, self-intersecting structures. Each step of structural adaptation optimizes the entire system, and at every stage of the development the safety of the total construction is ensured.

Another possibility for structural optimization looks to natural constructions for inspiration. Computer-generated genetic algorithms use goals to achieve optimization. Using algorithms, mechanical selection, mutation and recombination improves the structure with a fixed parameter size and quality. The basis for the optimization is a vast array of possible solutions (population), where every solution (individual) is defined through a particular parameter (chromosome). The individuals within a generation are in competition with one another (selection), in other words, the value (fitness) of the individual is what allows the survival of the parameter (gene) until the next generation. The results of this computer-supported process are automatically generated and optimized.

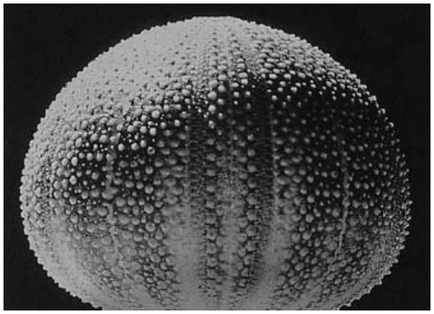
The Secondary Structure – A Fluoropolymer Pillow

As a result of roof structure's complex geometry and dynamic qualities, it was necessary to select a flexible membrane for the actual roofing material. We chose to use a three-ply transparent membrane made of fluoropolymer. It gave us approximately 96% transparency and was extremely lightweight (150 grams per m^3 in a material 0.2 mm thick). Glass would have performed far worse in these two criteria, letting in less light with much more weight. The fluoropolymer sheeting was also flexible, self-cleaning, and weather protected. Pillows of membrane sheeting are filled with air from tubes that run along the steel framework. The inflation pressure for the pillows is computer-adjusted to accommodate external forces such as wind and snow loads. Because the space between the building's roof and its walls must be able to withstand the expected large deformations of the roof, they were also planned as pneumatic pillows. The steel and glass wall system is independent of the roof.

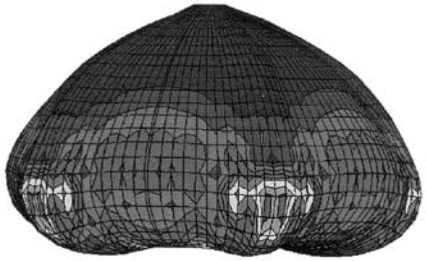
The Tempered Environment of the Habitat

The energy concept is designed to utilize wind and sun, minimizing the need for additional mechanical climate control. The roof membrane is an active component in this system, acting as an adaptable collector surface that can react to the changing parameters of light and temperature. On a summer day, surplus heat is expelled through cross-ventilation, aided by the aerodynamic qualities of the roof and louvers made of pneumatic tubes. During the night, trombe walls store cool air for release at peak heating times the following day. Conversely, heat stored during the day is released at night to keep the temperature balanced.

On a winter day, the roof is able to collect solar heat even on cloudy days, pre-heating fresh air, the intake of which is regulated. On cold nights, the trombe wall can be provided with supplemental warmth, using an earth heat pump. In this way, the walls serve as low-temperature radiators, their large storage capacity and surface dimension creating a balanced interior climate.



7: Structure optimization in the shell structure of a sea urchin. (From Klaus Teichmann and Joachim Wilke, eds. Prozeß und Form: Natürliche Konstruktionen, Berlin: Verlag Ernst & Sohn, 1996.)



8: Finite element analysis of sea urchin shell. (From Teichmann and Wilke 1996)

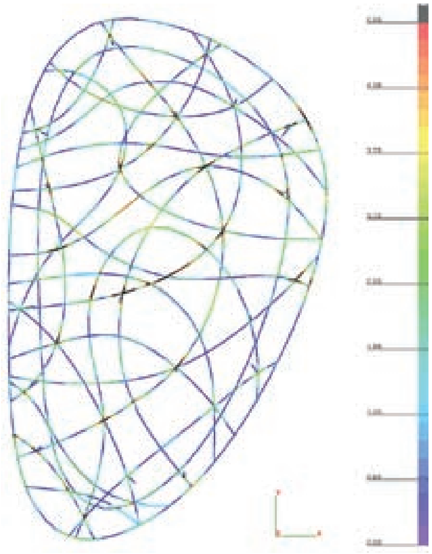
Future Trends

The combination of a form-optimized structural system with an extremely light and flexible material creates an extremely low ratio of steel per square meter. To be sure, tent or cable systems are still lighter, yet the construction system presented here allows new forms in the realm of optimized structural systems. It could also take advantage of new materials, other than steel, which we will look at now.

