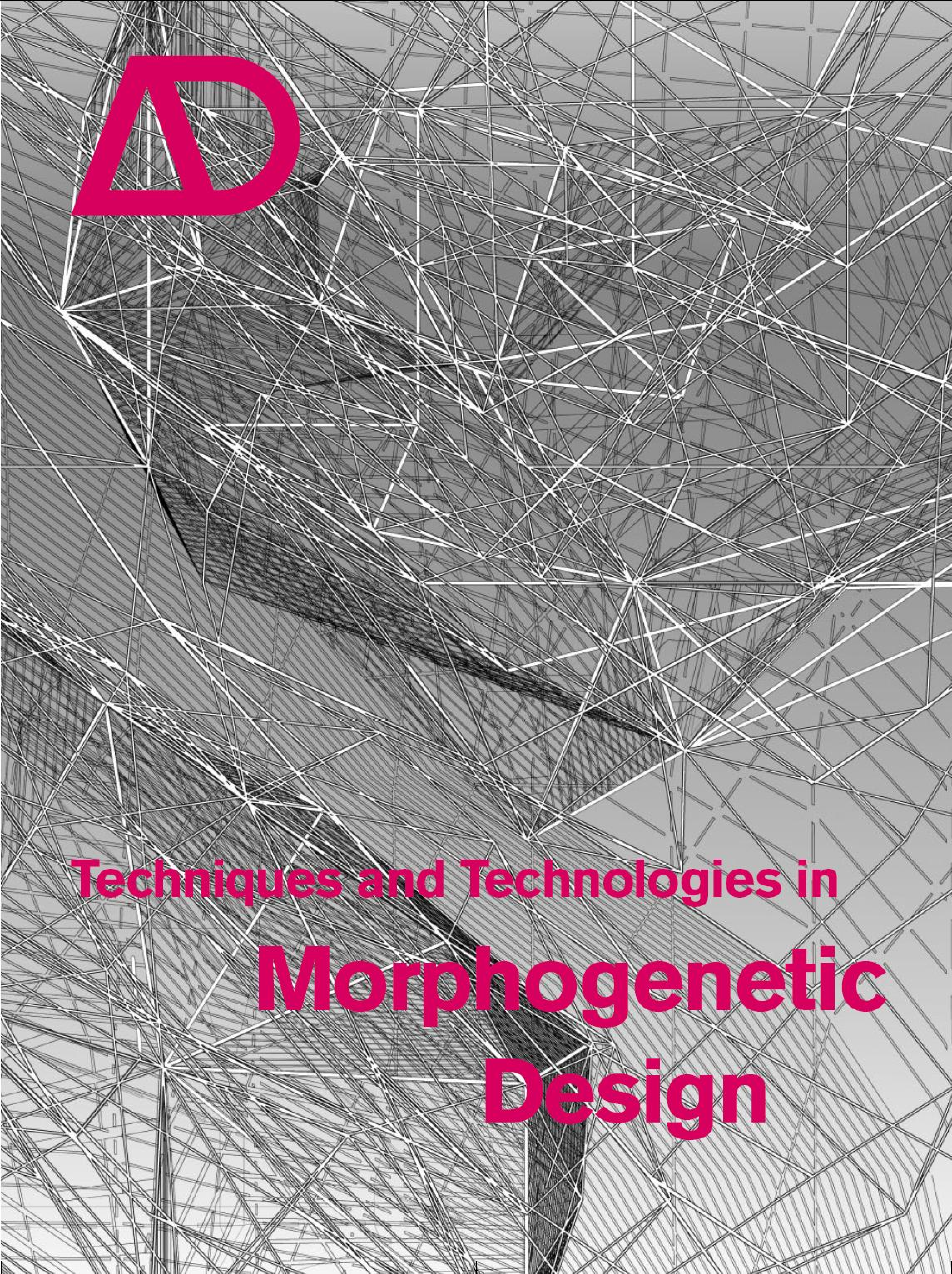

Techniques and Technologies in

Morphogenetic Design

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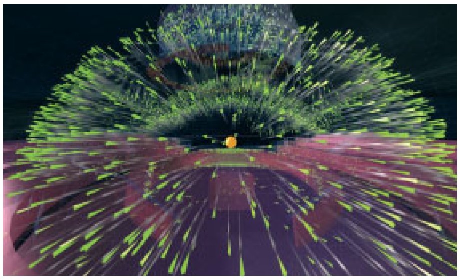

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Editorial

The cover title of this issue, *Techniques and Technologies in Morphogenetic Design*, provides it with a very wide frame: morphogenesis pertains not only to the development of form and structure in an organism, but also to an organism's evolutionary development over time. It is, in effect, a substantial signpost that in a broad brushstroke takes in the whole gamut of natural systems, both current and in evolution. It is indicative of the not inconsiderable, some might say infinite, project that guest-editors Michael Hensel, Achim Menges and Michael Weinstock have taken on through their activities in the Emergence and Design Group and their teaching and research at the Architectural Association (aa) in London. By studying the complex and dynamic exchange between organisms and their environment, they have sought out a new model for architecture – one that through the application of biochemical processes and the functionality of life is in empathy rather than at odds with natural ecology. By keeping their eye on this higher goal, the group is providing a prescient new ecological paradigm for architecture that seeks, through new scientific advances in the visualisation and understanding of natural processes and systems, to leave behind the known structural and material building blocks of architecture.

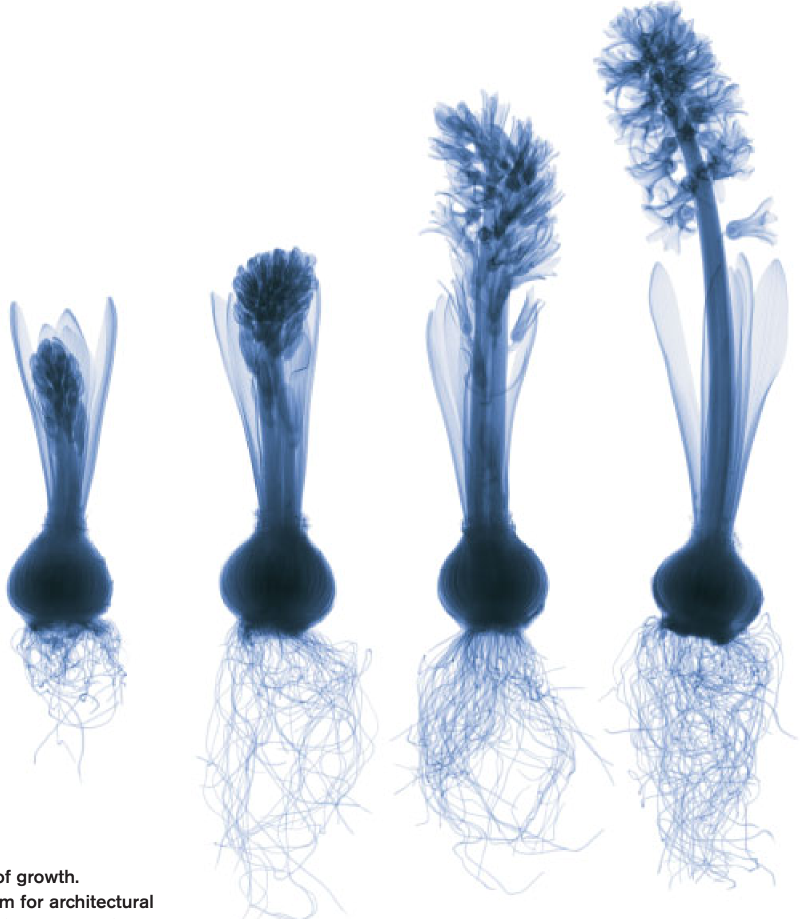
What the generic quality of the 'morphogenetic design' tag belies is the specificity and focus that Hensel, Menges and Weinstock have brought to their subject in this volume. This issue is the sequel to AD *Emergence: Morphogenetic Design Strategies*, published two years ago. It is, however, no Emergence II. Whereas in the first issue, the potential of the project was broadly being asserted through an understanding of what emergence could bring to architecture (emergence insinuating the complexity that is acquired through the evolution of organisms over time, where the sum is more than the parts), the stress on self-organisation in this issue isolates a particular aspect. The content spirals outwards, as outlined by Hensel in his introduction opposite, clarifying first what self-organisation can mean in the natural world and then discussing its application for material sciences and engineering. There is also further investigation of morphogenetic techniques and technologies, as illustrated by the group's own research and the network they have built up among fellow-minded practitioners in aligning disciplines. While the group's approach is becoming more established and they are boring down effectively into it, their influence is also widening. All three proponents are regularly invited to teach in venerable institutions abroad, with Menges having recently been awarded a professorship of form generation and materialisation in Germany. In 2004, the focus of the group's activities was largely concentrated in the recent establishment of the Masters programme at the aa, but two years later its first few years of graduates are working and spreading the word as practitioners in key firms and other international institutions are buying into this approach and recognising its inherent potential. AD

Helen Castle

Introduction

Towards Self-Organisational and Multiple-Performance Capacity in Architecture

Techniques and Technologies in Morphogenetic Design expands and develops the themes of the previous, highly successful *Emergence: Morphogenetic Design Strategies* issue of AD (Vol 74, No 3, 2004), which was also guest-edited by Michael Hensel, Achim Menges and Michael Weinstock of the Emergence and Design Group. While the first volume elucidated the concepts of emergence and self-organisation in relation to the discipline of architecture, this issue augments its theoretical and methodological foundation within a biological paradigm for architectural design, while also discussing promising, related, instrumental techniques for design, manufacturing and construction. **Michael Hensel** introduces the issue and explains how it addresses a much broader range of scales, from the molecular to that of macro-structure and, beyond, to ecological relations.



Coloured X-ray of hyacinth flowers at different stages of growth. Environmentally sensitive growth can deliver a paradigm for architectural design, as discussed in ‘Computing Self-Organisation’ (see page 12).

Robotic timber-manufacturing employed for the 2005 Serpentine Pavilion, as discussed in 'Manufacturing Diversity' (see page 70).

Complex adaptive systems entail processes of self-organisation and emergence. However, both concepts express very different characteristics of a system's behaviour.[1] Self-organisation can be described as a dynamic and adaptive process through which systems achieve and maintain structure without external control. The latter does not preclude extrinsic forces, since all physcial systems exist within the context of physics, for as long as these do not assert control over intrinsic processes from outside. Common form-finding methods, for example, deploy the self-organisation of material systems exposed to physics to achieve optimisation of performance capacity. Self-organisational systems often display emergent properties or behaviours that arise out of the coherent interaction between lower-level entities, and the aim is to utilise and instrumentalise behaviour as a response to stimuli towards performance-oriented designs.

