Systems Architecture: A New Model for Sustainability and the Built Environment using Nanotechnology, Biotechnology, Information Technology, and Cognitive Science with Living Technology

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Abstract This report details a workshop held at the Bartlett School of Architecture, University College London, to initiate interdisciplinary collaborations for the practice of systems architecture, which is a new model for the generation of sustainable architecture that combines the discipline of the study of the built environment with the scientific study of complexity, or systems science, and adopts the perspective of systems theory. Systems architecture offers new perspectives on the organization of the built environment that enable architects to consider architecture as a series of interconnected networks with embedded links into natural systems. The public workshop brought together architects and scientists working with the convergence of nanotechnology, biotechnology, information technology, and cognitive science and with living technology to investigate the possibility of a new generation of smart materials that are implied by this approach.

The concept of sustainability within the practice of the built environment can be summarized as the management of the energy flow between the natural and built environments. Current approaches to generating sustainable cities aim to minimize the flow of energy from natural resources into man-made structures. Internationally agreed-on targets are implemented to reduce and minimize the amount of energy transferred from the natural to the urban environment. Modern architects endeavor to set exemplary standards of sustainable building practice, which can influence the construction industry. However, architects have a limited influence on the reduction of energy flowing from the natural world into the built environment, since most existing building stock was constructed before sustainability became a primary concern for designers, developers, and policymakers. Strategies for sustainability include the reduction of water consumption, recycling or use of materials with low environmental impact, the conservation or enhancement of natural systems, and the generation of energy from renewable sources such as light and wind.

Best sustainable practice within the field of architecture is currently demonstrated by designing a wide variety of iconic buildings, such as Gordon Graff's Sky Farm [2] proposed for downtown Toronto's theatre district. Graff's design advocates 58 floors, 2.7 million square feet of floor area,

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and 8 million square feet of growing area that can produce as much as a thousand-acre farm, feeding 35 thousand people per year. Other versions of model sustainable architectures include ecologically friendly houses such as Panasonic's Eco & UD (Universal Design) house, built for the Eco-Products Exhibition in Tokyo 2006 [1], which was designed to minimize environmental impact with a 60% reduction in greenhouse gas by using Panasonic's own products in conjunction with environmentally friendly technologies such as solar panels and a green roof.

Despite their outwardly ecological appearance, this approach to generating iconic sustainable buildings is problematic, since the basic model on which the architectures are constructed does not require a fundamental change in the way that buildings are assembled, which is a key issue in sustainable building practice. Even within the field of architecture the current fashion for "green-skinned" architecture, where modernist architecture is lavishly adorned with plants, transforming the environment into an urban greenhouse, is recognized to be a superficial approach to the systemic issues at the heart of sustainability and is colloquially referred to as gling,[1] or green bling, by the British architect Richard Rogers.

The Architect Neil Spiller, director of AVATAR (see below) and vice dean of the Bartlett School of Architecture, attributes the environmental malaise of contemporary architectural practice to its obsession with permanent, immutable objects [24], whereas true sustainability is derived from the collective attributes of complex, dynamic systems. He argues that the dichotomy between artificial and natural worlds and their lack of genuine connectedness are problematic for architects working with sustainability. Spiller's vision is that the built and natural environments need to be coupled together so that energy and information flow freely from the biosphere to the metropolis and back again. In this way resources are shared between the built and natural environments; this should be regarded as an integrated, complex process. This energetic and informational holism is lacking in contemporary architecture, compounded by modern building design practices that adopt a Cartesian, object-centric view of architecture. This view, involving inert materials, which are assembled using Victorian construction methods [25], has profound limitations when dealing with issues of sustainability. It has effectively constrained innovation in the built environment to the practice of aesthetics.

Spiller founded the Advanced Virtual and Technological Architecture Research (AVATAR) Group in 2004, to explore these systemic problems of formalist aesthetics and superficiality in the discipline of the built environment from a design perspective. AVATAR's research agenda explores all manner of digital and visceral terrain and considers the impact of advanced technology on architectural design, engaging with cybernetics, aesthetics, and philosophy to develop new ways of manipulating the built environment.

Professor Spiller and Dr. Rachel Armstrong, a research fellow at the Bartlett School of Architecture, proposed a new theoretical framework to critique sustainability within the built environment during an interdisciplinary workshop and public forum at the University College London on Darwin Day, 12 February 2009. Architects were brought together with scientists working with the convergence of nanotechnology, biotechnology, information technology, and cognitive science (NBIC) and living technologies, to reflect on the possibility of architectural practices as having materially embedded connections with nature, using a *systems architecture*[2] approach to enable the flow of information and energy between the natural and built environment.

Spiller and Armstrong's framework was a new methodology and model for the practice of systems architecture. This is a specific interdisciplinary application where the discipline of the study of the built environment is contextualized within the scientific study of complexity, or *systems science*, and adopts the perspective of systems theory[3] [5]. Using the systems architecture model, which

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1 "Gling" is a colloquialism created by the fusion of the words "green" and "bling," the latter being derived from hip-hop culture to refer to flashy or elaborate accessories that are worn for their high aesthetic impact rather than their practical value.

2 Systems architecture is the study of the built environment described in the context of complexity science, or systems science. It is distinct from the perhaps more familiar terminology used to describe information infrastructure in computing that refers to the fundamental structure and overall vision of a system, its functionality, and human interaction with these components [6].