New Materials

Over the last two decades, architects have increasingly begun to use composite fiber materials made from glass, carbon fiber, or Kevlar™ in buildings. In many conditions, these fiber-reinforced plastics perform better than steel for strength, as well as offering stability, minimal weight, and resistance to corrosion. Such composite fibers might well replace steel, aluminum or wood in conventional construction, but they also offer new possibilities with respect to structurally optimized systems.

Unlike steel, which is an isotropic material with properties that are equivalent in all directions, composite fibers are an-isotropic. This means that, like wood, their properties are different along their length than along their breadth. Such directionality allows composite fibers to react extremely well to specific requirements. At the RWTH Aachen, new production methods in the textile industry allow carbon fibers to be made into a variety of three-dimensional building elements, using modified weaving and braiding machinery. These techniques permit highly complicated shapes and sandwich panels to be formed from one piece. In this way, the fibers can be given the precise directionality required by the loading trajectory. Similar material and form optimization processes have been in use since the 19th century in the biological sciences (Culmann; Herschel) and is similar to the 'spongy' structures in bones (Fig. 11). These so-called bone beams are



9: E. Stach, S. Bringman, D. Roos, Spatial stress analysis within the finite element model and visualization of force paths.

always directed along the path of the greatest tension or compression, in other words along the path of the force. In this way, such materials can be used to carry the principle of structural optimization to an ever-greater level of detail – distributing material and weight only where it is structurally necessary. It opens a new dimensions in the optimization of connections, using adhesives developed for plastics and aluminum in the airplane industry.