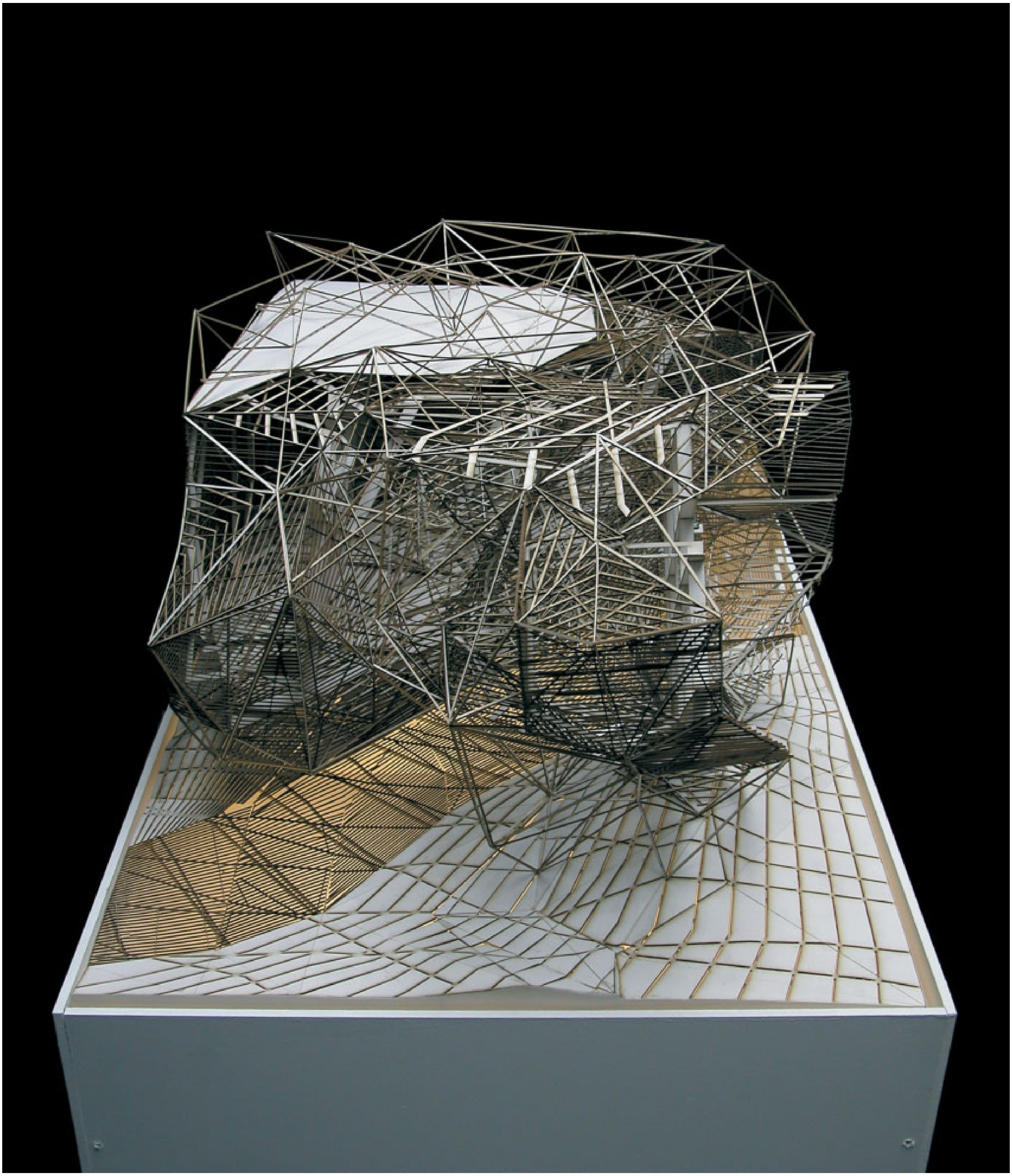
Both issues of AD guest-edited by the Emergence and Design Group seek to outline processes of self-organisation and emergence, and to integrate them within a theoretical, methodological and practice-oriented agenda for architectural design. This issue investigates how self-organisation promotes functions and properties of systems through an increase of order, how behaviour and performance capacity arises from these processes, how materials and material systems can be conditioned accordingly, which manufacturing and assembly approaches can facilitate this, and how these processes and approaches can be harnessed for architectural design to achieve a higher level of performativity and, thus, ultimately a higher level of sustainability.

Self-Organisation

The first section focuses on the introduction and discussion of processes of self-organisation based on a biological paradigm, and examines their uses in architectural design.

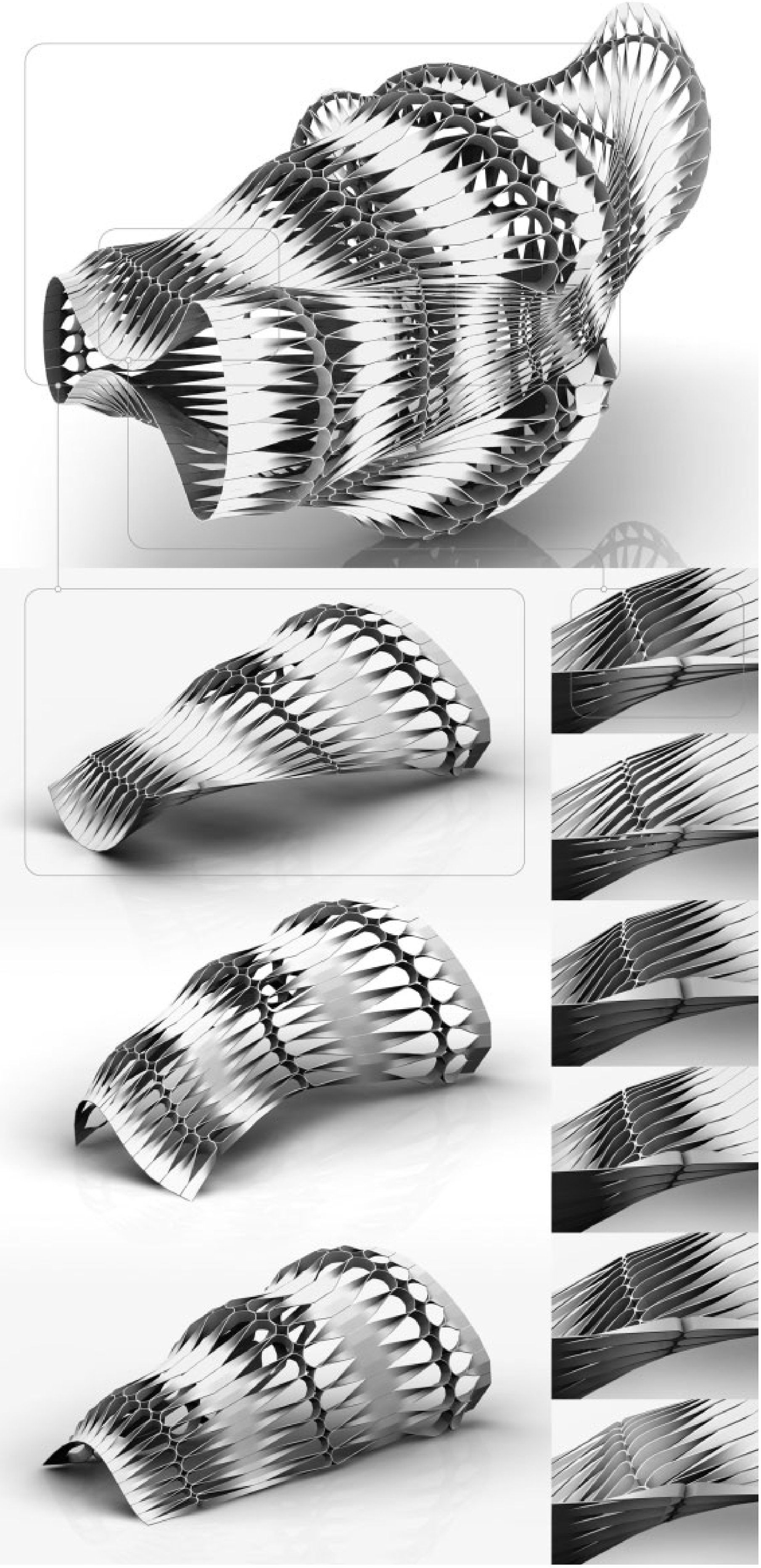
How do plants grow in relation to multiple extrinsic influences? How can environmentally sensitive growth be instrumentalised in architectural design? What are the available methods and tools, and how can they serve architectural design? Such questions are pursued by Michael Hensel in 'Computing Self-Organisation: Environmentally Sensitive Growth Modelling'. The article examines the work of Professor Prusinkiewicz's team at the Department of Computer Science at the University of Calgary in Alberta, Canada, and explicates its potential value for architectural design.

In '(Synthetic) Life Architectures: Ramifications and Potentials of a Literal Biological Paradigm for Architectural Design', the currently prevailing biological paradigm is taken to its most literal extreme in an inquiry into the consequences of understanding architectures as living entities and the potential benefits of applying life criteria to architecture. Here, Hensel examines recent advances in



Laser-cut model scale 1/75 of the Jyväskylä Music and Art Centre by OCEAN NORTH, as discussed in 'Differentiation and Performance' (see page 60).

Polymorphism is the state of being made of many different elements, forms, kinds or individuals. In biology it refers to the occurrence of different forms, stages or types in individual organisms or in organisms of the same species. Typogenesis refers to the occurrence of a new type.



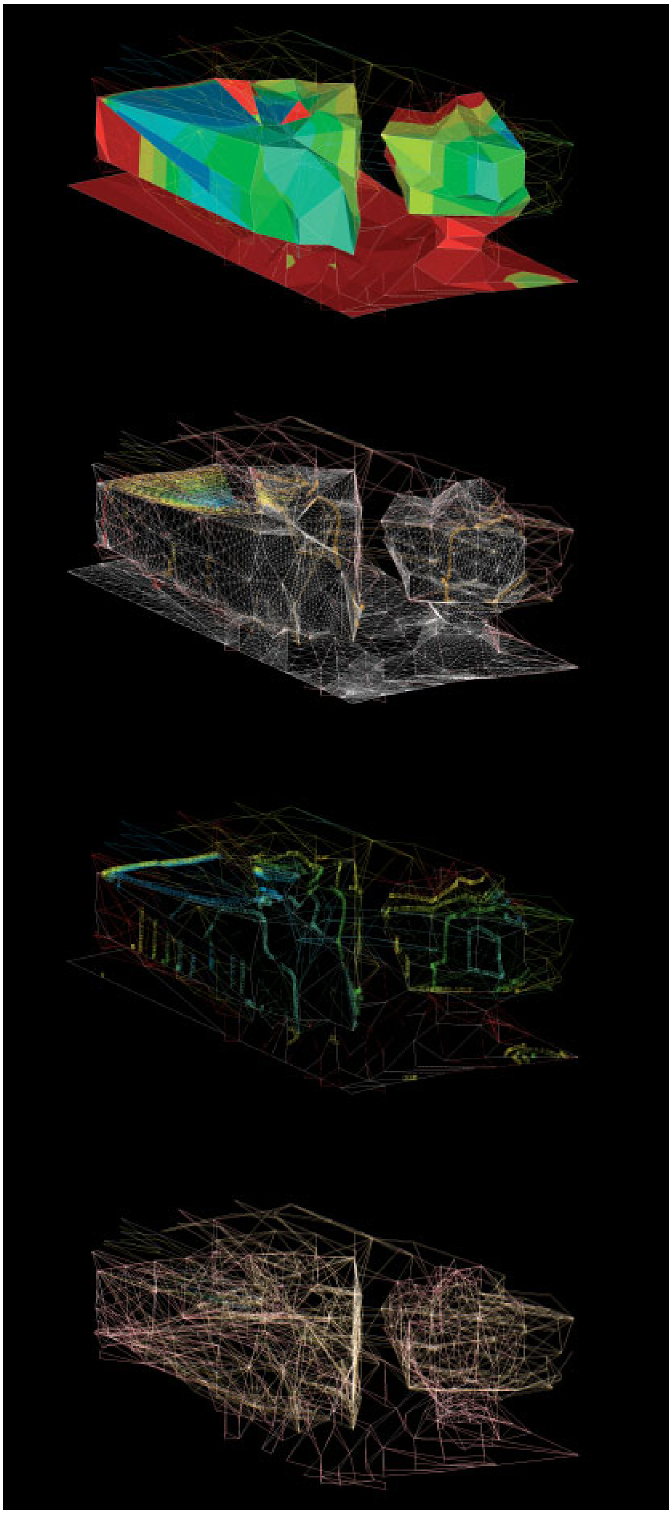
Proliferation and differentiation of a digital parametric component, as discussed in 'Polymorphism ' (see page 78).