3 Our architectural investigation into complexity examines complex systems in terms of their design and organizational context, following the principles of systems theory, which is an interdisciplinary field of science that provides a framework by which any group of objects that work in concert can be described. This could be a single organism, any organization or society, or any electromechanical or informational artifact; we are particularly interested in how these systems become embodied.

can be seen as similar to systems architecture in computer science (CS), the built environment (or the system in CS) becomes integrated with the natural world (the hardware) and a series of networks or functions that are orchestrated through organizing *hubs* of activity and computation (the software). This radical departure from traditional architectural perspectives enables architects to consider the built environment as a series of interconnected networks with embedded links to natural systems [18]. The architectural subject of interest moves away from simple, inert objects to what is happening at the site of the hubs of activity in the systems architecture model. For architectural purposes these theoretical events need to be embodied, and the practice of systems architecture requires them to possess a materiality. Materials with organizing capabilities that are able to function as hubs within this new model do not exist currently in architectural practice. Systems architecture anticipates the development of a new set of materials that possess the ability to connect nonliving (traditional) structures with vital structures (e.g., nature or the products of living technologies or NBIC technologies) The theoretical organizing nature of these materials implies that they are likely to exhibit some of the properties of living matter such as self-organization, responsiveness, growth, or movement, and would essentially constitute a new generation of smart materials. Unlike contemporary smart materials, these speculative organizing systems would possess embodied complexity, be capable of chemical computation,[4] and not need to rely on traditional computing methods or human intervention to generate their responsiveness.

Although these new materials are speculative, recent developments in NBIC technologies and living technology, many of which were demonstrated at Artificial Life XI [7], suggested that it might be possible to conduct an interdisciplinary experiment in an architectural context, to determine whether it is possible to design and engineer materials that meet the requirements of a new generation of smart materials. The guest speakers at the workshop were selected from architectural practice and complexity science for their vision of the possibilities of self-assembling or self-organizing systems with the potential to give rise to new materials, and included Martin Hanczyc, Alexandru Vladimirescu, Klaus-Peter Zauner, Seth Bullock, Christian Kerrigan, Turlif Vilbrandt, Bruce Damer, and Sylvia Nagl.

Spiller's introduction to the workshop described the departure of systems architecture from contemporary models of the built environment and outlined the field of architectural research in which the workshop's agenda was located. Spiller introduced his own work and original vision of architecture that explored the possibilities of architectural space and what has constituted architectural practice over the last 15 years. Spiller was one of the first architects to work with notions of *cyberspace* [21–23] that enabled him to break down the formalist constraints of architecture, which he reinterpreted in a much broader context and summarized in his notion of *plectic architecture*[5] [25]. This term refers to the parameters that need to be considered for architectural composition in a technologized, early-twenty-first-century society. Spiller also noted that the study of complexity within the discipline of the built environment was not a new concept and was, historically, extensively recognized. However, he also argued that systems architecture could be applied to material issues in ways that enable practitioners to look for embodied solutions to complex architectural problems. Spiller observed that the use of computational tools to address architectural complexity was not a new practice, and generally resulted in the mass production of various ambiguous shapes that were subsequently used to construct iconic buildings composed of inert materials. Spiller also noted that culturally we are at an important perturbation point in technology and epistemology that would radically affect architectural practice. Spiller suggested that cell biology would be as important for generating new possibilities within the discipline of the built environment as cyberspace and nanotechnology were in the 1990s.

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4 Also known as material computing, chemical computation is performed by molecules that are able to make decisions about their environment and respond to local cues in complex ways that result in a change of their fundamental form, function, or appearance. Material computers are responsive to their environment and make decisions that result in physical outcomes like changes in form, growth, and differentiation.

5 Plectic architecture is an architectural theory developed by Neil Spiller, described in the context of the *post-digital* world, where "post-digital" does not mean lacking any digital component, but rather means a synthesis between the virtual, the actual, the biological, the cyborgian, the augmented, and the mixed. The term "plectics" was first coined by Murray Gell-Mann [12] as a way of describing the relationship between simplicity and complexity in all phenomenological systems.
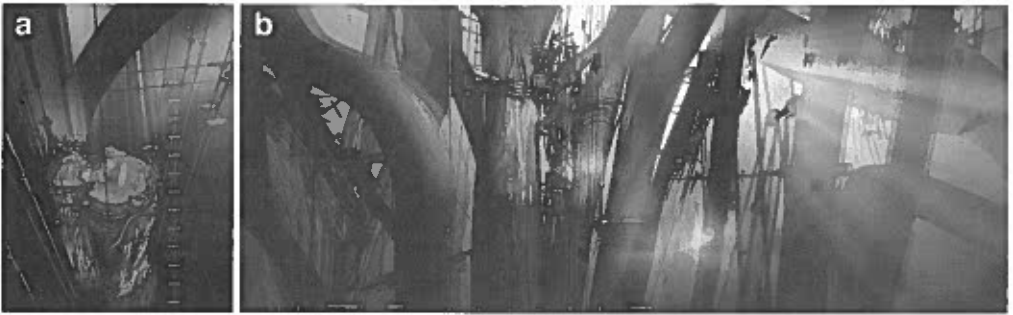
Figure I. 200-year project. The 200-Year Continuum explores the possibilities of growing a hidden architecture that is driven by the growth imperative of trees, using a form of extreme bonsai technique that generates a symbiotic relationship between the natural material and speculative nanotechnology. The mechanism used in this system harvests the growth imperative of yew trees to grow a ship, and exploits the change in density of a growing tree when it is restrained and compressed in a metal corset so that it can be more effectively used for construction. The project was envisaged with a 200-year life span, and a design experiment to explore the time-based nature of the work was conducted on the system. An arbitrary point at a late stage in the construction of the system was chosen at around 150 years, in order to understand and choreograph the effect that a radical brief change would produce. It was assumed that the system was no longer needed to produce a ship, but was rather to be harnessed to excavate an obelisk using the partially formed ship's timbers, and the design challenge was to rearticulate the system to achieve these new ends.