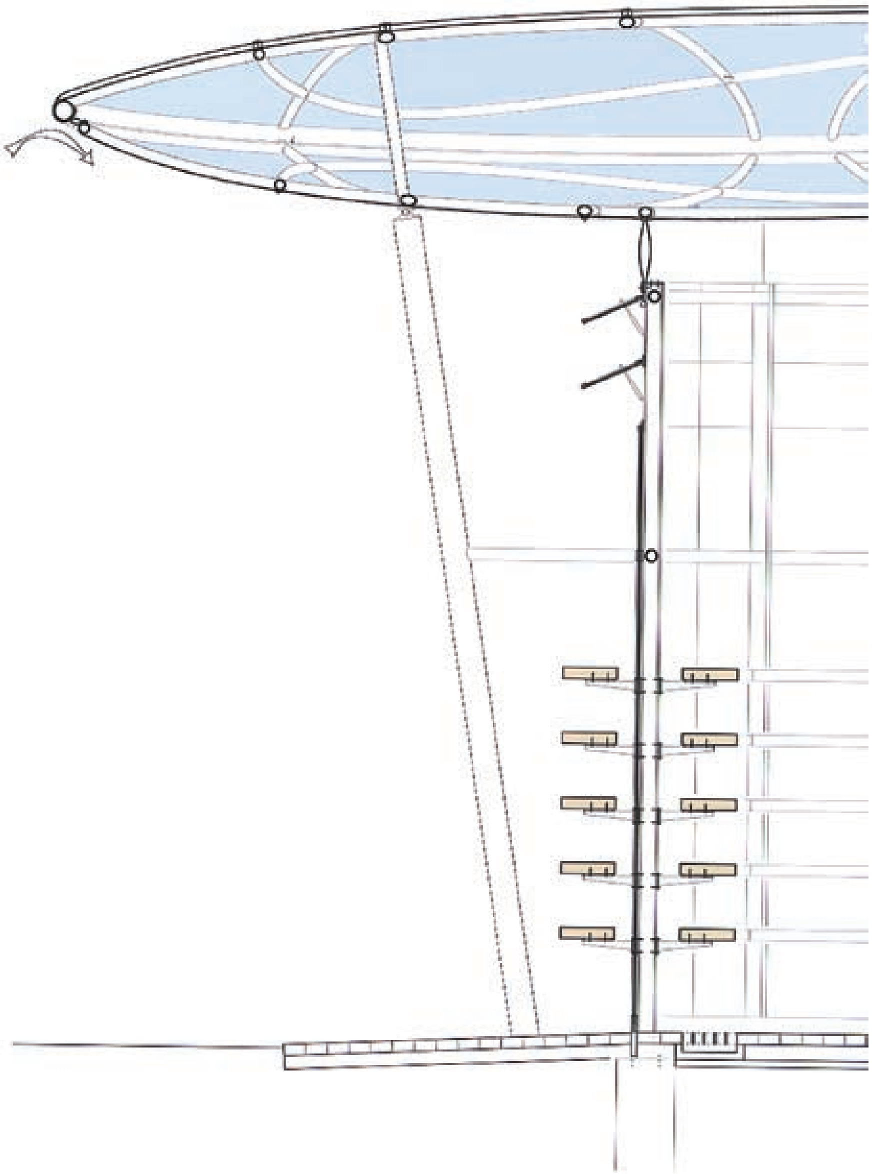
Smart Material Systems

A look into the future of lightweight structures shows that 'smart materials' have a wealth of unexplored possibilities. These are composites made of one or more components, that can adapt themselves to particular external requirements – responding to external changes such as temperature, radiation, loading or electrical current. They generally have reversible properties, so for instance, if they shrink on electrical stimulus, they will later gradually relax. Or if they turn opaque on stimulation, they will become transparent when the stimulation is stopped. In this sense, they somewhat resemble the adaptable, self-repairing structures in nature that can identify a failure and react accordingly. Shape-memory alloys of nickel-titanium (nitinol), form-variable piezoelectric or electro-viscous fluids are already in use in the airplane and space industries.

These 'intelligent structures' have *actuators* that act (like muscles), *sensors* that receive input (like sensory systems), and *communication/calculation networks* that are analogous to the messages and delivery systems in biological creatures. Actuators can vary in shape, stiffness, position, oscillation frequency, or other mechanical characteristics in response to changes in temperature or electromagnetic field. They include shape-memory alloys, piezoelectric ceramics, magnetostrictive materials, and electrical and magnetic rheological fluids that can increasing in viscosity.

Intelligent materials promise to transform building construction. Engineers will no longer ensure safety through determining quantities and costs of materials, and simple structural analysis will no longer suffice. Instead, self-organizing structures will define a new way of building. The concept of self-organization is not new; it is a defining principle of nature. It defines things as simple as a raindrop or as complex as living cell – as a result of the physical laws implicit in the material. One example of self-organization used in the building industry today, is the production of float glass. The defining principle of self-organization is that atoms, molecules, molecular structures and constructive elements can create ordered and functional entities. Human beings might conceive of them or initiate such processes, but once they are started, they move forward according to their own internal plan, searching for an energy-conscious form that develops into a system whose shape and function is directly keyed into the elements of their make-up.

In the future, materials engineers will develop constructions out of self-structuring materials that consciously use the principles of self-organization, creating not only materials with brand new properties, but inspiring architects to define their constructions in a more intelligent way.



10: Detail of roof and wall system, Elephant-Haus, Cologne, Germany, 1999.

Notes

SLang [The Structural Language] was developed at the Institute for Structural Mechanics at the Bauhaus-Universität Weimar. The SLang software package uses the finite-element method as well as probability calculations to model stochastic loading along with physical and geometric improbabilities.

[2] Project team: Steve Bringman and Josef Knipping; Renderings: Peter Hillerman; Structural consultants: Ove Arup and Partner (Düsseldorf); Professors Dr. Bucher and Dr. Dirk Roos, Bauhaus University Weimar.

Ernst Haeckel, born Feb. 16, 1834, Potsdam, Prussia [Germany] died Aug. 9, 1919, Jena, Germany. A zoologist who was a strong proponent of Darwinism proposed a new notion of the evolutionary descent of man.