Double curvature resulting from differential surface actuation, as discussed in 'Polymorphism' (see page 78).

synthetic life research and their potential implications for, and applications within, architecture.

The engineering principles of biological systems, the high degree of redundancy and complexity in the material hierarchies of many natural structures, and the means by which biological systems respond and adapt to environmental stresses and dynamic loadings, is discussed by Michael Weinstock in 'Self-Organisation and the Structural Dynamics of Plants'. Analysis and case studies reveal that the robust design of natural living systems is not produced by optimisation and standardisation, but by redundancy and differentiation. In this article, Weinstock gives an account of the experimental use of engineering analysis (finite element analysis/FEA) on two plant systems, presents an explanation of the nonlinear dynamics of natural structures, and suggests the abstraction of these principles for application in architectural engineering.

Recent advances in material science and related innovative methods of producing synthetic materials have had a radical impact on advanced industries, and new composite materials are being 'grown' that have increasingly complex internal structures based on biological models. In 'Self-Organisation and Material Constructions', Weinstock examines the manufacturing of advanced cellular materials informed by concepts of self-organisational processes in biological structures. New cellular materials, such as foamed metals, ceramics, polymers and glass, are indications of a significant change in the design of materials, where the boundaries between the 'natural' and the 'manufactured' begin to be eradicated.



Digital structural analysis of the Jyväskylä Music and Art Centre by OCEAN NORTH, as discussed in 'Differentiation and Performance' (see page 60). From top: Vertical displacement contours for deformation produced by gravity loading; vertical displacement vector plots for deformation produced by gravity loading; plot showing the deformed shape of the structure produced by gravity loading. (Red indicates highest deformation, blue indicates lowest deformation.)

Behaviour

Self-organising systems display capacity for adaptation in the presence of change, an ability to respond to stimuli from the dynamic environment. Irritability facilitates systems with the capacity to adapt to changing circumstances.

Adapting geometry to changing circumstances throughout the design process can be a time-consuming and costly ordeal or, on the other hand, can be anticipated and tools designed that facilitate the possibility of significant changes right up to the manufacturing stage. Whenever the design requirements and constraints and performance profiles of a design change, it is important that the design can absorb such changes through a modifiable geometric modelling setup capable of retaining geometric relations while being substantially modified.

Over the last two decades, the members of the SmartGeometry Group have worked on the conception of such tools, and pioneering new techniques and technologies in the field of computer-aided design (CAD). They are now in key positions in international companies and involved in the development of a new generation of parametric design software. In 'Instrumental Geometry', Achim Menges discusses with SmartGeometry Group members Robert Aish (Director of Research at Bentley Systems), Lars Hesselgren (Director of Research and Development, KPF London), J Parrish (Director of ArupSport) and Hugh Whitehead (Project Director of the Specialist Modelling Group, Foster and Partners, London) the group's instrumental approach to geometry and their unique collaboration based on the careful integration of architectural practice and interrelated software development.

In technology, simulation is the mathematical representation of the interaction of real-world objects. It is essential for designing complex material systems with respect to analysing their behaviour over time. In 'Advanced Simulation in Design', Michael Weinstock and Nikolaos Stathopoulos present a survey of concepts and techniques of advanced simulations within physics and engineering. Simulation is examined as a method for analysing behaviour, including the advanced physics of nonlinear behaviour, and the dynamic changes structures and materials undergo in response to changing conditions. In aerospace and maritime design, as well as automotive engineering, physical behaviour – including wear and fatigue throughout the life of a vehicle – is simulated during the design phase. In numerous industries, manufacturing processes are also simulated digitally during the design phase to facilitate 'virtual' manufacturing, prototyping and construction processes. In this article, a series of examples is used to demonstrate the incorporation of simulation methods and techniques within architectural design.

In biology, differentiation entails the process by which cells or tissues undergo a change towards a more specialised form or function, to become increasingly oriented towards fulfilling specific tasks, to acquire specific performance capacity. In 'Differentiation and Performance: Multiple-Performance Architectures and Modulated Environments', Hensel and Menges argue for an ecological model for architecture that promotes an active modulation of environmental conditions across ranges and over time through morphological differentiation. This approach promises both a new spatial paradigm for architectural design and advanced sustainability that links the performance capacity of material systems with environmental modulation and the resulting provisions and opportunities for inhabitation. Projects by OCEAN NORTH, Neri Oxman and Daniel Coll I Capdevila illustrate different approaches to designing differentiated and multi-performance architectures.

Material Conditioning

Conditioning refers to a learning process in which an organism's behaviour becomes dependent on the occurrence of a stimulus in its environment. In turn, this implies a careful calibration between behavioural and, by extension, performative scope in relation to specific ranges of environmental conditions. The capacity for this can be embedded in the makeup of materials and in the logic of material assemblies. Self-organisational and behavioural capacity of the built environment can thus be facilitated by a related material, manufacturing and assembly approach. This must be based on a related understanding and utilising material characteristics, behaviours and capacities, and ranges from using existing materials in different ways, to using computer-aided manufacturing (CAM) technologies strategically and, finally, to designing materials with greater performance capacities.

Recent developments in digital fabrication and CAM in the building sector have a profound impact on architecture as a material practice by facilitating a much greater and much more differentiated formal and material repertoire for design. In 'Manufacturing Diversity', Achim Menges describes advanced digital manufacturing techniques and technologies for steel, timber and membrane fabrication and construction, and introduces the pioneering work of selected manufacturing companies, including Covertex, Finnforest Merk, Octatube Space Structures, Seele and Skyspan.

Polymorphism is the state of being made of many different elements, forms, kinds or individuals. In biology it refers to the occurrence of different forms, stages or types in individual organisms or in organisms of the same species. Typogenesis refers to the occurrence of a new type. In 'Polymorphism', Menges instrumentalises the two concepts and presents morphogenetic design techniques and technologies that synthesise processes of formation and materialisation. Along a series of designs and design experiments, undertaken by himself along with Andrew Kudless, David Newton and Joseph Kellner et al, Menges explains an understanding of form, materials and structure as complex interrelations in polymorphic systems that result from the response to extrinsic influences and are materialised by deploying the logics of advanced manufacturing processes as strategic constraints upon the design processes.

In 'Material and Digital Design Synthesis', Michael Hensel and Achim Menges discuss the ramifications of integrating material self-organisation, digital morphogenesis, associative parametric modelling and computer-aided manufacturing into a seamless design process. They describe how the advanced material and morphogenetic digital design techniques and technologies presented call for a higher-level methodological integration, which poses a major challenge for the next generation of multidisciplinary architectural research and projects. This collaborative task encompasses the striving for an integrated set of design methods, generative and analytical tools and enabling technologies that facilitate and instrumentalise evolutionary design and evaluation of differentiated material systems towards a highly performative and sustainable built environment. The article includes works produced within the context of the Emergent Technologies and Design Masters programme at the Architectural Association (AA) in London, and a recent competition entry by Scheffler + Partner Architects and Achim Menges.

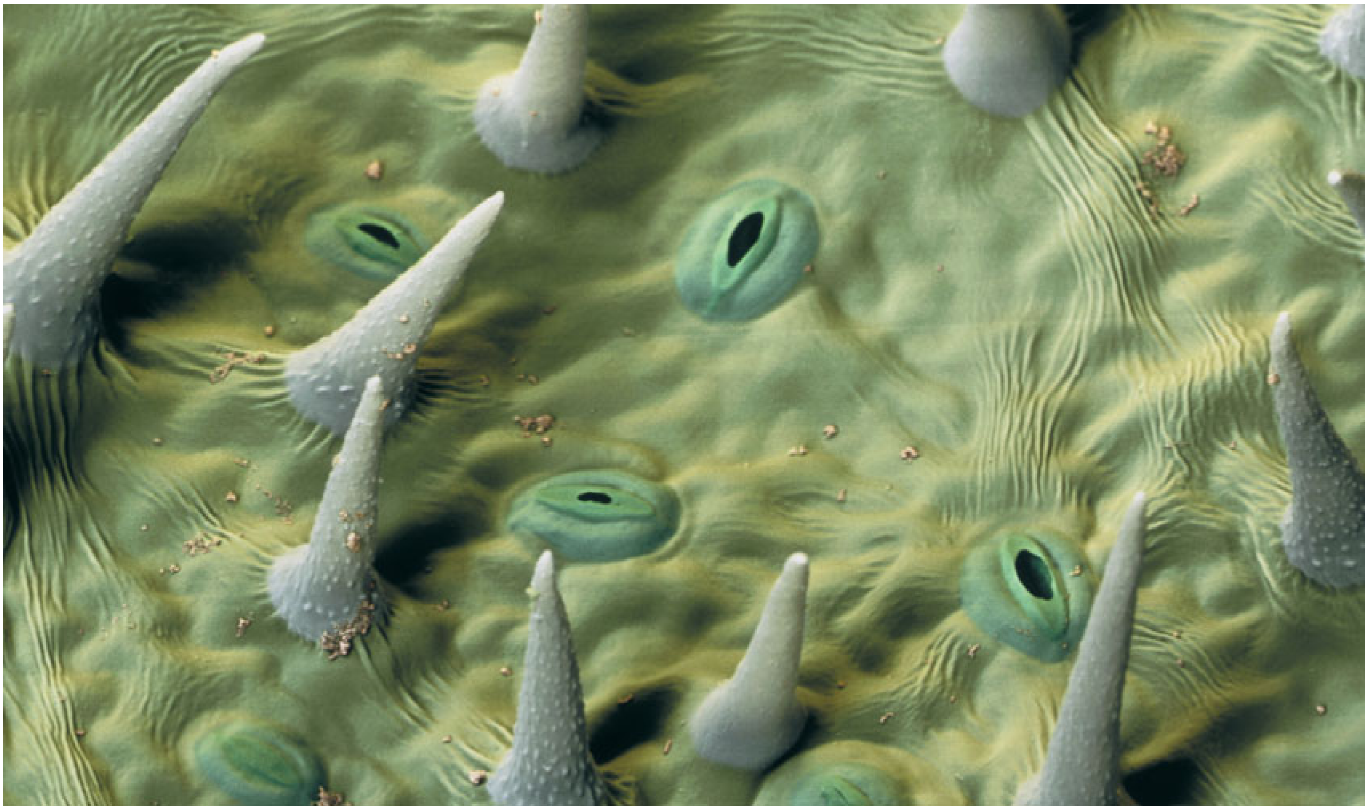
Throughout the issue, the authors have listed further references and recommended literature to provide further avenues of enquiry for interested readers. Unfortunately, due to space constraints, many relevant and important references have been omitted. However, since this publication introduces only the beginning of a new approach to multiple-performance-driven and sustainable architectural design, it is hoped that the key spectrum of concepts, methods, techniques and technologies has been presented, and that readers have been inspired to join in the quest to innovate and continue to develop such a morphogenetic design approach. Frei Otto stated that 'it is only of importance that we recognise our future tasks'.[2] It is in this spirit, and with great enthusiasm, that we hope to meet you as collaborators to work together on solving the complex tasks that today's and tomorrow's human environment and state of our biosphere present. ∆

Notes

1. For further elaboration see Tom De Wolf and Tom Holvoet, 'Emergence and Self-Organisation: A Statement of Similarities and Differences', in S Brueckner, G Di Marzo Serugendo, A Karageorgos and R Nagpal (eds), *Proceedings of the International Workshop on Engineering Self-Organising Applications 2004*. www.cs.kuleuven.be/~tomdw/.
2. Frei Otto in conversation with the Emergence and Design Group.