Armstrong described systems architecture as a utopian, hypothetical, interdisciplinary strategy to generate new sustainable design possibilities in architectural practice [4]. Importantly, the propositions made by systems architecture were testable, which had been made possible by the development of embodied technologies capable of self-organization. Some embodied technologies had reached an experimental stage of development that facilitated testable propositions requiring collaborative projects with architects and scientists working at the intersections of NBIC and living technology [3]. The objective of the workshop was to catalyze discussion about the possibilities and intersections between the attending architects and scientists making the presentations, and to take the first steps toward an interdisciplinary exploration that would result in architectural design outcomes. Armstrong noted that the resultant social and cultural implications of the experimental work were an integral part of the methodology, and the audience (which included scientists, architects, and researchers from the humanities) was actively encouraged to participate with questions following the speaker presentations and the roundtable discussion at the end of the workshop.

Nic Clear, a teaching fellow at the Bartlett School of Architecture, demonstrated a new way of thinking about the practice of architecture, enabled by the systems architecture model, using his notion of *synthetic space*. Clear used video as his architectural medium to explore the complexity of psychogeographical[6] narratives that exist within cities, and the changing nature of architectural practice in the context of new technologies. Clear proposed that digitally created images were an architectural medium in themselves, which did not allude to "something else," but speculated that a whole new series of possibilities for architectural production would be possible if the "virtual" medium were made tangible and accessible in other ways. This could be achieved through the production of new materials generated through the convergence of the NBIC technologies.

The Architect Christian Kerrigan presented his recent project entitled "200 Year Continuum" (Figure 1), which had been conceived of as an architectural thought experiment that raised questions about the permanence of buildings, and speculated on the plausibility of life cycles within an urban setting. 200 Year Continuum harnessed the growth imperative of a copse of yew trees to grow a ship that theoretically unfolded over two centuries and exploited their potential for change over time using speculative nanotechnology to achieve the design outcomes. Kerrigan's design work visualized how natural and artificial systems could potentially work symbiotically to generate a new kind of

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6 *Psychogeography* was defined in 1955 by Guy Debord as the "the study of the precise laws and specific effects of the geographical environment, consciously organized or not, on the emotions and behavior of individuals" [11].

dynamic architectural phenomenon whose effect would be most clearly observed over an extended period. Kerrigan also noted that new possibilities within architectural practice were possible through an alternative engagement with the dimensions of space-time that are currently absent from architectural practice. These raised the possibility of gathering real-time data about our emerging cultures, environmental interactions, and digital interventions as a means of communicating a new disposition to future natures or synthetic ecologies.

Kerrigan also referred to his collaboration with another guest speaker, Professor Martin M. Hanczyc from the Center for Fundamental Living Technology at the University of Southern Denmark, who was working with simple chemical models of natural living cells, or *protocells* (Figure 2). Hanczyc's protocell agents could be constructed using a bottom-up approach by mixing together a small set of molecules
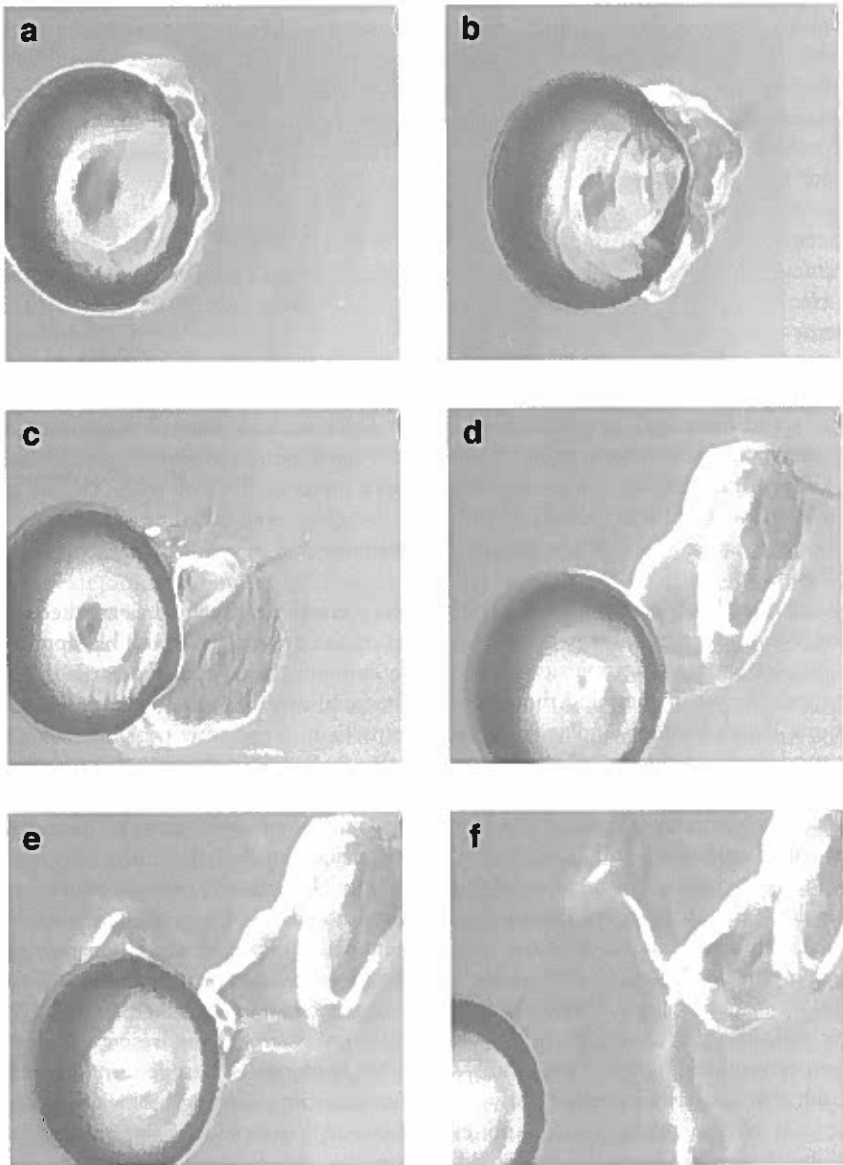