Design of Elephant-Haus by Klinkhammer and Stach Architects, all drawings are by the author unless otherwise noted.

APPENDIX

Manuel Báez is an architect and an Associate Professor at Carleton University, School of Architecture. Previously, he worked and practiced in New York City while teaching at The Cooper Union for the Advancement of Science and Art and the Rhode Island School of Design. Báez has exhibited and lectured internationally on his research. Funding has been provided by The Canada Council for the Arts, The New York Foundation for the Arts, The Cooper Union for the Advancement of Science and Art, Cranbrook Academy of Art and Carleton University. He received his B. Arch. Degree from The Cooper Union and M. Arch. Degree from Cranbrook Academy of Art.

Sarah Bonnemaison teaches in the architecture faculty of Dalhousie University. Her research focuses on the relation between nature and architecture both historically and in her own design practice. This research has resulted in a book entitled Architecture and Nature: Creating the American Landscape (Routledge 2003) co-authored with C. Macy. She also has a long standing interest and a design practice in ephemeral architecture for festivals and special events which has resulted in numerous articles and a co-edited book entitled Festival Architecture (Routledge 2007).

Nat Chard is currently working on a research project titled "Drawing indeterminate architecture, indeterminate drawings of architecture." He is professor and head of architecture at the University of Manitoba. Prior to this he held a professorship at the Royal Danish Academy in Copenhagen for five years and before that taught in London at the Bartlett, University College London as well as North and East London universities. He has lectured and run workshops internationally and spent many years in practice.

Dörte Kuhlmann is professor of Architecture Theory and Gender Studies at the Vienna University of Technology. Previously she has worked as a visting professor at UIC in Chicago and lectured at the Bauhaus University in Weimar. Among her major publications are Lebendige Architektur. Metamorphosen des Organizismus (1998), Mensch und Natur. Alvar Aalto in Deutschland (1999),Cybertecture (together with Heimo Schimek 2001) Building Gender (together with Kari Jormakka 2001), Building Power (together with Sonja Hnilica, Kari Jormakka 2003), Raum, Macht&Differenz (2003), Design Methods (together with Kari Jormakka, Oliver Schuerer 2007)

Christine Macy is a professor in architecture at Dalhousie University. Her research areas include the representation of cultural identity in architecture and public spaces, civic infrastructure, temporary urbanism and festival architecture. A graduate of UC Berkeley and MIT, in 1990 she formed Filum, a design-research partnership with S. Bonnemaison, specializing in lightweight structures and designs for festivals. They have lectured on and exhibited their work internationally and are co-authors of Architecture and Nature (Routledge 2003), and Festival Architecture (Routledge 2007). Macy has also recently completed a visual history of dams in the United States, Dams (W.W. Norton, forthcoming) and a chapter on the architectural design of dams in TVA: Design and Persuasion (Princeton Architectural Press 2007).

Reinhold Martin is Associate Professor of Architecture Columbia University, where he directs the PhD program and the Master of Science program in Advanced Architectural Design. He is also a founding co-editor of the journal Grey Room, a partner in the firm of Martin/Baxi Architects, and has published widely on the history and theory of modern and contemporary architecture. He is the author of The Organizational Complex: Architecture, Media, and Corporate Space (MIT Press, 2003), and the co-author, with Kadambari Baxi, of Entropia (Black Dog, 2001) and Multi-National City: Architectural Itineraries (ACTAR: forthcoming in 2007). He is currently working on a book that re-theorizes postmodernism.

Hans Joachim (Hajo) Neis holds a Dipl.-Ing. from the Technical University of Darmstadt and graduate degrees in architecture and planning as well as a Ph.D. from the University of California, Berkeley. He is an associate professor at the University of Oregon, where he teaches urban architecture and urban theory at the Portland architecture programs, where he is also the director since 2005. Before joining the faculty at Oregon, he taught 'Building Process' at UC Berkeley for ten years with Christopher Alexander. His main interests in research include quality and value in architecture and urban structure, and the processes which create quality. The author of numerous articles in English, German, Japanese and Greek journals, he is also co-author of several books, including A New Theory of Urban Design (Oxford 1987), Schule des Sehens (Fachhochschulverlag 2000), and the forthcoming Battle (Oxford).