Computing Self-Organisation: Environmentally Sensitive Growth Modelling

The self-organisation processes underlying the growth of living organisms can provide important lessons for architects. Natural systems display higher-level integration and functionality evolving from a dynamic feedback relation with a specific host environment. Biologists, biomimetic engineers and computer scientists have begun to tackle research in this field and there is much to learn from their work. Here, **Michael Hensel** examines the work undertaken by Professor Przemyslaw Prusinkiewicz and his collaborators at the Department of Computer Science at the University of Calgary in Alberta, Canada,[1] outlining its potential application for architectural design.



Coloured scanning electron micrograph of the underside of a leaf of the herb lemon balm (*Melissa officinalis*). Numerous hairs, so-called trichomes, cover the undersurface of the leaf. These hairs may have both a protective function against predators and serve to reduce evaporation from the leaf. Stomata, or pores, appear as small, green rounded structures and exchange gases and water from the leaf surface. Magnification: x 900 at 6 x 7 centimetres.

Over the last few decades, visualisation of our environment has profoundly shaped our understanding of it and has yielded entirely new sensibilities. Photos of the earth from outer space enhanced the awareness of climatic and tectonic dynamics and a feel for the planet's fragile balance of flows. Microphotography revealed the most exquisite details of even the smallest organisms and the fine calibration of their size-dependent performance capacities in relation to a specific environmental context. Now there are new visualisation and simulation techniques that focus on self-organisational processes such as environmentally sensitive plant growth. What can be learned from these new methods is not only new sensibilities relative to the visualised processes, but also the specific configurations and features of the tools and their potential contribution in rethinking approaches to design that aim for instrumentalising self-organisation.

Self-organisation is a process in which the internal organisation of a system adapts to the environment to promote a specific function without being guided or managed from outside. In biology this includes the processes that concern developmental biology, which is the study of growth and development of organisms and comprises the genetic control of cell growth, differentiation and morphogenesis. Cell growth encompasses increases both in cell numbers and in cell size. Cellular differentiation describes the process by which cells acquire a 'type'. The morphology of a cell may change dramatically during differentiation. Morphogenesis involves the shapes of tissues, organs and entire organisms and the position of specialised cell types.

When attempting to set forth a paradigm for differentiated and multi-performance architectures, it is interesting to examine available methods for modelling biological growth informed by a hosting environment. Through this investigation it is possible to derive architectural strategies and methods that are informed by environmentally specific conditions and, thus, to achieve advanced levels of functionality and performativity.

Biologists and computational scientists have collaborated on this task with very interesting results. It is possible to evolve plants digitally that are 'grown' according to environmental input. Every change in the input yields a different growth result. In other words, a different articulation of the modelled species. This is called modelling environmentally sensitive growth and could be of interest for architects, in that it could deliver a method and toolset in which design preferences are embedded within a parametric setup, and that is simultaneously informed by a specific environmental and material context. Overall, such an approach would promise an advanced take on sustainability.

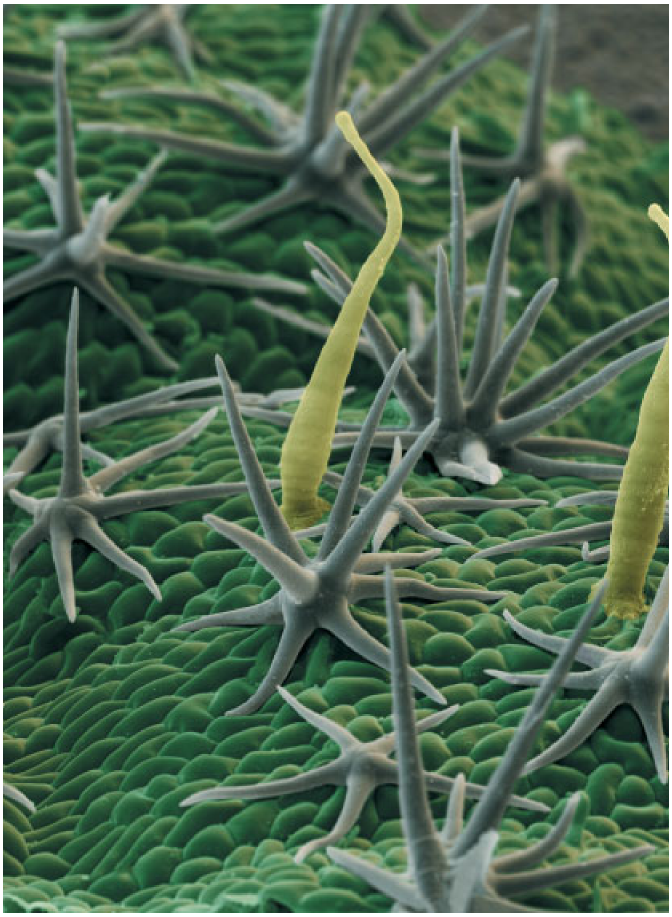
The following section introduces the research that has been undertaken in the field of computational modelling of plant growth and development, specifically by Professor Przemyslaw Prusinkiewicz's team at the Department of Computer Science at the University of Calgary, and through their collaborations with other leading experts and institutions, and outlines some of the opportunities for applications in the field of architectural design.

In 1968, the Hungarian biologist Aristid Lindenmayer researched the growth patterns of different, simple multicellular organisms. The same year he began to develop a formal description of the development of such simple organisms, called the Lindenmayer system or L-system.[2] An L-system is what in computer science is called a formal grammar, an abstract structure that describes a formal language through sequences of various simple objects known as strings. For L-system-based plant modelling, these might describe specific modules. There are two categories of formal grammars: analytical and generative. An analytical grammar determines whether a string is a member of the language described by the grammar. A generative grammar formalises an algorithm that generates strings in the defined language and consists of a set of rewriting rules for transforming strings, beginning from a single start symbol and applying iteratively the rules to rewrite the string. The specific feature of L-system grammars that allows them to faithfully capture the dynamics of plant growth is that the rewriting rules are applied in parallel to all the symbols in the string at each iteration. For L-system-based plant modelling, the rewriting rules capture, for example, the behaviour of individual modules over predetermined time intervals. The respective language consists of all the strings that can be generated by the given set of rules. This recursive process, which defines L-systems, facilitates the modelling of growth processes of organismal development, such as plant modelling.

Modelling plant growth and development is predominantly based on mathematical, spatial models that treat plant geometry as a continuum or as discrete components in space. Components might include the local scale of individual plant cells, the regional system scale of modules such as nodes, buds, apices, leaves and so on, or the plant taken as a whole for ecological models.

Modelling plant growth and development is predominantly based on mathematical, spatial models that treat plant geometry as a continuum or as discrete components in space. Components might include the local scale of individual plant cells, the regional system scale of modules such as nodes, buds, apices, leaves and so on, or the plant taken as a whole for ecological models. Developmental models that describe form as a result of growth are very interesting, as growth-influencing variables can be altered and the resulting changes compared with previous stages. Such models can involve a large number of parameters in calibrated descriptive models of specific plants. Simulations produce numerical output, which can be complemented by rendered images and animations for the purpose of easily comprehensible visualisation.

According to Professor Prusinkiewicz, the use of computational models has several benefits. Firstly, they can 'provide quantitative understanding of developmental mechanisms; secondly, models might lead to a synthetic understanding of the interplay between various aspects of development'.[3] In doing so, such models might also provide a new analytical and generative sensibility to architectural design, as they may facilitate a much better understanding of synergies between systems and environments, or subsystem interaction, in terms of their behavioural characteristics and capacities with respect to the purpose they serve locally and within the behavioural economy of a larger system.



Coloured scanning electron micrograph of the differentiated leaf surface and leaf hairs of the rock (or sun) rose (*Cistus longifolius*). These trichomes guard the leaf against attack by pests, the glandular hairs, shown in yellow, producing defensive chemicals, while the other hairs shown in grey provide mechanical protection. Magnification: x 125 at 6 x 6 centimetres.

Professor Prusinkiewicz speaks of 'models of plant architecture based on the ecological concept of a plant as a population of semi-autonomous modules … describing a growing plant as an integration of the activities of these modules'. He identifies the specifically useful feature of L-systems as the capacity to 'give rise to a class of programming languages for specifying the models [which] makes it possible to construct generic simulation software that is capable of modelling a large variety of plants at the architectural level, given their specifications in an L-system-based language. Entire model specifications, as well as model parameters, can easily be manipulated in simulation experiments.'[4] Such architectural models can be used for the modelling of entire plants, or groups of plants, potentially embedded within a given ecology, or of various parts and subscales of a single plant.

With respect to the modelling of individual plants, one of the most striking features is the integration of biomechanics into plant development, which allows informing the plant growth with extrinsic physical, biological and environmental input. Advanced models incorporate the combined impact of gravity, tropism, contact between the various elements of a plant structure and contact with obstacles.[5] The methodological setup, the toolset and the choice of determining variables are equally interesting for architectural design. Entire building systems and envelopes could thus be informed by multivariable input and optimised to satisfy multi-performance objectives. The gravity input can inform structural behaviour that is then negotiated with exposure to environmental input, for example to collect sun energy, rainwater and so on. Instead of a step-by-step, objective-by-objective optimisation at the end of the design process, undertaken by specialists who are not central to the design process, response to extrinsic stimuli can now be a part of the generative process of architecture. What might require some work is the way in which physics are integrated in the toolset beyond the purpose of visualisation, and how the output of each stage might tie into necessary analytical methods and processes.

The software developed by the Calgary team enables various plant characteristics to be modelled. These include spiral phyllotaxis, which serves to optimise the packing of seeds or scales, or the orientation and exposure of leaves towards environmental input such as sunlight.[6] This is of particular interest for architecture as it enables an informed distribution of specific performative architectural features – for example, energy-generating photovoltaic or photosynthetic elements – over a building envelope that is at the same time optimised towards multiple objectives, including the way the elements populate the building envelope relative to its overall orientation to multiple input sources, such as sun path, prevailing wind directions, and so on. Plants are capable of doing precisely this. Hair on plants, often organised in phyllotactic distribution like thorns or other such features, fulfils various functions, such as repelling water from plant stems that would otherwise rot, or repelling feeding animals through toxins contained within the hair. A very interesting function is that provided by hair around the stomata of leaves. In this case, hair modulates airflow so that leaves and plants do not lose too much water through the combination of evaporation and transpiration. This often occurs in locations that experience severe weather conditions, such as coastal climates affected by gale-force winds.