Figure 2. A time-based series of images, ranging from 0 to 150 s, showing a protocell shedding a skinlike coating that has potential architectural properties.

that self-organized into analyzable embodied structures. Some of the protocell structures possessed properties that are characteristic of living systems, and are examples of living technology. Hanczyc hypothesized that it might be possible to appreciate the fundamental properties of living matter and perhaps begin to understand what constitutes life itself through observation and analysis of these spontaneously occurring structures. Hanczyc had constructed a very simple protocell system that consisted of only five different chemicals and exhibited self-propulsion [13]. Movement in the proto-cell system was self-directed and responsive to external chemical signals that caused the protocell to exhibit a primitive form of *chemotaxis*, or directional movement toward a chemical signal in the environment. Hanczyc's current research investigated how such a lifelike self-propulsion system could emerge in simple chemical systems. Hanczyc regarded the protocell system as exhibiting a form of computation, since it was able to navigate a complex environment by responding to environmental cues with directional and controlled movement using chemotaxis, enabling the individual protocell agents to make decisions. These "smart" protocell agents could be used as experimental model systems for the investigation of abstracted living processes that could subsequently be physically manipulated to produce architectural design outcomes from a unique, bottom-up perspective. Hanczyc had also observed that protocells exhibited additional architectural properties with a nonlinear relationship between individual protocells and their populations. Since one protocell acted as part of the environment for a neighboring protocell, a large group of protocells could exhibit more complex population-scale behavior. It was also possible to manipulate the landscape, leaving local decisions and computations to the agents themselves, so that the role of the designer was to define the operational parameters of the system by constructing the agents and establish the location in which they operated. Hanczyc noted that protocells could be used as *architectural living technology* (ALT), representing a systems science approach to architectural design, which blurred the distinction between artificial and natural living systems and, by implication, the boundary between the built environment and the landscape.

Kerrigan's and Hanczyc's presentations suggested that architects and scientists working with complex systems have a common point of entry and language through exploring visualization techniques as a form of experimental hypothesis. Kerrigan's protocell-inspired work, created in collaboration with Hanczyc, graphically visualized the possible architectural outcomes of such a system and speculated on the nature of the protocell generated materials and how this technology might work in practice (Figure 3).

Speculative models of the behavior of the technology could be presented as architectural graphic design outcomes, under an informed understanding of the system as a possible approach in the study of complex systems. Complexity is notoriously unpredictable even when using sophisticated computer modeling techniques, and the use of architectural visualization techniques could contribute to a more detailed understanding of these systems than is currently possible using traditional computer modeling techniques and could thereby offer fresh approaches toward the development of a new generation of smart materials based on NBIC technologies and living technology.

Dr. Alexandru Vladimirescu, a scientific researcher at the National Institute of Research and Development for Microbiology and Immunology (Cantacuzino) in Bucharest, Romania, outlined the potential of the green algae *Bryopsis* as an experimental model that could form a connection between synthetic biology and architectural design. Vladimirescu noted that many resources had been allocated to create life from scratch or to use genetic methods to create synthetic organisms following the pioneering work of J. Craig Venter, using a systems genomics approach to transplant a *minimal* genome [14]—one containing the fewest possible genes to keep an organism alive—to a genome-free prokaryotic cell, in order to obtain the first "artificial" organism. Vladimirescu outlined his non-genetic approach to building living organisms, which has been made possible using a synthetic biology approach that aimed to construct new cells by reorganizing existing biological systems at the subcellular level. New functions that did not exist in the original biological system could be created by rearranging the working *organelles* that could be found in biological systems, such as chloroplasts and nuclei. Vladimirescu observed that completely new elements could be introduced into the cell matrix, including artificial structures like magnetic particles or even whole bacteria [30]. Vladimirescu's
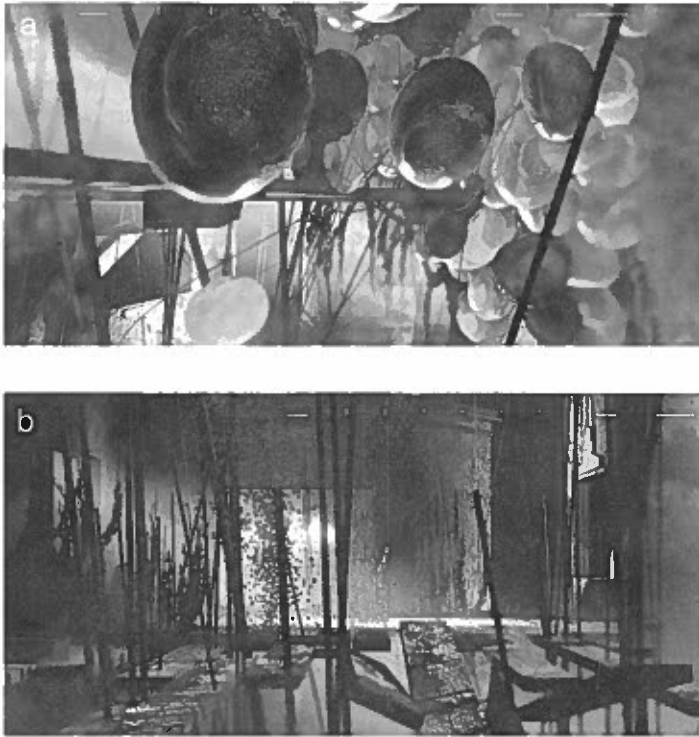
Figure 3. Architectural design of protocell technology. (a) Kerrigan, working in collaboration with Hanczyc, explored the design possibilities implicit in the observed properties of protocell technology to speculate on the kind of material the system could produce for architectural use. (b) Architectural design of an aqueous architecture generated from a protocell-generated, bottom-up assembly process.