Kevin Nute is a professor of architecture at the University of Oregon. He trained as an architect at the University of Nottingham in England before going on to work in professional practice in London, Hong Kong and Singapore. He earned his doctorate at Jesus College and the Martin Centre for Architectural and Urban Studies at Cambridge University, and is the author of the A.I.A. award winning monograph Frank Lloyd Wright and Japan (Van Nostrand, 1993/2000), and Place, Time and Being in Japanese Architecture (Routledge, 2004). He taught part-time at Cambridge until 1995, when he accepted a research fellowship at Tokyo University. He was an associate professor of architecture at another Japanese national university for five years before moving to the University Oregon in 2000, where he now teaches architectural theory and design. He is currently working on his third book, The Architecture of Here and Now, which concerns the human benefits of natural phenomenal change in built spaces.

Ann Richards is trained as a biologist at the University of Wales and Chelsea College, London. After working in biology for several years, she studied woven textiles at West Surrey College of Art & Design (now the University College for the Creative Arts, Farnham), where she later also worked as a lecturer. Her background in biology has influenced her approach to designing textiles and she draws on fundamental principles of growth and form in nature as a source of ideas. Contrasts of fibre and yarn twist allow her to create pieces that transform themselves into highly textured and elastic fabrics. Recent exhibitions include: Artists at Work: New Technology in Textiles and Fibre Art at the Museo del Tessuto, Prato, Italy (2003), a solo exhibition at the Kunstindustrimuseum, Copenhagen (2006) and Digital Experience at Walford Mill Crafts Centre (2007). Her work is in many public collections, including the Crafts Council, London and the Deutsches Technikmuseum, Germany.

Ryszard Sliwka is an associate professor at the University of Waterloo School of Architecture where teaches in the design and cultural history streams. He trained as an architect in England before working and completing a Masters in Architecture and Urban Design at Washington University in St. Louis Missouri. He also trained as a painter and has had numerous exhibitions, both nationally and internationally. Part of the current series of paintings, entitled 'Portraits from the Orphanage' is based on his research of Rome and was shown recently both in Rome and subsequently Turin (2007). A parallel critical practice involves the writing, editing and publication of numerous articles on art and contemporary design. He is currently working on a series of essays entitled "Selective Modernities".