It is remarkable how such tiny features on plants manage to modulate very strong forces in such a way that the plant can survive rather extreme conditions. The lesson here for architects is that these features and their functions do not scale. However, there are two ways in which one can utilise the lesson learned from living nature: first by producing same-size features to achieve the performance observed in nature, and second to determine appropriate sizes for other features to modulate chosen conditions over required ranges. With respect to the methodological approach, very small features such as hair on plants can be mapped onto plant models. The Calgary team achieves this by generating plant skeletons using L-systems and then graphically interpreting these as generalised cylinders. Hair properties are then specified and the hair mapped onto the surface and adjusted according to positional information.[7] Interestingly, standard software such as 3D studio and Cinema 4D have recently incorporated hair simulation in relation to airflow, in such a way that specific properties of hair and airflow can be determined. While this was initially important for the film industry – for example, to produce effective hair simulation for films like *King Kong* – these tools can now be of great value in architectural design. Analysis and design generation can thus again be synthesised.

Modelling growth processes that are sensitive to system-extrinsic influences and negotiated with system-intrinsic organisational information and related features hold great potential for architecture with respect to evolving buildings from similar processes. This suggests an expansion of the endeavour to incorporate ecological organisation and relations. Ecology is the study of the relation of organism to their hosting environment, which can be studied at various levels ranging from the individual organism to populations, communities of species, ecosystems and, finally, the biosphere.

At the level of the individual organism or species, there is the study of behavioural ecology. Behaviour is an observable action or response of an organism or species to environmental factors. Behavioural ecology entails, therefore, the ecological and evolutionary basis for behaviour and the roles of behaviour in enabling organisms to adapt to their ecological niches. It concerns individual organisms and how these organisms are affected by (and how they can affect) their biotic and abiotic environment. This involves: firstly, a stimulus, in other words an internal or external agent that

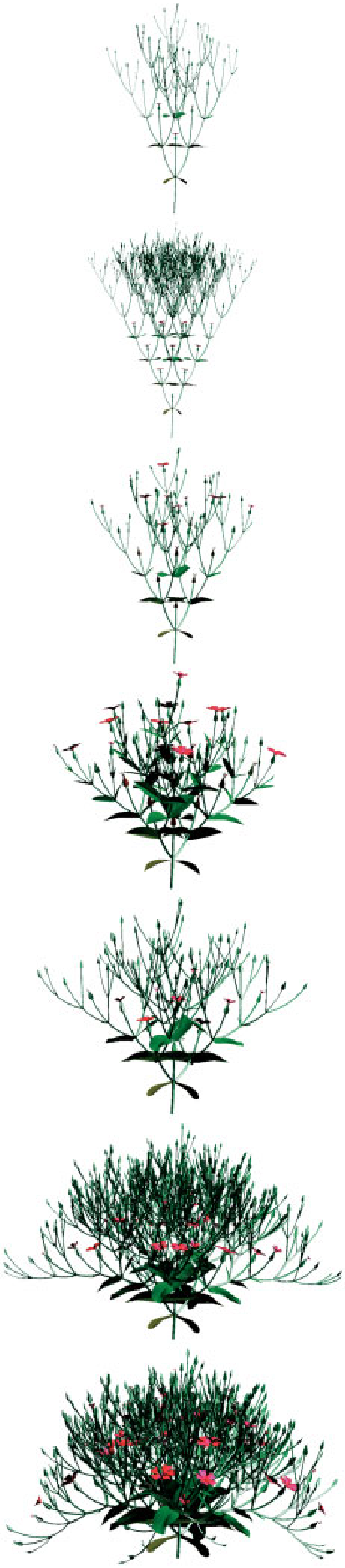
Phyllotaxis (Greek *phyllo*: leaf + *taxis*: arrangement) is the study of the arrangement of repeated plant units and the pattern of their repetition within the same alignment. These include leaves arranged around a stem, scales on a cone or pineapple, florets in the head of a daisy, and seeds in a sunflower.
Spiral phyllotaxis is a phyllotactic pattern where the elements are arranged as a spiral lattice, an arrangement of points on concentric circles with a radius increasing at a constant rate and with a constant (divergence) angle between successive points. The photo shows a Menzies Banksia (*Banksia Menziesii)* seed cone. Menzies Banksia is a shrub that produces large red flower spikes. After pollination, the seeds are produced in this cone-like structure. The cone shows a finely detailed spiral phyllotactic pattern of its unit arrangement, modified, yet not disrupted, by the larger features of the openings for seed release.

produces a reaction or change in an organism; secondly, sensibility, which is the capacity to perceive a stimulus; and thirdly, sensitivity which is the capacity of an organism to respond to stimuli. The last is regarded as a property common to all life forms and is also called ‘irritability’. The related processes of sensing, growth and actuation are often embedded capacities within the material make-up of living nature. The modelling of context-sensitive growth processes described above is based on this understanding and incorporates it in its methodological setup.

The next level concerns populations or, in other words, all organisms that constitute a specific group and occur in a specific habitat. Population ecology involves the dynamic of populations within species, and the interaction of these populations with environmental factors. The level concerning communities, which are species that interact with one another in a specific region under relatively similar environmental conditions, is called community ecology, and encompasses the interaction between species within an ecological community and their shared environment.

For population- and community-level ecologies, the Calgary team developed interesting simulation tools that generate spatial distributions for plant communities. There is a considerable level of complexity involved in the modelling of ecosystems, including the geometric articulation of individuals and their particular features, which needs to be consistent with their position within the ecosystem and the related environmental input, as well as the interaction between species and with a specific environment. For this purpose, the team combined two types of models into a bidirectional one that incorporates, first, a local-to-global direction comprising an ecosystem simulation based on individual plants and their proliferation and distribution and, second, a global-to-local direction, which infers positions of individual plants from a given distribution of plant densities. This is then further informed by a specific pattern of clustering and succession of plants. However, rather than the integration of all data into one single and very complex detailed model, a multilevel approach was developed. A higher-level model determines the distribution of plants, while a lower-level model determines the plants’ shapes and features.[8]

While this type of modelling might have obvious theoretical and practical applications for biologists, it holds similar potential for architects and urban designers. One application might involve the distribution of buildings specific to a given environment. Depending on their particular interaction with the environment, buildings can be distributed and clustered in appropriate ways, so as to accumulate or disperse the effects of their interaction and its impact on the evolution of their further relationship. A further application might concern the distribution of building elements or features across a larger building envelope. This



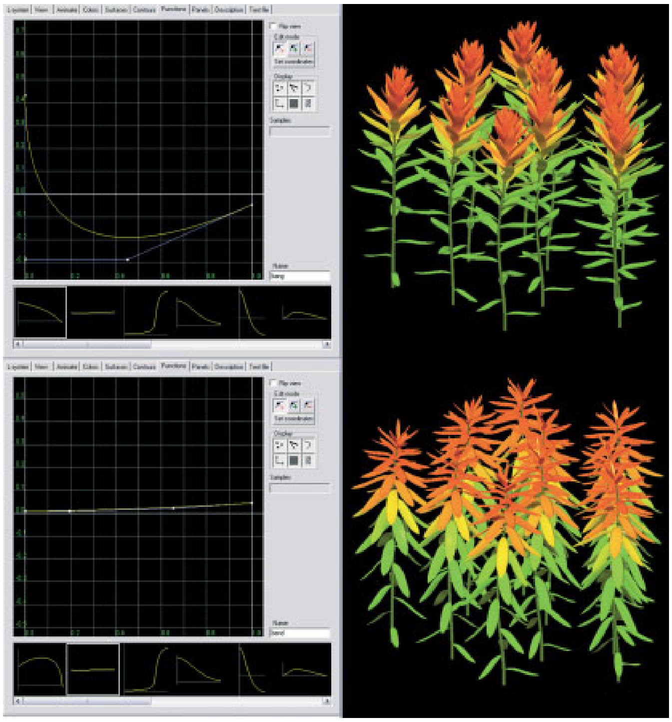
Model of rose campion (*Lychnis coronaria*) expressed using a context-free L-system generated with L-Studio, a software package developed at the Department of Computer Science at the University of Calgary.

ties in an obvious way into the modelling described above.

While these two approaches operate on a discreet and divided relationship between buildings, and buildings and their environment, or interior and exterior space, a third approach introduces a different proliferation mode that challenges and disentangles this artificial dichotomy. As many plants grow wherever conditions are beneficial, irrespective of seams that divide entities or surfaces they grow on, so could elements of the built environment be distributed according to performance-based criteria, instead of adhering to the potentially disadvantageous constraint of ownership or exterior/interior thresholds. A fairly trivial example would be a distribution of photovoltaic elements that is informed by required performance-based orientation and density into a local mat or patchwork irrespective of ownership boundaries. With systems overlapping ownership boundaries, several questions arise as to who owns what, who pays for what and who is liable for what. Some answers to these questions already exist with respect to the status and supply of current building infrastructure and energy, and one could easily start building on the existing rules and regulations. By and large, this approach delivers a very different understanding of entities and conditions of the built environment, away from the discreetness of elements towards the synergetic interrelation between environmentally sensitive and performance-oriented growth processes and their time- and context-specific output.

Our human biosphere could only benefit from an approach towards multi-performance systems distributed according to a related logic and facilitated by rigorous performance-oriented modelling tools.

Thanks to Martin Hemberg for expert advice.



Model of Indian paintbrush field generated with L-Studio. L-studio is Windows software for creating simulation models and performing virtual experiments using L-systems. The software consists of L-system-based simulators, editors and other modelling tools for creating and modifying objects, and environmental programs that simulate environmental processes that affect plant development.

Notes

1. Information on Professor Przemyslaw Prusinkiewicz's team at the Department of Computer Science at the University of Calgary, including articles and software downloads (Virtual Laboratory for Unix or L-Studio for Windows) can be found at: http://algorithmicbotany.org.
2. See Aristid Lindenmayer, 'Mathematical models for cellular interaction in development', *Journal of Theoretical Biology* 18, 1968.
3. See Przemyslaw Prusinkiewicz, 'Modelling plant growth and development', in Vivian Irish and Philip Benfey (eds), *Current Opinions in Plant Biology 2004*, Special Issue: *Growth and Development*, Elsevier, 2004.
4. ibid.
5. See Catherine Jirasek, Przemyslaw Prusinkiewicz and Bruno Moulina, 'Integrating biomechanics into developmental plant models expressed using L-systems', in H Ch Spatz and T Speck (eds), *Plant Biomechanics 2000, Proceedings of the 3rd Plant Biomechanics Conference 2000*, Georg Thieme Verlag (Stuttgart), 2000.
6. See Deborah Fowler, Przemyslaw Prusinkiewicz and Johannes Battjes, 'A collision-based model of spiral phyllotaxis', from the proceedings of SIGGRAPH '92, in *Computer Graphics*, 26 (2), July 1992.
7. See Martin Fuhrer, Henrik Jensen and Przemyslaw Prusinkiewicz, 'Modelling hairy plants', *Proceedings of Pacific Graphics*, 2004.
8. See Brendan Lane and Przemyslaw Prusinkiewicz, 'Generating spatial distributions for multi-level models of plant communities', *Proceedings of Graphics Interface*, Calgary, 2002.