model organism was the green alga, *Bryopsis plumos* (Figure 4), a single giant cell (maximum 30 cm in length) with extraordinary powers of regeneration that had been demonstrated in previous experiments where *Bryopsis* was able to return to its original structure even after it had been completely mechanically destroyed [29]. Over the course of a month the *Bryopsis* protoplasm could regenerate new cells and thalli in a very hostile medium, such as seawater. Vladimirescu also noted that during the regeneration process *Bryopsis* protoplasm could entrain foreign elements, such as fluorescent *E. coli* bacteria harboring the gene for green fluorescent protein, or inorganic elements such as magnetic particles. Vladimirescu suggested that the systems architecture methodology, where synthetic biology worked in concert with architectural design, offered new possibilities for scientific researchers and architectural designers where natural materials could be connected to artificial environments at a fundamental level and from which it would be possible to build a cell into a functional whole according to a set of design specifications. Vladimirescu supposed that the resultant materials had a broad range of potential applications in biotechnology, and in synthetic ecologies such as those used in terraforming and architecture.

Dr. Klaus-Peter Zauner, a senior lecturer in the Science and Engineering of Natural Systems Group (SENSe), explored adaptability as a function of semibiotic systems that facilitated the integration of the built environment with the natural world at a basic level of organization. Zauner observed that the sharp boundary separating the animate from the inanimate world is a fairly recent development of science and conjectured that it is already about to blur again with the advent of engineered systems that incorporate functional biological components such as molecules, cells, and tissues [31]. Zauner noted that current design methodologies are inadequate to deal with this new realm of engineering and that the dictatorial control paradigms that have governed the engineering of physical systems are too brittle and require too much predictability to cope with autonomous

components [26]. Zauner argued that evolution itself had only been possible because the computational and engineering laws governing the materiality of systems were capable of diverse responses to changes in their environment. Zauner highlighted unpredictability as one of the essential characteristics of complexity, citing Michael Conrad [9], who declared that the degree to which a system can be controlled, its evolvability, and its efficiency could not be maximized simultaneously. Zauner explored this paradoxical situation in engineering design, which Conrad called the "tradeoff principle," with examples from the laboratory ranging from molecular computing architectures to cellular controlled robots. Zauner then reflected on the adequacy of contemporary engineering toolkits to accommodate semibiotic systems and what kind of augmentation to the existing design methodologies would be necessary in order to engineer systems comprising autonomous components that cannot be programmed or otherwise prescriptively controlled.

Dr. Seth Bullock, director of the Institute for Complex Systems Simulation at the University of Southampton, reported on how self-assembling architectural systems generated by primitive life forms such as termites continued to be poorly understood. He presented research that explored possibilities in the construction mechanisms underpinning termite cathedrals, using computer modeling techniques. Bullock observed that the assembly of autonomous agents with primitive behavior could generate architectural structures from a bottom-up perspective and argued that analysis of this phenomenon could offer a methodology for research into how distributed intelligence might be connected to living systems. Bullock's hypothesis was formulated around the behavior of social insects, such as termites, ants, wasps, and bees, which create some of the most spectacular structures seen in nature. Termite nests in particular have been built on a scale that is matched only by human
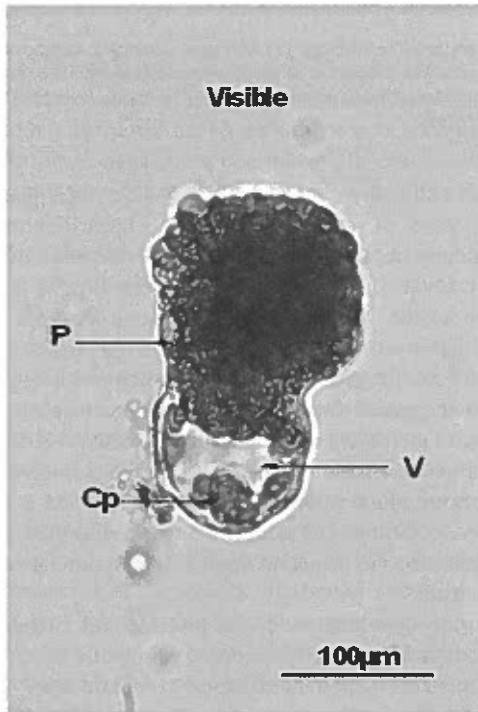

Figure 4. *Bryopsis plumosa* protoplasm aggregation in the presence of foreign magnetic particles under different fluorescent stains. V = vacuole-like structure, Cp = chloroplast, P = magnetic particles. A droplet of *Bryopsis* protoplasm, consisting of a vacuole, chloroplasts, and a developing cell wall, that has been generated by mechanical destruction of the giant cell thallus. Following regeneration in seawater that included magnetic particles, the *Bryopsis* protoplasm is observed to selectively take up the magnetic fragments and place them in the chloroplasts. Courtesy Alexandru Vladimirescu, National Institute for Research and Development in Microbiology and Immunology (Cantacuzino), Bucharest, Romania, 2008.