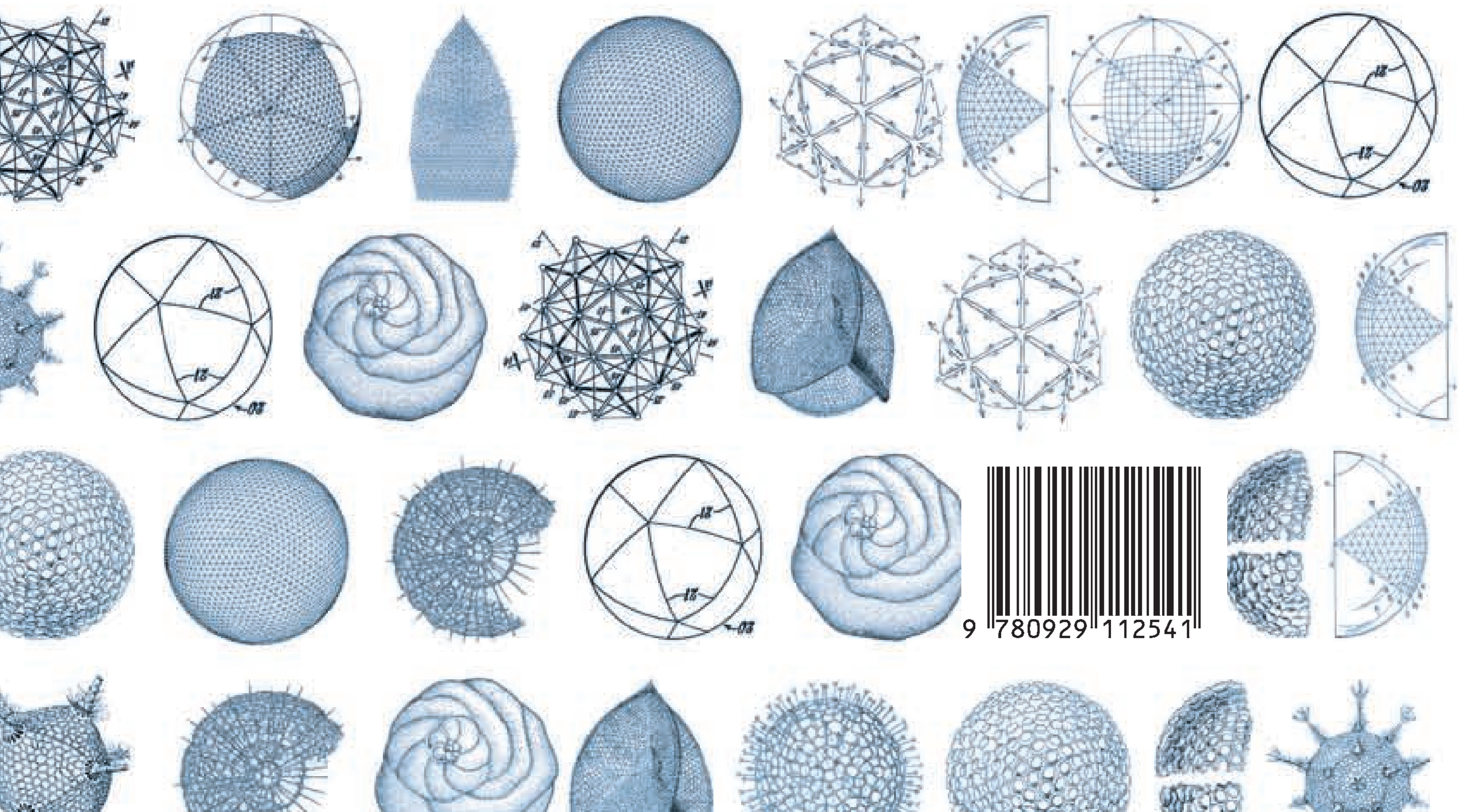
Edgar Stach is founder of the studio Smart Structures and principal at Stach Architects. He established the architecture practice in 1995 in Weimar, Germany and since 1999 in Knoxville, USA. His focus on materials, technology and sustainability is supported through a mode of working that combines practice, teaching and research. He actively takes part in the discourse of contemporary architecture through participation in international design competitions. The work focuses on efficiency, ecological sensitivity and responsibility and reflects our concern for the built environment. Smart Structures, Stach Architects received national and international design awards and recognition including the Cologne Zoo and the New City Hall Weimar.

Stach is an Associate Professor at The University of Tennessee, College of Architecture and Design. Before joining the faculty at the University of Tennessee, he taught at the Bauhaus University Weimar. His current research centers on lightweight structures in architecture with regards to new materials and construction methods.

Hadas Steiner is an associate professor of architectural history and theory at the University at Buffalo, SUNY whose research concentrates on the cross-pollinations of technological and cultural aspects of architectural fabrication in the postwar period. She is the author of two books on the Archigram magazine and group: Beyond Archigram: The Technology of Circulation (Routledge 2007) and the Archigram Network (pending with Infolio). Work in progress includes manuscripts on the photographic documentation conducted by Reyner Banham while in Buffalo, the techno-zoological architecture of Cedric Price, as well as the architecture of extreme conditions, including the work of John McHale. She received a PhD in the History, Theory and Criticism of Architecture from the Massachusetts Institute of Technology in 2001. Her research has been supported by a Visiting Scholarship from the Canadian Centre for Architecture, as well as grants from the Graham Foundation and numerous institutional awards from SUNY and MIT.

On Growth and Form

This collection of essays by architects and artists revisits D'Arcy Thompson's influential book *On Growth and Form* (1917) to explore the link between morphology and form-making in historical and contemporary design. This book sheds new light on architects' ongoing fascination with organicism, and the relation between nature and artifice that makes our world.



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