Further Reading

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Aristid Lindenmayer and Przemyslaw Prusinkiewicz, *The Algorithmic Beauty of Plants*, Springer Verlag (London, New York), 1990.
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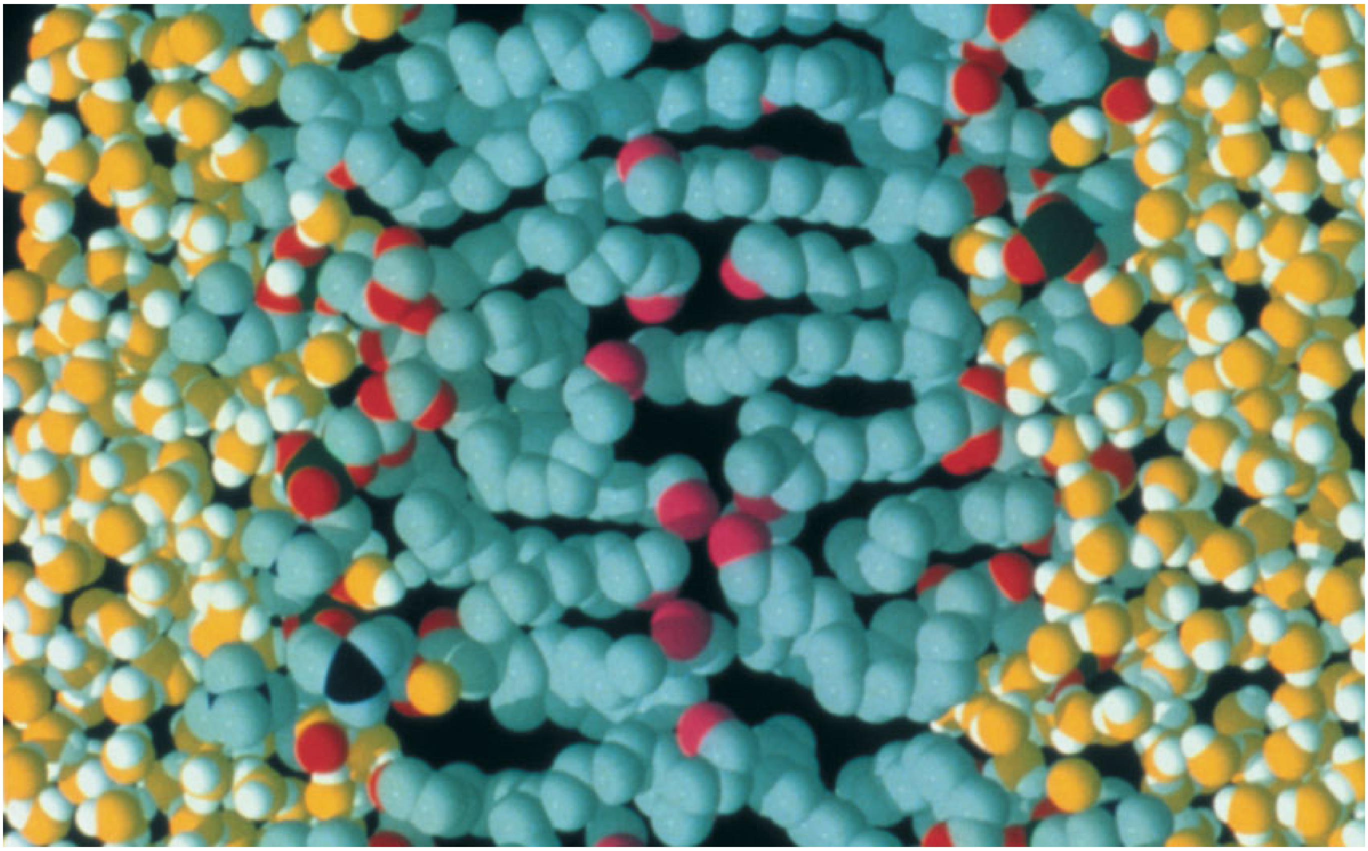
Una-May O'Reilly, Martin Hemberg and Achim Menges, 'Evolutionary computation and artificial life in architecture: Exploring the potentials of generative and genetic algorithms as operative design tools, AD Emergence: Morphogenetic Design Strategies, Vol 74, No 3, 2004, pp 48–53.

(Synthetic) Life Architectures: Ramifications and Potentials of a Literal Biological Paradigm for Architectural Design

Biology is the science of life. It concerns itself with the living. The long-proclaimed biological paradigm for architectural design must for this reason go beyond using shallow biological metaphors or a superficial biomorphic formal repertoire. The consequence is a literal understanding of the design product as a synthetic life-form embedded within dynamic and generative ecological relations. **Michael Hensel** examines the repercussions of this proposition and surveys current developments in biology and biochemistry with respect to synthetic-life research, gathering insights into their potential application in architectural design.



Molecular graphic of the phospholipid bilayer that forms the membrane around all living cells. The cell membrane is made of phospholipid molecules, each of which has a hydrophilic (soluble in water) and hydrophobic (insoluble in water) end. The hydrophobic part of the phospholipid is a fatty-acid chain, shown here in blue. The molecules line up in two sheets, with the fatty-acid chains forming a hydrophobic layer in the middle. The hydrophilic surface on both sides of the membrane, shown here in yellow and white, is the point of contact for molecules leaving or entering the cell.

To pursue seriously the proposition of synthetic-life architectures it is important to take a close look at biological processes and materials, all the way down to the molecular scale, involving biochemistry in the understanding of the advanced functionality and performance capacity of biological organisms. The composite material organisation of biological structures is typically morphologically and functionally defined across a minimum of eight scales of magnitude, ranging from the nano- to the macro-scale. While inherent functionality is scale dependent, it is nevertheless interrelated and interdependent across scales of magnitude. It is, in effect, nonlinear: the whole is more than the sum of the parts. A central role is played by processes of self-organisation and the functional properties that emerge from them.

Self-organisation is a process in which the internal organisation of a system increases automatically without being guided or managed by an external source. It is central to the description of biological systems, from subcellular to ecosystems. Self-organising systems typically display emergent properties, which arise when a number of simple entities or agents cooperate in an environment, forming more complex behaviours as a collective. Emergent properties arise when a complex system reaches a combined threshold of diversity, organisation and connectivity.

Thanks to biomimetic engineering, the strategic consideration of the interrelated make-up and functionality of biological materials is slowly beginning to make its way into architectural design. However, in relation to architecture, thus far this concerns, at best, the arrangement and properties of fibres and matrix in anisotropic composite materials. It would seem logical and necessary to also include the molecular scale, which promises to yield a functionality of an as yet unrealised extent and to make possible advanced performativity and sustainability. Such an approach would involve biochemistry, the discipline concerned with the study of molecules and their chemistry in reactions that facilitate the processes that make living systems possible.

An inquiry into synthetic-life research reveals a broad range of activities and involved institutions. The Programmable Artificial Cell Evolution (PACE) project, for example, is an integrated project funded by the European Commission and is made up of 14 European and US universities and businesses. Together these organisations pursue research related to the development of artificial cells and methods to programme their chemical functions. The PACE project aims at creating the foundation for an embedded information technology using programmable, self-assembling artificial cells.[1] One of its members, the European Center for Living Technology (ECLT), based in Venice, conducts research and training for scientists and engineers with the aim of utilising programmable artificial-cell evolution, and hosts public debates on the social, ethical and safety issues related to living technology.[2] And ProtoLife, also based in Venice, is dedicated to the development of ‘evolutionary chemistry with the long-range goal of creating artificial cells from nonliving raw material, and programming them with desired chemical functionality’.[3]

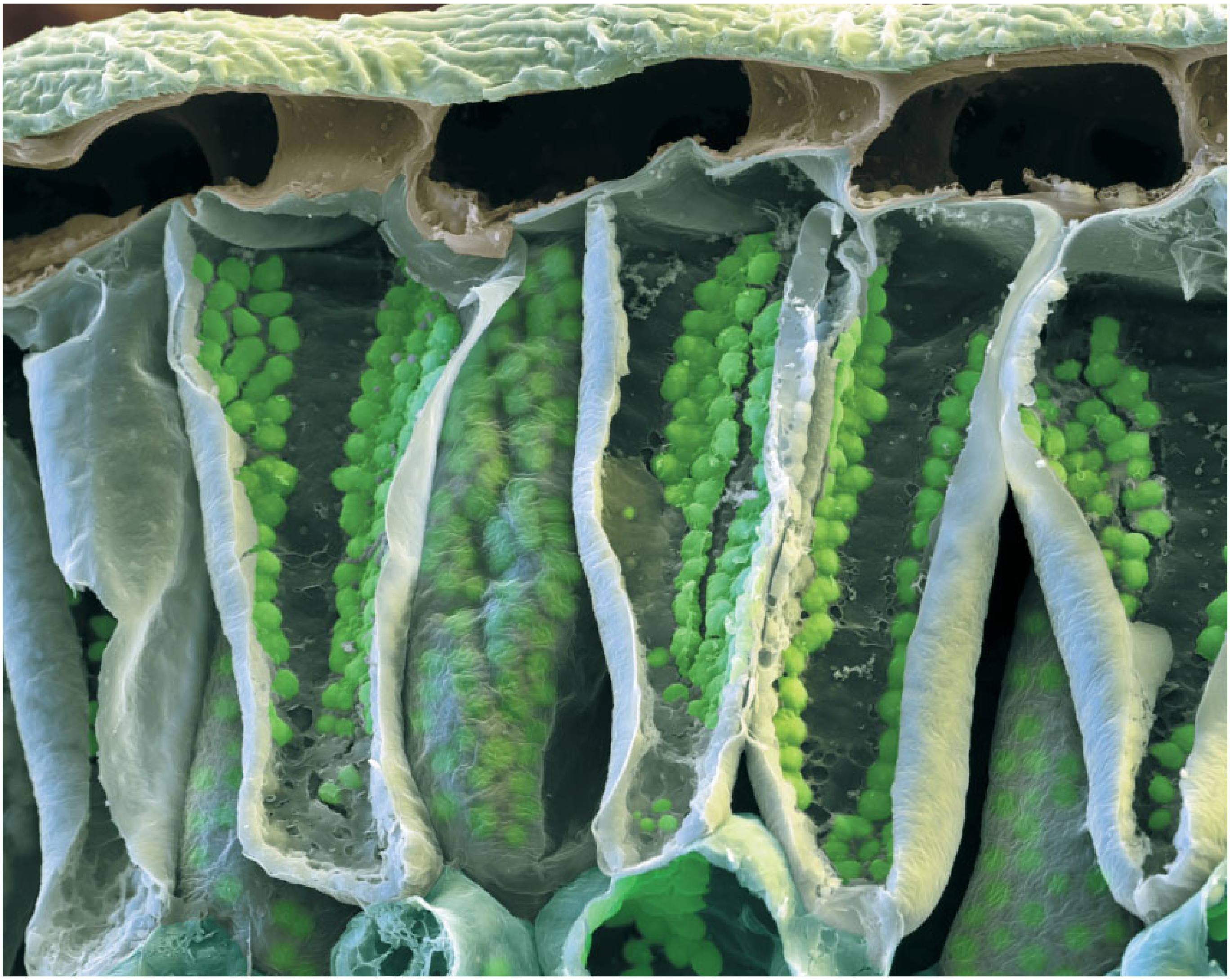
While some of the PACE research teams attempt to create synthetic life from existing biochemical structures that can be found in biological organisms, others try to create synthetic life from compounds that do not occur in living nature. However, whatever their approach, it must be based on fulfilling criteria on the basis of which it can be established whether something is alive or not.