cities. Over and above their impressive scale, these architectures were of interest owing to their sophisticated functionality that included purpose-built structures for fungus farming and inbuilt air conditioning properties. Bullock noted that these achievements were even more impressive considering that termite constructions are often built over many generations, and require the cooperative enterprise of many millions of individual insects, each of which is in possession of only relatively simple mechanisms of communication and control. In particular, Bullock observed that the termites' collective building behavior could not be explained through a centralizing hub, either in the form of a "site foreman," such as the queen termite, or some kind of explicit or genetic "blueprint" [15]. Instead, the behavior of individual termites appeared to be driven by local environmental cues, such as the local intensity of various pheromone chemicals, arising as a consequence of the insect colony's own building activity. These *stigmergic* mechanisms could be combined in often subtle and complex ways so that a colony could coordinate as a whole in order to construct complicated architectures. Bullock presented his findings as simple simulation models of termite constructions to demonstrate that some of the characteristic architectural features of early mound construction resulted directly from the interplay of simple physical and chemical mechanisms [7]. Bullock reflected on the extent to which human societies might exploit similar design and construction approaches in the construction of the built environment once the design principles of collective construction were better understood, and pointed out that some of these primitive organizing principles already arose in certain human gatherings, such as refugee camps.

Turlif Vilbrandt, cofounder and board member of the Digital Materialization Group in Japan and cofounder and director of technology at Uformia Inc., USA and Norway, addressed the complex relationship between natural structures and artifice, particularly with respect to the representation of nature in the manufacturing process. Vilbrandt observed that humans and animals had evolved (and live in) an enormously complex dynamic system known as the natural world. Lacking the vast computational resources necessary to explicitly represent and navigate the complexity of the world, the animal and human minds had developed the ability to represent objects implicitly, as simple, clearly delineated, and identifiable boundaries in space. (See Figures 5 and 6.) Vilbrandt noted that traditional manufacturing and design processes, which characteristically have been made by humans without the aid of rapid and exact computation, assumed that any given object or independent part of a larger object was made from a single, homogeneous material.

Currently, raw materials that have been extracted from nature are separated and purified for easy use within this framework. Vilbrandt observed that the lack of explicit computation and the subsequent homogenization of nature resulted in "man-made" objects that clearly stood apart from natural ones (Figure 7). Vilbrandt noted that inexpensive digital computation was allowing us to change the way we saw and interacted with the world so that it could be understood as heterogeneous and could be operated in and modified accordingly. Computation could now be used to control matter and to design and fabricate "natural" solutions and objects with the potential to create products that would be universally superior physiologically, environmentally, and functionally to the current generations of homogeneous manufactured products.

Vilbrandt also argued that it was possible to change methods of fabrication rapidly once people were given access to the digital medium so that they could collaborate globally and share complex information. Such collaboration would result in the decentralization of hierarchical manufacturing systems and replace them with peer-based and localized designs. Vilbrandt predicted that decentralized forms of manufacturing had the ability to place the power of innovation into the hands of the individual and the many at the same moment. Vilbrandt warned that current digital design and fabrication systems had actually failed to capitalize fully on such computation and peer production to date, since existing systems were non-exact, non-volumetric, closed, often complex to use, and fundamentally incapable of accurately representing any real objects [27, 28]. For example, modern computer-aided design (CAD) systems cannot provide for the design of truly heterogeneous or blended objects, such as several colored inks in a glass of water. Noting these limitations, Vilbrandt proposed *digital materialization* (DM) as a new paradigm and framework that offered a holistic, coherent, volumetric modeling system, a symbolic language that was able to handle infinitely many
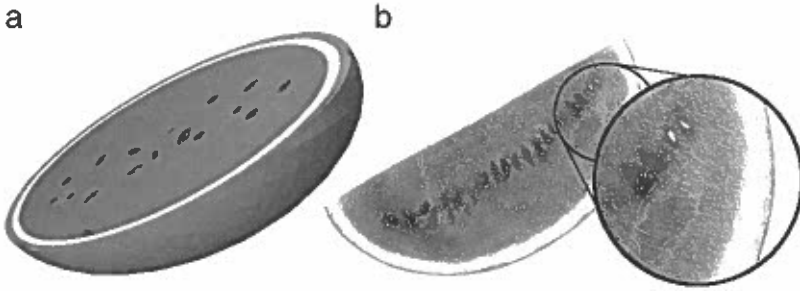
Figure 5. FRep modeling technique. Watermelon informatics: (a) traditional CAD model, (b) real object with heterogeneous structure.

degrees of freedom and detail in a compact format, and control for the direct digital fabrication of any object at any spatial resolution. DM enabled accurate description of objects across all scales and complexity. It was based on the observation that languages and process could computationally and spatially describe real objects [19, 20]. In this way they were able to surpass simple human-made environments and interact more naturally with the complex world. This enhanced ability to describe objects accurately made it possible to capture the complexity and quality of natural and real objects.

To calculate this description, DM was proposed on the basis of *function representation* (FRep), which can represent any given design or object as one continuous constructive function in space and provide whichever level of detail is necessary to suit any computational or machine requirements. (See Figures 8 and 9.) FRep is ideally suited for digital fabrication or other kinds of real-world interactions. Vilbrandt suggested that DM could be thought of as a two-way communication or conversion between reality and information that will enable people to exactly describe, monitor, manipulate, and create any arbitrary real object. Digital and human-made objects would no longer stand apart, but instead would be seen to increasingly emulate and seamlessly integrate with the natural world as part of a systems architectural paradigm.

Bruce Damer, a visitor at the Institute for Advanced Study, was investigating the process by which inert material became vitalized using computer simulation to model molecular representations thought to be present at the time of the origin of life. Damer's computer simulation was intended as a long-term project, and was at a very early stage in its own genesis [10]. From an architectural
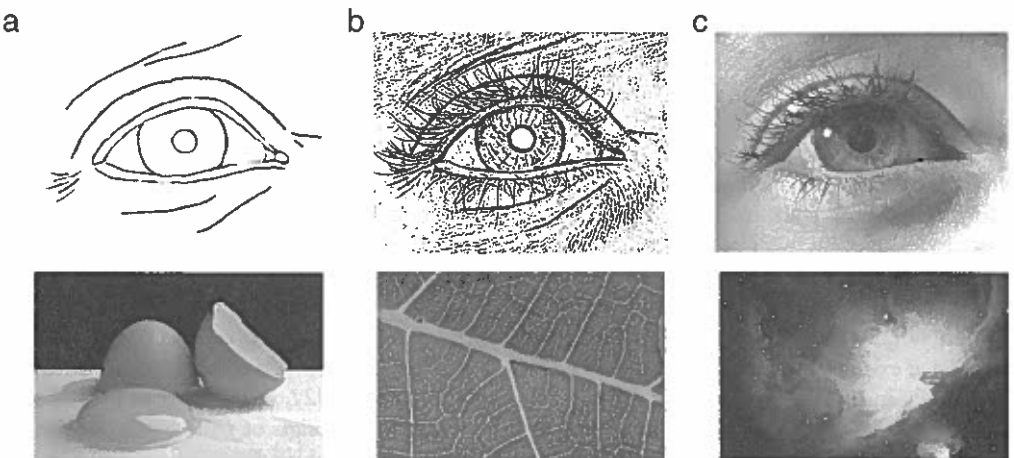

Figure 6. The top set of graphic images shows the different ways humans represent objects: (a) simple, (b) complex, (c) heterogeneous. The images below are examples of real objects that can be represented by these categories.
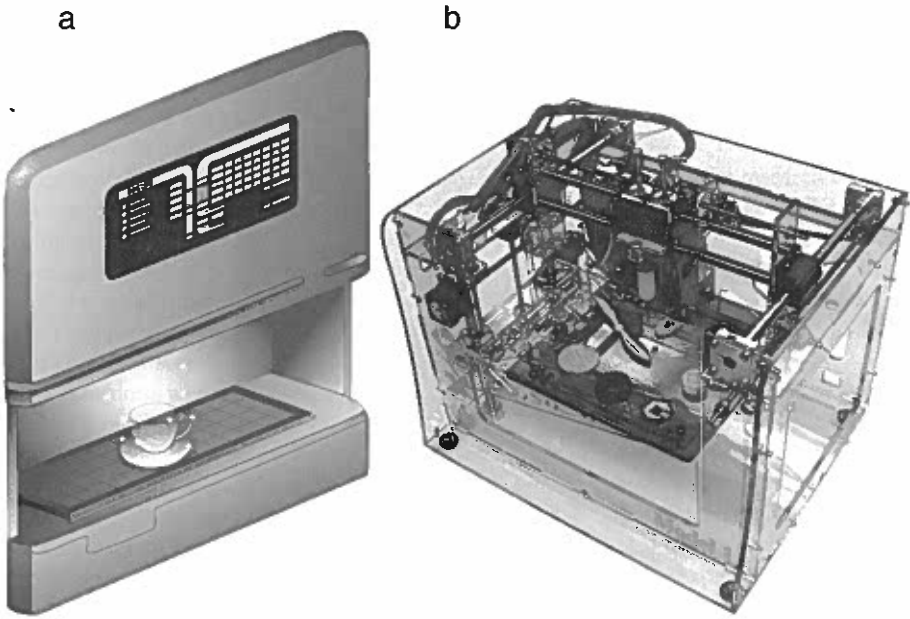
a b

Figure 7. Television's imaginary Star Trek Replicator and the real Fab at Home, a low-cost, 3D desktop printer.

design perspective, Damer's Evo Grid provided a mechanism for creating variations in form based on environmental parameters. This provided an interesting source of self-organizing possibilities with the potential to offer clues to the nature of materials that could function as hubs of activity and forge a more immediate relationship, through computational phenomenology, between the virtual and the real world.

Dr. Sylvia Nagl, head of Biological Complexity at the Cancer Institute at University College London, explored the complex relationships between self-organizing systems, the production of architecture, and evolutionary processes that were implicit in all the previous speakers' presentations. Nagl observed that life is a coherent space-time phenomenon of organized complexity comprising an entangled web of relations within dynamic, nonlinear fluxes of matter, energy, and information that have been established over the course of four billion years of evolution. Some of the information-containing free energy that reached the Earth's biosphere in the form of sunlight could be converted into cybernetic information by organisms. This information was preserved in the intricate structures and processes in these embodied configurations. Subsequently, these gave rise to novelty that resulted in an increase in complexity and statistical improbability that have come to represent the diversity of terrestrial life's form and function. Nagl observed that the methodology of systems architecture was seeking to exploit the creative processes characteristic of life so that they could
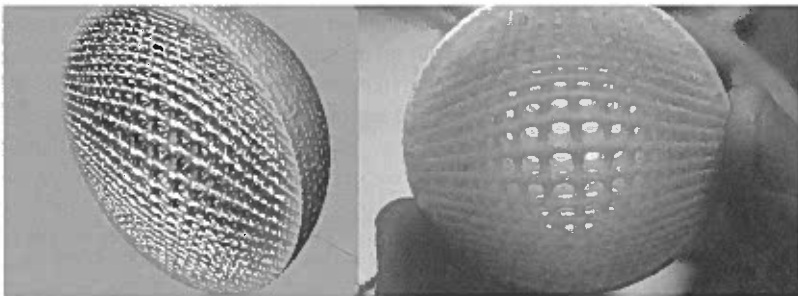