Protocell Assembly, a project sponsored by the Los Alamos National Laboratory, ‘seeks to assemble a minimal self-replicating molecular machine’, and focuses on the conditions under which simple synthetic life-forms can be assembled. According to its mission statement: ‘The project seeks to develop the underpinning science for the assembly of functional proto-cells, ie simple self-reproducing nano-systems that can perform useful tasks.’[4] The Los Alamos team is currently attempting to achieve a synthetic life-form nick-named the ‘Los Alamos Bug’.

While some of the PACE research teams attempt to create synthetic life from existing biochemical structures that can be found in biological organisms, others try to create synthetic life from compounds that do not occur in living nature. However, whatever their approach, it must be based on fulfilling criteria on the basis of which it can be established whether something is alive or not.

In 1971, the Hungarian chemical engineer and biologist Tibor Gánti provided a ground-breaking elaboration of life criteria in his seminal work *The Principles of Life*,[5] in which he distinguished between real or absolute life criteria and potential life criteria. According to Gánti, the former are necessary for an organism to be in a living state, while the latter are necessary for the organism’s survival in the living world. Real-life criteria are: 1) inherent unity – a system must be inherently an individual unit; 2) metabolism – a living system has to perform metabolism; 3) inherent stability – a living system must be inherently stable; 4) an information-carrying subsystem – a living system must have a subsystem carrying information that is useful for the whole system; 5) programme control – processes in living systems must be

Coloured scanning electron micrograph of a section through the leaf of the Christmas rose (*Helleborus niger*). In the body of the leaf in the centre of the image are numerous cells containing chloroplasts (green). These are small organelles that are the site of photosynthesis within the leaf. Photosynthesis is the process by which plants use sunlight to turn carbon dioxide into sugars. Magnification: x 750 at 4 x 5 inch.



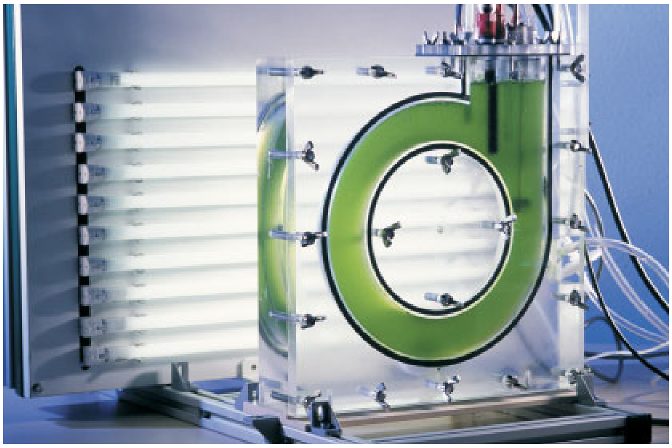
regulated and controlled. Potential life criteria are: 1) growth and reproduction; 2) the capability of hereditary change and evolution; 3) mortality. Synthetic-life research embraces a similar, if abbreviated, list of criteria, including containment (inherent unity), metabolism, heredity and evolution.[6] Synthetic life must fulfil these criteria, driven by deep self-organisational capacity that reaches across the involved scales of magnitude of articulation of biological materials. These criteria are further examined below, and their current or potential application discussed in relation to their prospective use for architecture.

Containment

Containment implies that a system must be inherently an individual unit, a function provided by biological membranes. These are structures composed mostly of lipid and protein that form the external boundary of cells and of major structures within cells. A lipid bilayer membrane is a membrane composed only of lipid. Lipid bilayer is the foundation of all biological membranes, and is a precondition of cell-based life. A lipid is an organic compound that is insoluble in nonpolar organic solvent. Lipids, together with carbohydrates and proteins, constitute the principal structural materials of living cells. The basic functions of cell membranes are to provide for integrity of the cell: that is, in general, to separate the outside from the inside, as well as carrying out intelligent filtration of material through the membrane. While water and a few other substances, such as carbon and oxygen, can diffuse across the membrane, most molecules necessary for cellular functions traverse the membrane by means of transport mechanisms. Information can also be transmitted across the membrane: specific membrane proteins, so-called receptors, bind hormones or other such informational molecules and subsequently transmit a signal to the interior of the cell.

As membranes form the boundary between cytoplasm and the surrounding environment, they are affected by

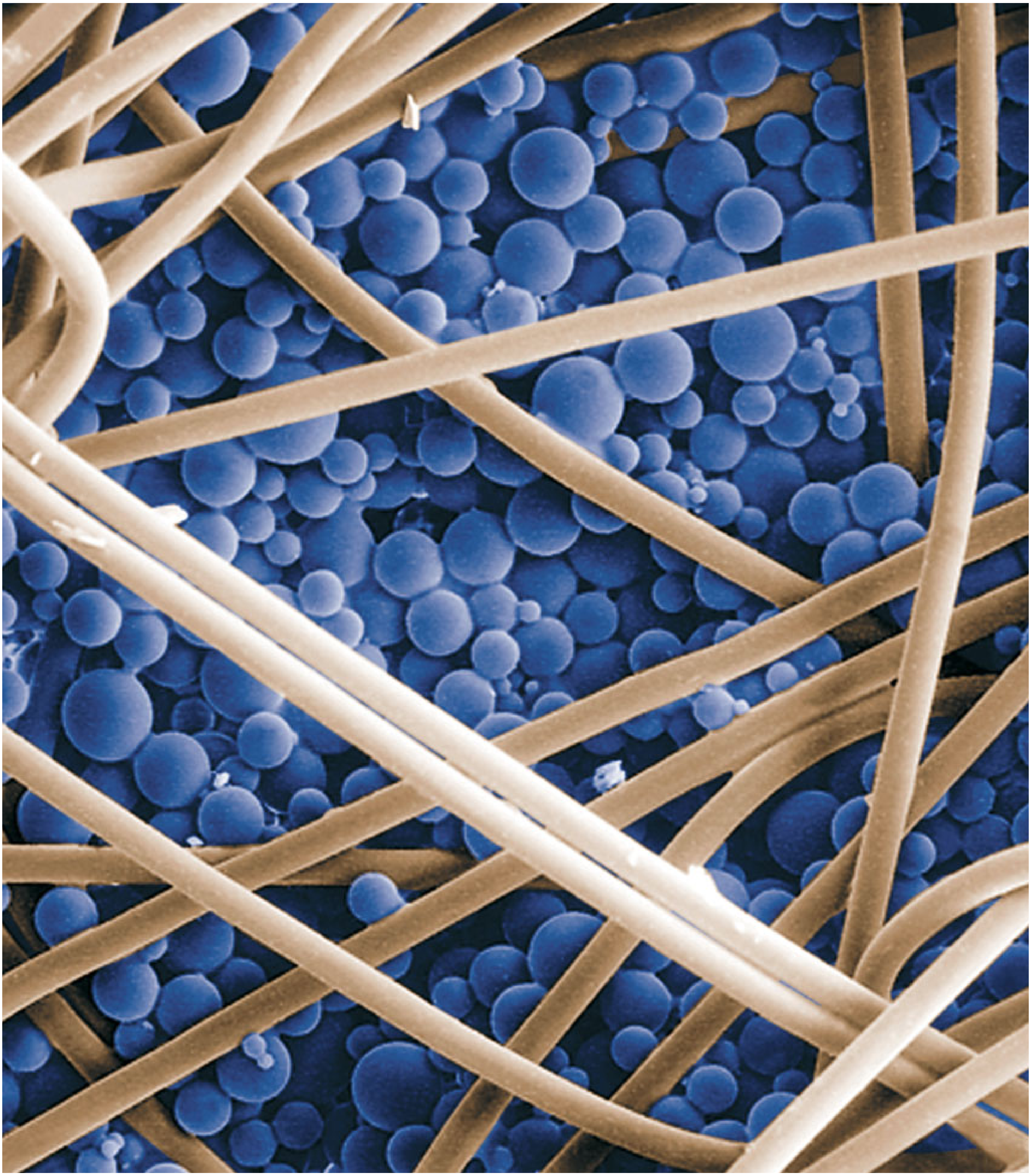
Algal bloom turning waves green on the Gulf of Tadjoura, Djibouti, near the Red Sea. The green colour of the water is due to millions of marine algae, microscopic plants that increase in number between spring and autumn due to increased levels of sunlight. Algae are available in great abundance and can be grown and used in artificial photosynthesis technologies to provide the built environment with energy and the means to improve the environment.



Bioreactor using algae (green) to produce hydrogen gas for use as a fuel. The light source fuels the growth of the algae. Burning hydrogen produces water vapour and is a cleaner source of energy than burning fossil fuels like coal, gas and oil. Photographed in 2003, at the University of Nantes, France.

environmental stresses from the exterior as well as the pathogenic processes from the interior of the cell. The continuous control of chemical processes in membranes typically involves three components: first, a sensor that will provide a response to the chemical whose concentration is to be controlled; second, a controller that translates the response provided by a sensor into a signal that is then transmitted to an actuator; and third, an actuator that will drive the controlling mechanism. Systems combining all three components exist in living cells. Ligan-gated ion channels, for example, are protein molecules that are embedded in the plasma membrane of the cells, and respond to the presence of a biological molecule by opening a channel in the cell membrane that allows a selective passage of ions through the hydrophobic membrane.

Scientists at a number of universities are currently conducting research into membrane materials that incorporate biological molecules capable of selective



Coloured scanning electron micrograph of microcapsules (blue) that contain a phase-change material (PCM) coating fabric fibres. The PCM can absorb and release heat generated by a person wearing the fabric, warming or cooling it as required. If the wearer's body temperature rises after exercise, the PCM absorbs the heat and melts, preventing heat reflecting back onto the body. If the wearer's temperature then falls, the PCM refreezes, releasing its absorbed heat and warming the garment. The PCM can undergo this melting/refreezing cycle almost indefinitely. PCMs are being developed by Outlast Technologies, US. Magnification unknown.

recognition of a specific signal in such a manner that the membrane will respond by changing its porosity. This change enables other molecules to permeate the membrane. In so doing, the flux through the membrane will be controlled at a local level without the need for central control. While biomembranes are currently not available on a scale relevant to the building industry, the current research is nevertheless promising and includes smart biological membranes that can interact with their environment based on self-assembling biological structures and polymers.[7] Current scales of applications encompass mainly micro-filtration and gaseous diffusion. Medical research focuses on coating for therapeutic agents that can release drugs in response to the condition of the patients, or self-repairing coating in replacement joints.

With research progressing at such a fast pace, biological membranes could deliver a completely new level of interaction and exchange between exterior and interior environments through programmable intelligent filtration and distribution on a molecular scale. In combination with metabolic processes, this might entail the removal of pollutants and improvement of the quality of air and water in both the exterior and interior environments.