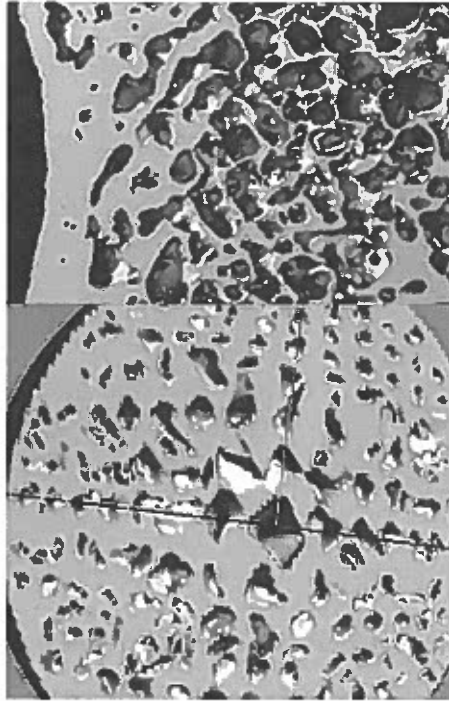Figure 8. FRep-based microstructure and resulting 3D printed object.

Figure 9. Early attempts at applying DM to design and model new objects (or new bones) with the properties of human bone (voxel-based bone model at top, and FRep-based model at bottom).

be seamlessly employed in the context of the built environment. Systems architecture does not strive to mimic these processes, however; rather, it proposes new forms of "biology" that had not been previously encountered. Nagl reflected on how architecture had used biological models as inspiration for generating novelty within the built environment, such as the dynamics of swarms, multicellular systems, symbiosis, parasitic systems, evolution of natural and artificial ecosystems, evolution of molecular networks, and aberrant processes of somatic evolution in cancer [16]. Nagl argued that new methodologies such as systems architecture were needed in order to achieve a new architectural design approach that did not seek to mimic biological systems, but rather to create alternative versions. These methodologies could create high-dimensional networks of embodied structures and processes composed of a range of materials covering the inanimate, the living, the semi-living, the digital, and the nanotechnological. The basic components of these materials would be manifest in physical, biological, and artificial forms of terrestrial matter to differing degrees, and various new assemblages of these components could exhibit original properties. Nagl envisaged animate-inanimate assemblages that could be designed using systems architecture on the meso scale—on the scale of buildings that might, for example, be composed of unicellular organisms, artificial cells and tissues, and digital components with the ability to dynamically adapt and evolve as complex "ecosystems." Nagl also raised the possibility of new evolutionary dynamics between these engineered systems, the human body, societies, and the biosphere, which needed to be considered as a consequence of this process [17]. Nagl also speculated that the contemporary sciences of evolution and complexity could offer valuable conceptual and practical approaches for design and management of these new applications of NBIC technologies and living technology; these could include not only new simulation methods for the design of emergent processes [8], but also thorough ethical and cultural discussion.

A roundtable discussion chaired by Nic Clear raised a few themes as popular topics of interest, the first being the interdisciplinary nature of the proposed work regarding the compatibility of art

and science methodologies. Several of the panelists had an affirmative response to this. It was evident from the presentations by scientists working with new technologies that collaborative experimentation to develop a new generation of smart materials possessing embodied complexity was feasible. It was also notable that the architects had already conceived of applications for these materials, having worked speculatively with these principles through graphics, computer modeling, and film. Kerrigan and Hanczyc's collaboration was especially notable in that their research indicated that synergies existed between architects and scientists working with new technologies. This implied that that interdisciplinary work had the potential to be a mutually beneficial pursuit where visualization techniques, grounded in a common interest in material processes, appeared to play a role in the success of the collaboration. Such synergies, through the practice of systems architecture, were regarded as having the potential to generate new technologies and tools with the capacity to address major challenges in sustainability.

Further questions were related to the implementation of the materials that would be speculatively generated as a result of the workshop. The panelists proposed that systems architecture in practice would operate through a symbiotic relationship between new materials and traditional architectures. For example, the traditional material sandstone, which is able to hold a lot of water, could be used to channel rainwater to support materials made from NBIC technologies and living technology that perform architectural functions within the context of the built environment, such as oxygenation of the atmosphere or removal of toxins. These hybrid materials would be expected to have a life cycle, senesce, and decay as well as to erode and transform the supporting inert matter, thereby sustaining it. In this way it would be possible for architecture to become genuinely dynamic by virtue of the interaction between the two systems, and their connectivity through information and energy exchange with the natural environment. Additionally, NBIC technologies and living technology required architects to think about materials and their applications differently, requiring engagement in collaborative partnerships with the scientists developing these technologies to address a range of design problems in sustainable practice that have not been solvable using traditional techniques. Ultimately, through the practice of systems architecture, these technological developments could lead to the creation of more idealized metropolitan environments that would be sensitive to the needs of their populations and able to anticipate change, evolve, and even respond effectively in the face of emergencies or disaster.

Finally, the implications of these new materials in the context of the contemporary understanding of evolution were raised in the context of the workshop being held on Darwin Day, the 200th anniversary of Darwin's birth and 150 years after the publication of his book *The Origin Of Species*. The fact that these materials potentially would exhibit properties normally characteristic of living systems invoked a whole spectrum of issues regarding the nature of life itself and the implications of design interventions in this process. The panelists concurred that issues relating to the potential for autonomy and spontaneous change in nonliving matter and its manipulation required detailed ethical, social, and philosophical discussion. The implementation of NBIC technologies and living technology has far-reaching consequences, and extensive public engagement would be necessary for an informed debate. The workshop was the start of an upstream engagement process designed to occur at an intentionally early stage in the interdisciplinary collaborations, and further public forums were planned to review the work later in the year.

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