Metabolism

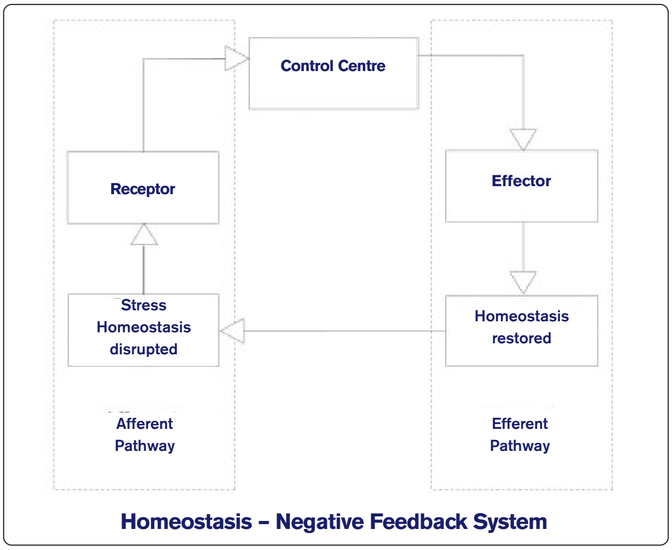
Metabolism encompasses the physical and biochemical processes that occur within a living organism that are necessary for the maintenance of life. The biological purpose of metabolism is the production and storing of usable energy. Metabolism entails that organic molecules necessary for life are synthesised from simpler precursors in a process called anabolism, while other complex substances are broken down into simpler molecules in a process called catabolism, so as to yield energy for vital processes. Photosynthesis is the qualitatively and quantitatively most important biochemical process on the planet. The entire energy-dependent process called 'life' is enabled through photosynthesis. The process entails the conversion of energy in sunlight to chemical forms of energy that can be used in biological systems. More specifically it is a biochemical process in which plants, algae and some bacteria harness energy from light to produce food. Carbohydrates are synthesised from carbon dioxide and water using light as an energy source. Most forms of photosynthesis release oxygen as a by-product. Nearly all living beings depend on the oxygen and energy production from photosynthesis for their survival.

The process has been studied in great detail and photosynthetic systems are frequently used for the development and application of advanced technologies. Artificial photosynthesis attempts to replicate the natural process of photosynthesis, converting sunlight and carbon dioxide into carbohydrates and oxygen. One of its potential applications is clean fuel production, such as hydrogen – the burning of which yields only water and energy – and the conversion of carbon dioxide into organic material and oxygen. On an industrial scale, this possibility might have a dramatic effect upon sustainability and climatic phenomena, for example global warming.

Harnessing artificial photosynthesis might eventually lead to self-sufficient and zero-pollution buildings that are independent from centralised energy-grids and improve their hosting environment. Future applications for artificial photosynthesis are within the solar-energy field (silicone-based technologies require a highly energy-intensive production process and are less efficient in energy output), the production of enzymes and pharmaceuticals, bioremediation, which entails the clean-up of environmental pollutants, and the production of clean-burning fuels such as hydrogen.

Several lines of research currently under way seek to deliver feasible technologies. The main goals are to overcome the energy-consuming production and use of silicon-based photovoltaic cells and the mechanics needed to orient them in an optimal way to the sun path over time. Light photosynthesis-capable membranes are a promising direction for further development. Others include the use of living organisms, such as algae and bacteria.[8] Thus synthetic metabolism has the potential to provide the energy needed for all significant synthetic-life processes. Synthetic-life architectures, fuelled by artificial

Frozen vials containing fragments of DNA known as BioBricks. Each BioBrick performs a specific function and is combined with others to produce novel forms of genetically altered cells. These cells are designed in the same manner as electronic circuits. This new field of genetic engineering is known as synthetic biology and is a simpler method of producing genetically modified cells. In the future, synthetic biology may be used to create new drugs, biosensors and biological computers, or diagnose diseases. Photographed at Massachusetts Institute of Technology, US.



Biological organisms rely on controlling and stabilising internal conditions through homeostasis, a process controlled by negative feedback. When a state of disruption or stress is registered by receptors, the information is sent to the control centre, which evaluates it and sends a signal to an effector that restores homeostasis.

photosynthesis, might generate their entire energy-requirement from this process, provide a whole series of useful by-products and contribute to cleaning environmental pollutants.

Homeostasis

Homeostasis is a property of open systems, especially living organisms, which regulates their internal environment so as to maintain required stable conditions: for example, stable body temperature. The technical equivalents are thermostats. This commonly involves negative feedback, by which positive and negative control is exerted over the values of a variable or set of variables, and without which control of the system would cease to function. Like the previous criteria, homeostatic systems require sensors to measure the parameters being regulated: signal transmission to a local or global control centre where the deviations from desired values are measured; control centres – if the measured values are different from the set points then signals are sent to effectors to bring the values back to the needed levels; and effectors capable of responding to a stimulus.

The range of biological and available technical sensors, detectors, transducers and actuators is impressively broad.[9] Furthermore, technological setups that can facilitate conditions of homeostasis in a simple negative feedback are often so ubiquitous that one no longer takes notice of them, for as long as they work well. Overall, there are two main questions. First, which stimulus or range of stimuli needs to be registered and transmitted to effectors or actuators to yield a desired response? Second, how to develop technologies that operate more on biochemical principles than mechanical ones, so that the required functionality can be embedded into the material make-up of a synthetic-life architecture? In addition, it might be useful for architectural design to consider negative as well as positive feedback, beyond the criterion of homeostasis, to include responsiveness that can both stabilise or yield change in conditions and behaviours.

Heredity + Evolution

In biology, heredity entails the conveyance of biological characteristics from a parent organism to offspring through genes. Evolution entails change in the genetic composition of a population across successive generations. This is posited as the result of natural selection acting on the genetic variation among individuals, which, over time, results in the development of new species. The research team that is building the Los Alamos Bug posits that if containment, metabolism and genome (heredity) fit together, they should provide the basis for evolution. Evolution is thus seen as an emergent process, the capacity for which may be provided by the correct functional relation and calibration between containment, metabolism and heredity, together with the necessary capability of reproduction.

Growth and reproduction, so argues the Los Alamos team, will yield natural selection, favouring, for example, the individuals that can perform metabolic processes most effectively. This argument suggests that evolution can be understood in some way as a process of optimisation of functionality and performance capacity. Biological systems are, however, so complex that it is often still too difficult to deduce optimisation criteria and constraints in such a way that optimisation goals could be defined. Moreover, biological systems are characterised by multiple-performance capacities across ranges facilitated by the interaction of subsystems across a minimum of eight scales of magnitude. Disentangling this into single-objective optimisation goals is not only difficult, but also simply the wrong approach. Interdependent subsystem functionality results in higher-level integration and functionality. Again, the whole is more than the sum of its parts. Learning this from living nature is already a major achievement for architectural design that will yield new methods of analysis and design generation. However, above and beyond the methodological retooling is the question of how to embed this capacity within, or yield it from, materials and for which purpose.

This brings us back to the criterion of heredity. The challenge is how to embed information within a material so that it can be both passed on and evolve, and to achieve reproduction in order to yield evolution. Particularly interesting here is the Los Alamos team's approach to this problem. Its 'bug' features short strands of peptide nucleic acid (PNA) that carries the genetic information. Like DNA, PNA is

It is precisely the complex and dynamic exchange between an organism and its environment, and the functionality that evolves from it, that makes synthetic life interesting for architecture. Understandably, the very notion of architecture that is alive may sound scary to some and blasphemous to others. However, what is proposed here is not a version of Mary Shelley's *Modern Prometheus*. Instead, it involves embedding into buildings the biochemical processes and functionality of life for the advantage of humans, other species and the environment.

made of two strands. Due to their chemical characteristics and specific 'environmental' conditions, these strands can combine or separate into single strands. Single strands have the ability to attract fragments of matching PNA from their 'environment'. Doubling, splitting and attracting new fragments is a very simple form of reproduction and heredity.

Returning to the question of evolution towards higher levels of performance capacity, it is interesting to consider the field of smart material research. One definition is that 'smart materials and structures are those objects that sense environmental events, process that sensory information, and then act on the environment'.[10] In stable environments this capacity would neither be of use, nor would it depend on evolution to adjust to changing stimuli. Life and its evolution depend on the exchange between organisms and a dynamic environment. To make any sense, smart materials would also need the capacity to evolve, in order not to be immediately redundant if there was an environmental change beyond their capacity to respond in a manner that is in some way beneficial for the overall system. Material research and biochemistry need to cross-inform one another to deliver smart materials that deserve this label. Obviously there is a lot of work to be done in this field before specific industrial applications can be delivered.

In general, there is, of course, the added difficulty of not only fulfilling the above-introduced life criteria, but also of linking them into an interdependent process that amounts to synthetic life. Moreover, the hierarchical functional organisation of biological organisms across a vast range of scales of magnitude must be seen in relation to a specific context: in other words, to the numerous scalar interrelations within and between ecological systems. Ecology is the branch of biological science that studies the distribution and abundance of living organisms, as well as the interactions between organisms and their environment. Environment is a collective term for the conditions in which an organism lives. It encompasses the complex physical, chemical and biological surroundings that make up the habitat of an organism at any given time.

It is precisely the complex and dynamic exchange between an organism and its environment, and the functionality that evolves from it, that makes synthetic life interesting for architecture. Understandably, the very notion of architecture that is alive may sound scary to some and blasphemous to others. However, what is proposed here is not a version of Mary Shelley's *Modern Prometheus*. Instead, it involves embedding into buildings the biochemical processes and functionality of life for the advantage of humans, other species and the environment. One might think of it as a highly performative synthesis between house and garden embedded within its specific micro-environments and niches and embedded within macro-ecological systems. This promises a powerful, if partial, solution to increasing environmental problems at a time when governments continue to place economic development over environmental concerns, in the face of a world climate that might have begun to go bonkers.

Notes

1. For PACE see http://134.147.93.66/bmcmyp/Data/PACE/Public.
2. For ECLT see http://bruckner.biomip.rub.de/bmcmyp/Data/ECLT/Public/.
3. For ProtoLife see http://www.protolife.net. See also Bob Holmes, 'Alive! The race to create life from scratch', *New Scientist*, Issue 2486, 12 February 2005.
4. See http://www.protocell.org.
5. Tibor Gánti, *The Principles of Life*, Oxford University Press (Oxford), 2003, first published in Hungarian as *Az élet principiuma*, Gondolat (Budapest), 1971.
6. Bob Holmes, op cit, pp 28–33.
7. For further information see, for example, the Biochemical and Biomedical Engineering Research Group at Bath University http://www.bath.ac.uk/chemeng/research/groups/babe.shtml.
8. For a detailed elaboration, see Werner Nachtigall, *Bionik: Grundlagen und Beispiele für Ingenieure und Naturwissenschafter*, 2nd edn, Springer Verlag (Berlin, Heidelberg, New York), 2002, pp 318–36.
9. See Michelle Addington and Daniel Schodek, *Smart Materials and Technologies for the Architecture and Design Professions: Elements and Control Systems*, Architectural Press (London, New York), 2005, pp 109–37.
10. John J Kroschwitz (ed), *Encyclopaedia of Chemical Technology*, John Wiley & Sons (London), 1992.

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